

IMPERIAL COLLEGE LONDON

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# Modelling and Design of Shear Wave EMATs

by

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**Doctor of Philosophy**

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# Declaration of Originality

The content of this thesis is my own research work, which was completed with the supervision of Dr. Frederic Cegla. Wherever other work was used I clearly acknowledged, and provided references.

Jaime Alberto Parra Raad

28/05/2022

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# Abstract

In this thesis two physical phenomena were investigated: the mechanical load generation and wavefield radiation of Electro-Magnetic Acoustic Transducers (EMATs). The conceptual results obtained in this work addressed two major research questions: how the transduction of EMATs and the properties of materials affect the EMAT's wavefield generation, and how orthogonal shear waves can be used to detect and characterise surface-breaking defects. The outcome of these two research questions were tested in the design of an orthogonal and co-located coils shear wave EMAT and in the design of a shear wave phased array EMAT.

EMATs, are transducers that by means of electromagnetic forces excite mechanical loads in metallic materials. EMATs are often utilised in the Non-Destructive Evaluation, NDE, of a material to detect and characterise the material anomalies. Compared to their counterpart, Piezoelectric transducers, EMATs have several properties that make them a desirable means of transduction for NDE applications. EMATs are contactless and special designs can tolerate high temperatures. Hence, EMATs do not require direct contact with the inspected material to perform the NDE inspection nor cooling system to keep them operational during a NDE procedure. Nevertheless, the use of EMATs in NDE inspections is not standard procedure in industry. This is because there are concerns over the strength and orientation of the mechanical loads that EMATs produce, and the lack of knowledge about the effects that the magnetic properties of the inspected material have on the wavefield generated with EMATs. To address these concerns, the excitation mechanisms of EMAT transduction were studied on different metallic materials. The three excitation mechanisms -the Lorentz force, the magnetisation force and the magnetostriction force- of a shear wave phased-array EMAT were estimated on paramagnetic, diamagnetic, ferromagnetic and magnetostrictive materials. The results obtained showed

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that by designing an EMAT to maximise the Lorentz Force mechanism, an EMAT can maximise the strength of the mechanical loads it excites and yield a consistent wavefield in the inspected material.

The interaction of orthogonal and co-located shear waves with surface-breaking defects was also studied in this thesis. The study focused on the detection and characterisation of surface-breaking defects in isotropic and anisotropic materials. To execute the mentioned analysis, the design of an EMAT that can simultaneously excite two co-located shear waves with orthogonal polarisation was proposed. Once the wave interaction with the defects was understood, a methodology that by means of the two shear waves can gauge the inspected material, detect the presence of a defect, characterise the principal shear direction of the inspected material and characterise the height of the surface-breaking defect was presented.

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# Chapter 1

## Introduction

### 1.1 Motivation

#### 1.1.1 Permanently installed EMATs for surface-breaking defect detection and characterisation

The presence of cracks, corrosion patches and material defects are constant threats to the structural health and integrity of petrochemical, Oil & Gas and energy industry structures. In 2014, the USA Oil & Gas industry dedicated 8bn USD to mitigate problems related to corrosion [3]. This spanned over 700000 km of pipeline network [4]. The structural health of these infrastructures is paramount for the human society wellbeing. The disruption of a pipeline network or nuclear plant due to an unattended defect can lead to catastrophic events. It can leave the industry sector and millions of houses without energy to perform their normal activities. Or it can generate substantial ecological damage to the environment and ecosystem [5–7]. The actions to prevent these undesired events are to detect the presence of the anomaly, monitor its grow and repair it without disruptions of the service or unwelcome outcomes. Non-Destructive Evaluation (NDE) supplies diagnostic tools by which the petrochemical, Oil & Gas and energy industry can assess and evaluate the structural health and integrity of its infrastructure.

Common NDE inspection techniques used in industry are visual inspection testing, magnetic particles testing, ultrasound testing, liquid penetrant testing, acoustic emission test-

ing, radiography testing and eddy current testing. Visual inspection testing, magnetic particles testing, liquid penetrant testing and eddy current testing are NDE techniques that are used to detect surface-breaking defects in the material inspected. They require direct access to the surface of the material inspected. Hence, they are used to detect surface breaking defects on the external layer of the material inspected.

Acoustic emission testing, ultrasound testing, and radiography testing are NDE techniques that provide more information than the presence of an anomaly in the inspected material. Acoustic emission testing detects and quantify active defects present in the material inspected. They are often used to detect defect activity that loads the inspected material beyond its service load. While ultrasound testing and radiography testing are NDE techniques used to detect, localise, and quantify geometrical defects, material anomalies, and material properties of the inspected material.

Among the NDE inspection techniques, ultrasound testing is the most used in industry, with an approximated share of the NDE market of approximately 27% in 2020 [8, 9]. The providers of ultrasound testing offer their service by using piezoelectric transducers, laser ultrasound and Electro-Magnetic Acoustic Transducers (EMATs). Among them, the piezoelectric transducers heavily dominate the market. While EMATs and laser ultrasound share a small part of the NDE ultrasound market. This is because EMATs and laser ultrasound are younger NDE technologies, and their implementation is more expensive compared to piezoelectric transducers. Despite this, EMATs and laser ultrasound are emerging technologies. They are fast growing in the NDE market. They are becoming less expensive to implement due to the development of cheaper electronics. In addition, they have practical advantages over piezoelectric transducers on specific NDE applications. EMATs are more suited than piezoelectric transducers for defect monitoring and for inspections where no direct contact with the inspected material is needed. While laser ultrasound is more suited than piezoelectric transducers when precise and highly accurate measurements are necessary [10].

Conventionally, to detect the presence of surface-breaking defects (crack) placed at the opposite side of the sample to the transducer, i.e., cracks or pitting holes, ultrasound waves travelling at an oblique angle are used [11, 12]. Oblique ultrasound waves are traditionally generated by means of a piezoelectric transducer placed on a Perspex wedge. The

ultrasound wave is generated by the piezoelectric transducer, this ultrasound wave travels through the wedge, arrives at the wedge-inspected-material interface, refracts at the interface, and travels through the inspected material at an oblique angle. The squint angle of propagation depends on the acoustic impedance mismatch and the angle of incidence at the interface wedge-inspected material. If the inspected material is free of surface-breaking defects, the generated ultrasound wave travels through the material, bounces away at the back-wall of the material, and does not return to the transducer. Hence, no returning ultrasound wave is recorded by the piezoelectric transducer. However, when a surface-breaking defect is present, the ultrasound wave interacts with the walls of the defect and bounces back towards the transducer. The transducer records the bounced ultrasound wave and generates an electric signal from the interaction. The electric signal is later analysed, and the presence of the defect is determined. However, the use of piezoelectric transducers on a wedge for permanently installed monitoring applications is not convenient. Piezoelectric transducers require direct contact with the inspected material, couplant and a cooling system for its correct operation on materials with elevated temperatures. Characteristics that complicate their implementation in industrial applications as they require regular surface shapes, removal of the material coating, constant supply of couplant and the implementation of a cooling system.

Contrary to piezoelectric transducers, EMATs are contactless, do not require couplant and tolerate elevated temperatures. These advantages are due to the transduction principle of EMATs and the components that are used to build EMATs.

EMATs generate mechanical loads into a metallic material by means of electromagnetic forces. The electromagnetic forces are coupled into the inspected material through the magnetic field. Here, the magnetic field travels through any material and gap that is between the EMAT and the inspected material. Hence, the contactless nature of EMATs. In addition, EMATs are built out of materials like copper, ceramics, carbon steels and magnets, which can potentially operate at higher temperatures in comparison to piezoelectric materials. Nonetheless, EMATs have weaker transduction when compared with piezoelectric transducers, a feature that complicates their usage in applications that require fast deployment and high Signal-to-Noise-Ratio. Despite this, in the context of applications that do not require fast inspections, as in the case of permanently installed

transducers, EMATs become a desirable option.

The application of EMATs in industry have traditionally focused on in-line applications where the contactless nature of EMATs is desirable. EMAT are often used to inspect laminated plates, tubes, bars, welds, mild rolls, train wheels, pipes, tanks, layered metals, and casted metals [13–18] by means of bulk waves, guided waves, or surface waves. However, in recent years, the use of EMATs in industry has expanded to scanning and monitoring defects in supports, pipelines, tanks, metallic walls, nuclear and aerospace infrastructure with portable and permanently installed devices [13, 17–22].

Research on EMATs has focused mainly on three aspects: the understanding of the excitation mechanisms governing the EMAT’s transduction [23–31], the design of EMATs probes to excite ultrasound waves in metallic materials [28, 32, 29, 33–44], and the implementation of EMATs in different NDE applications [45, 39, 46–53]. The research community has designed EMATs for the excitation of bulk waves up to  $5MHz$  [53, 28, 29, 32, 33, 54, 55, 52, 51, 56, 57, 29, 45], guided waves [58–60, 44, 61, 40, 37, 62, 63], and surface waves [41, 47]. The community has explored how to optimise the EMAT’s performance [32, 36] and design [35, 38, 40]. They have also focus on applications where shear waves are desirable [32, 34], specially applications for shear horizontal waves due to their no mode conversion when interacting with defects facing along the polarisation of the incident wave [53, 33, 62].

EMAT’s transduction is composed of three excitation mechanisms: the Lorentz force, the magnetisation force and the magnetostriction force. The Lorentz force is main excitation mechanism used in NDE inspections that employ EMATs as a mean to excite ultrasound waves. The reason of its preference is that it can be used to excite ultrasound waves in any metal, and it can induce stronger ultrasound waves than the other two excitation mechanism [P3][23]. These advantages benefit the deployments of EMATs in industry. They reduce the manufacturing cost and size of the electronics needed to drive the EMATs. Hence, Lorentz force EMATs are often used for portable and monitoring applications where low voltage electronics are desired. The second most used EMAT excitation mechanism is the magnetostriction force. The magnetostriction force is an excitation mechanism that is material dependent. EMATs that employ the magnetostriction force as their main transduction mechanism can be used only on magnetostrictive mater-

ials. To use a magnetostriction force EMAT to inspect non magnetostrictive metals, it is often used a magnetostrictive strip bounded to the inspected metal. The magnetostriction force EMAT is used to excite ultrasound waves in the magnetostrictive strip, and then the ultrasound waves propagate through the strip and continues to the metal of interest. The deployment of EMATs that use the magnetostriction force as the main excitation mechanism often involve high power electronics to compensate the weak transduction of the EMAT. Contrary to the Lorentz force and magnetostriction force, the magnetisation force is not used in NDE applications as an excitation mechanism to induce ultrasound waves in metals. The reason for this is its poor transduction compared to the other two excitation mechanisms. The mechanical loads exerted by an EMAT using the magnetisation force mechanism can be several orders of magnitude smaller than the other two excitation mechanism. However, the magnetisation force is always present in the transduction of EMATs [P3].

Currently, permanently installed EMATs are used to measure the thickness of the metallic materials [28, 32, 64, 65]. In here, the EMAT is used to excite ultrasound waves at a right angle to the surface, the ultrasound waves travel through the inspected material, interacts with the back-wall of the inspected material, and bounce back to the surface where the EMAT is installed. The EMAT records the ultrasound waves that travelled through the inspected material. The electric signal generated by the EMAT from the ultrasound waves interaction with the material is later analysed to estimate the thickness of the metallic material. In practice, the thickness of the material is estimated by multiplying the time that it takes the ultrasound waves to travel through the inspected material with the wave speed of the ultrasound waves. This methodology works well for thickness gauging, it can detect and measure general corrosion or erosion processes [64–66, 55, 67]. However, the described methodology cannot estimate the presence of surface-breaking defects. These types of tests do not give sufficient information to accurately perform such estimations. Surface-breaking defects do not alter the time that the ultrasound waves take to travel through the material, nor the wave speed of the ultrasound waves sent. They made up the first motivation of my Ph.D. work:

propose a methodology that allows the user to measure the thickness of metallic materials and simultaneously investigate the presence of surface-breaking defects in the inspected

material by means of EMATs.

To address the problem, I proposed two solutions. The first solution was the usage of orthogonal and co-located shear waves for the inspection of metallic materials. Orthogonal and co-located shear waves can be used to measure the thickness of a material and detect the presence of a surface-breaking defect as they provide enough information to estimate both variables. In the proposed methodology, the two shear waves travel at a right angle with respect to the surface of the inspected material. Hence, the excited shear waves can be used for thickness gauging. The shear waves travel time can be used to estimate the thickness of the inspected material. When a surface-breaking defect is present, the interaction of the two orthogonal shear waves with the defect does not affect the travelling time of the two shear waves. However, the shear waves return with different amplitude. The amplitude of the scattered -and measured- ultrasound waves depend on the angle of incidence between the shear waves and the surface-breaking defect. The difference in amplitude between the two shear waves can be used to estimate the presence and height of the surface-breaking defect. This methodology can be used in isotropic and anisotropic materials.

To excite the two orthogonal and co-located shear waves simultaneously, an Orthogonal and Co-Located Coils (OCLC) EMAT was proposed. The EMAT was composed of two butterfly coils, placed one on top of the other forming a right angle, and a permanent magnet magnetic circuit. The combination of the electrodynamic and magnetic fields induced by the EMAT allowed the user to generate orthogonal shear waves with linear polarisation on the same location.

The second proposed solution was the usage of shear waves in phased array mode for the interrogation of metals. Phased arrays generate and steer ultrasound waves to produce ultrasound wave packages that travel at oblique angles. Then, by means of ultrasound waves travelling at oblique angles, phased arrays can be used to detect and size surface-breaking defects [11, 12].

With phased arrays, the ultrasound waves can only be steered over the range of angles to which a single array element radiates waves. This means that the selection and design of the wave source element dictates the steerability and usage of a phased array system. For a shear wave phased array EMAT, the source element of the ultrasound wave is dictated by

the mechanical loads that the transduction of the phased array EMAT element generates. The transduction of EMATs is described by three excitation mechanisms: the Lorentz force, the magnetisation force, and the magnetostriction force [28, 68, 69]. The orientation and magnitude of the mechanical loads that these three excitation mechanisms generate on a metal depend on the design of the EMAT and on the material that is inspected. Often, EMATs are designed to inspect a specific material and it is assumed that in the inspected material only one excitation mechanism is involved in the transduction of the EMAT designed. This limits the EMAT application to the inspected material that it was designed for. To overcome this constraint, it is necessary to design an EMAT that can maintain a constant wave radiation pattern independent of the material that it is inspecting. The second part of my PhD work was motivated by this problem:

design a shear wave phased array EMAT that can maintain a constant steerability and element wave radiation pattern independent of the inspected material.

To achieve this goal, a shear wave phased array EMAT that can be used in different metals without compromising its steerability was designed. The phased array EMAT was designed to maximise the Lorentz force excitation mechanism. The Lorentz force was selected from the three excitation mechanisms as it can be used in any metallic material yielding consistent orientation and amplitude ratios of the excited mechanical loads. The design of the proposed phased array EMAT consisted of a permanent magnet magnetic circuit and 8 race-track coils. To evaluate whether the proposed design maintained constant steerability, the three excitation mechanisms involved in the transduction of the phased array EMAT were estimated in paramagnetic, diamagnetic, ferromagnetic and magnetostrictive metals. Then, the proposed phased array EMAT was constructed and used to steer shear waves on aluminium, mild steel, stainless steel 304 and 316, and in nickel. The experimental results showed that the proposed shear wave phased array EMAT had the same steerability regardless of the material that it was used on.

## 1.2 Thesis Structure

The thesis structure is as follows:

**Chapter 2:**

In chapter 2, the basic concepts of wave generation and wave propagation using EMATs are presented. Section 2.1 gives a general overview of chapter 2. Section 2.2 explains what an EMAT is and what the essential components for EMAT design and construction are. Section 2.3 introduces the reader to the physical principles of the transduction of EMATs. Here, the electromagnetic material properties that affect the transduction of EMATs and the three excitation mechanisms -Lorentz force, magnetisation force and magnetostriction force- involved in the transduction of EMATs are explained. Section 2.4 presents a brief summary of the wave propagation phenomenon in infinite elastic media. Section 2.4 focusses on explaining the dilatation and distortional waves. Section 2.5 relates the wave propagation to the mechanical source orientation that excites the wave. Here, a single wave source element, a dipole wave source element, 8 single wave source elements and 8 dipole wave source elements are studied.

### **Chapter 3:**

This chapter presents the methodology of how to use two orthogonal and co-located shear waves to simultaneously thickness gauge a material and detect the presence of a surface-breaking defect. In section 3.1, the motivation for this chapter is presented with an overview of the chapter. In section 3.2, the design of the Orthogonal and Co-Located Coils EMAT is presented. Section 3.3 describes a finite element model used to study the interaction of the wavefield generated by the OCLC EMAT with surface-breaking defects. Section 3.4 presents the proposed methodology for surface-breaking defect detection using two orthogonal and co-located shear waves. Section 3.5 shows the experimental setup used to validate the proposed methodology. In section 3.6 the experimental results are compared with their equivalent finite element simulation results. Section 3.7 discusses the findings of chapter 3 and presents its conclusion.

### **Chapter 4:**

Chapter 4 presents the expansion of the methodology of surface-breaking defect detection introduced in Chapter 3 into anisotropic materials. Section 4.1 presents the introduction of this chapter. Section 4.2 describes the motivation for the work in this chapter. Section 4.3 explains the concept of wave splitting in anisotropic materials. Section 4.3.1 presents a detail description of the orthogonal and co-located shear waves propagating in an anisotropic material. Section 4.3.2 explains how the two orthogonal and co-located shear

waves can be used to characterise the principal shear directions of a material. Section 4.3.3 shows how two shear waves with arbitrary orientation can be used to excite shear waves polarised along the principal shear direction of an anisotropic material. Section 4.3.4 illustrates how two orthogonal shear waves can be used to detect the presence of a surface-breaking defect. Section 4.3.5 explains how two orthogonal and co-located shear waves can be used to estimate the orientation of a surface-breaking defect. Section 4.4 presents the experimental results. 4.5 gives a detailed discussion of the methodology and results obtained. Section 4.6 states the conclusions of this chapter. Section 4.7 give a mathematical explanation of how to estimate the orientation angle of a surface-breaking defect.

### **Chapter 5:**

Chapter 5 starts with Section 5.1, an introduction to chapter 5 and the motivation for the work presented in this chapter. Section 5.2 explains the design of a shear wave phased array EMAT for material inspection. In section 5.3 the transduction of the phased array EMAT is studied. Section 5.4 illustrates the effect of the three excitation mechanisms on the wavefield generated by the phased array EMAT. This section ends with the steerability analysis of the proposed phased array. Section 5.5 shows the experimental setup used to validate the findings. In section 5.6, the experimental results are compared with the theoretical results obtained. Section 5.7 discusses the findings presented in this chapter. Section 5.8 presents the conclusions of the chapter.

### **Chapter 6:**

Chapter 6 presents the conclusions of this thesis. Section 6.1 gives a general review of the work done throughout my Ph.D. Section 6.2 states the main findings of this thesis. Section 6.3 mentions how the work presented in this thesis can be continued.

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# Chapter 2

## Principles of wave generation and wave propagation using EMATs

### 2.1 Introduction

In this chapter, the physical principles of wave generation, wave radiation and wave directivity of bulk ultrasound waves in an elastic medium are presented. Specifically, I will discuss bulk ultrasound waves induced by means of an EMAT probe. The information presented in this chapter is intended to give the reader the theoretical framework needed to follow the discussions presented in the following chapters. However, this chapter can also be seen as a general overview of the EMAT transduction and its link to elastic wave radiation. It is a stand-alone summary of the theoretical framework related to the topic of this thesis. It presents the minimal theoretical concepts needed to understand the transduction of EMATs and its wave generation in metallic materials. The concepts presented in this chapter are from literature, excluding the study on ultrasound wave radiation patterns as a function of the ultrasound wave source, which is my contribution to the topic. For an in-depth documentation of the principles presented in this chapter, I suggest the following readings: [70–73, 68, 69, 2, 28, 25]; which were the references that I consulted throughout my studies.

The chapter starts with a discussion of what an EMAT is, and the components needed to build an EMAT. The most common EMAT configurations and the reasons behind select-

ing one configuration over another are discussed. This section is followed by a detailed explanation of the three excitation mechanisms that make up EMAT transduction. The Lorentz force, magnetisation force and magnetostriction force are introduced. Once the wave generation mechanisms of an EMAT are explained, the theoretical framework of bulk waves propagating into an elastic medium is presented. Finally, a study on the change in ultrasonic wave radiation pattern (wavefield) as the shape and orientation of its source are varied is presented.

### 2.2 Electro-magnetic acoustic transducers

An Electro-Magnetic Acoustic Transducer or EMAT is a transducer device that utilises the interaction of electrodynamic and magnetic fields to exert mechanical loading into a conductive, mainly metallic, material. To enable the conversion from electrodynamic and magnetic fields to mechanical loads, EMATs are built out of a magnetic circuit and a coil. The magnetic circuit is responsible for inducing a static magnetic field in the metallic material, while the coil is used to excite the electrodynamic field in metal. When the electrodynamic field is modulated in time as a wave pulse (or packet), the mechanical loads exerted by the EMAT follow the time modulation of the electrodynamic field and induce waves in the metallic material. These waves can be used for non-destructive evaluation of the metallic material.

The magnetic circuit that is used in an EMAT is often of two types: permanent magnetic circuit or electromagnetic. The permanent magnetic circuit, as its name indicates, is a magnetic circuit that is constructed of permanent magnets. In many cases, the permanent magnetic circuit is composed of one permanent magnet; however, more complex designs, involving several permanent magnets or permanent magnets and magnetic cores/yokes, can be found in the literature and industry. Periodically permanent magnet [50, 58, 59, 74], single magnet [75, 60, 76], Halbach array [44, 61, 29, 49] and cross permanent magnetic circuit [32][P1][P2][P3] are some of the common configurations. These types of magnetic circuits are frequently preferred in applications where: EMATs are permanently installed, EMATs are designed to work with low energy consumption or EMATs are installed using minimal space. These, thanks to the fact that permanent magnetic circuit do not require

external energy input (or sources) to operate, are compact and help to hold the EMAT on the metallic material after installation.

In contrast to permanent magnetic circuits, electromagnets can be composed of a magnetic core/yoke and a coil [36, 62, 39, 26] or coil only [40]. When the configuration of coil only is used, the static magnetic field is induced directly to the metallic material by means of the coil. While in the case of magnetic core/yoke and a coil, the magnetic core/yoke is utilised as a concentrator and guide of the magnetic flux and the coil is designed to induce the magnetic field in the magnetic core/yoke. Electromagnets are usually used in applications where the EMATs need to be in constant movement or in applications where a high magnetic field is needed. This is because electromagnets are active devices, they induce magnetic fields when a differential electric potential is applied across the terminals of the coil, leaving the user with the freedom of exciting the electromagnet coil when needed and with the electric potential necessary for the application.

The design of the EMAT's coil can be of several types: spiral [43, 35, 48, 42], race-track [41, 47, 37, 46, 77], meander line [45, 38, 78, 63], butterfly [32][P1][P2], etc. The shape of the coil is usually selected depending on the desired direction of the induced electrodynamic field in the metallic material. For example, the spiral coil, also known as the pancake coil, is used when an omnidirectional electrodynamic field is needed. The race-track coil is selected when an electrodynamic field forming two straight lines with opposite direction is intended for the operation of the EMAT. The race-track coils are often combined with a permanent magnetic circuit that induces a magnetic field with opposite polarity on top of the race-track coil, hence, generating homogenous mechanical loads under the tracks of the coils of the EMAT. Meander line coils are selected when an array of electrodynamic field paths is necessary for the operation of an EMAT. The paths of a meander line coil are used to control the location at which the excited mechanical loads are exerted, inducing a desired wavefield in an inspected material. The butterfly coil is used for EMAT designs that intend to induce electrodynamic field with linear polarisation. This is possible by only using the central area of the butterfly coil during the operation of the EMAT.

In general, when designing an EMAT, the combination of magnetic circuit and coil is selected based on the intended application of the EMAT. In NDE, EMATs are used as

## 2. Principles of wave generation and wave propagation using EMATs

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ultrasound wave transducer for defect detection and characterisation. Hence, the selection of magnetic circuit and coil is based on the ultrasound waves needed for a specific NDE methodology.

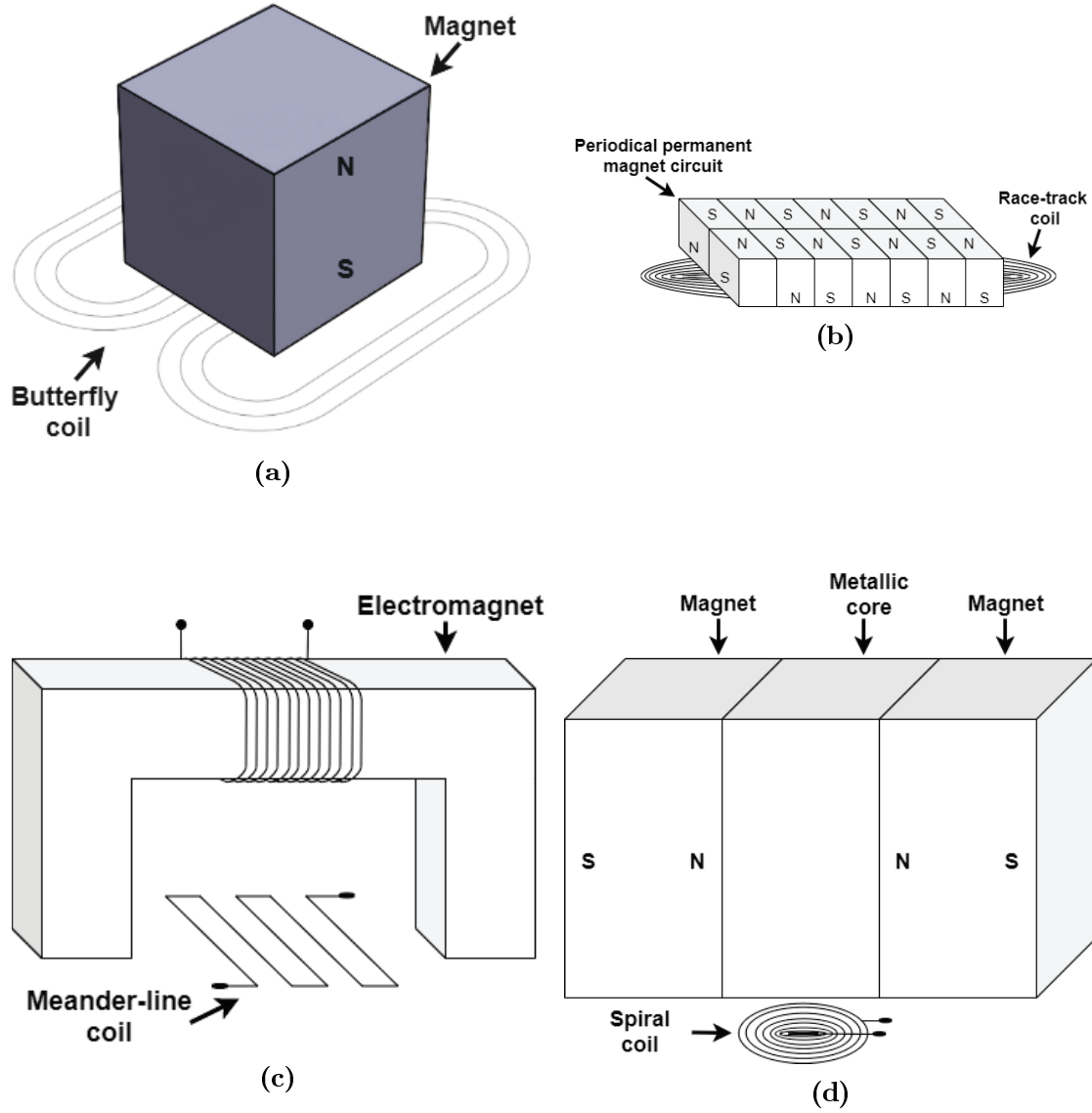


**Figure 2.1:** Four examples of EMATs for NDE applications. a) Single permanent magnet and butterfly coil EMAT. b) Periodical permanent magnetic circuit and race-track coil EMAT. c) Electromagnetic yoke circuit and meander-line coil EMAT. d) Magnetic circuit composed of two permanent magnets and metallic core, and spiral coil EMAT.

To illustrate possible EMAT configurations, figure 2.1 shows four examples of EMAT designs for NDE applications. Figure 2.1a presents the design of a single permanent magnet and a butterfly coil EMAT. This EMAT can be used for through thickness measurements by using the EMAT in pulse-echo mode. Figure 2.1b displays a periodically

permanent magnet circuit and a race track coil EMAT that can be used for detecting defects placed along the length of the inspected material. Figure 2.1c shows a EMAT design composed of an electromagnet and a meander line coil. This configuration can be used for defect detection along the length of the material inspected or to find defects inside the inspected material. Selecting one usage or the other depends on the design of the meander line coil. Figure 2.1d illustrates an EMAT composed of a two magnets and a core magnetic circuit and a spiral coil.

When a magnetic field interacts with an electrodynamic field in a metallic material, it generates mechanical stresses in the material. These stresses are located at the place where the interaction took place, and their polarisation depends on the orientation of the magnetic field and electrodynamic field that produced them. The transduction from magnetic and the electrodynamic fields to mechanical loads in a metallic material occurs in three forms, as the interaction of a static magnetic field with an orthogonal electrodynamic field, as the interaction of a dynamic magnetic field with a magnetised metallic material, and as the interaction of a dynamic magnetic field with the metallic material. These three mechanisms of transduction are known as Lorentz force, magnetisation force and magnetostriction force, respectively. EMATs benefit from these three excitation mechanisms and utilise them as a means of wave generation in metallic materials. In the next section, the three transduction mechanisms that are involved in the use of an EMAT and their interaction in different metallic materials are discussed.

### 2.3 Physical principles of Electro-Magnetic Acoustic Transducers transduction

The transduction of EMATs is material dependent. When an EMAT is used to exert mechanical loads onto a material, the generation of the mechanical loads will depend not only on the magnetic-circuit-coil configuration of the EMAT, but also on the magnetic properties of the material on which the EMAT is placed. Specifically, the properties that relate an applied static magnetic field, dynamic magnetic field, and electrodynamic field with the spontaneous magnetic and mechanical responses of the material. Hence, to give

a detail account of the EMAT transduction, in the following sections I discuss first the electromagnetic properties that affect the transduction of EMATs, and then, I continue with a description of the three excitation mechanisms that explain the transduction of EMATs.

### 2.3.1 Electromagnetic material properties

There are three main electromagnetic properties of an inspected material that affect the transduction of an EMAT: the electrical conductivity of the material, the magnetisation response of the material and the magnetostriction response of the material. The first two explain the electromagnetic response of the inspected material to the electrodynamic and magnetic fields induced by the EMAT. While the magnetostriction response of the inspected material describes the spontaneous elongation that a material experiences due to applied magnetic fields.

For an EMAT to induce mechanical loads into a material, the material must be electrically conductive. This property of materials lets electric charges flow freely in-between its boundaries, allowing an EMAT to induce the electrodynamic and dynamic magnetic fields needed for the transduction. The electrical conductivity of materials affects the strength of the transduction, the easier it is for electrical charges to flow in the material, the stronger will be the EMAT transduction in the material.

Good electrical conductivity, in ambient conditions, is a property commonly found in metals. Therefore, EMATs are used in NDE for the inspection of metallic materials. When an EMAT is placed on top of a non-electrically conductive material, the EMAT will not induce mechanical loads in the material, as the internal structure of the material will not let the EMAT induce the electrodynamic and dynamic magnetic fields needed for the transduction. Material examples of these are: wood, concrete, plastic, silicon, carbon fiber, etc. where the flow of electric charges in the material is poor or non-existent, preventing EMATs to exert mechanical loads. Some of the common materials inspected with EMATs are mild-steels, stainless steels, aluminium, aluminium composites, nickel alloys, nickel-cobalt alloys, and copper [28].

Like the electrical conductivity, the magnetisation response of a material influences the

mechanical loads that an EMAT can exert in the material. When the EMAT is used to interrogate a material, the static magnetic field produced by the magnetic circuit of the EMAT magnetises the inspected material. This magnetisation of the material has two components, the imposed magnetic field coming from the magnetic source and the spontaneous magnetisation response of the material. These two parts of the magnetic response fulfil the superposition principle and can be added to represent the full magnetisation response of the material.

The flow of an imposed magnetic field in a material -the magnetic flux generated by an external magnetic field source that flows through a material- is represented mathematically by the magnetic field of the source times the magnetic permeability of free space [68]:

$$\mathbf{B}_i = \mu_0 \mathbf{H} \quad (2.1)$$

Where  $\mathbf{B}_i$  is the imposed magnetic flux,  $\mathbf{H}$  is the external magnetic field and  $\mu_0$  is the magnetic permeability in vacuum. Analogously, the spontaneous magnetic flux that flows in the material due to the magnetisation experienced by the material is represented as:

$$\mathbf{B}_m = \mu_0 \mathbf{M} \quad (2.2)$$

Here,  $\mathbf{B}_m$  represents the magnetic flux due the spontaneous magnetisation of the material and  $\mathbf{M}$  is the spontaneous magnetisation of the material. The total magnetic flux in the material can be expressed in terms of its two components, the imposed magnetic flux and the spontaneous magnetic flux, as:

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \quad (2.3)$$

Where  $\mathbf{B}$  is the total magnetic flux flowing through the material.

In many practical cases, the imposed magnetic flux and the material spontaneous magnetic

flux cannot be measured separately. However, the total magnetic flux can be measured with respect to the magnetic field applied. Then, the relationship of total magnetic flux to applied magnetic field can be given in terms of the magnetic response of the material. This magnetic response is called the relative magnetic permeability of the material and it is represented by  $\mu_r$ . Hence, the total magnetic flux can be represented as:

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} \quad (2.4)$$

Materials can be classified based on their magnetic response. The material magnetic response affects the transduction of EMATs as it determines the interaction of the static and dynamic magnetic fields with the material. The most common materials found in the industry where EMATs are used are paramagnetic, diamagnetic, and ferromagnetic. Paramagnetic, such as aluminium or austenitic stainless steels 304 or 316, presents a relative magnetic permeability below but close to 1. A typical value of the relative magnetic permeability of paramagnetic materials can be  $1 + 2.5 \times 10^{-5}$ . While diamagnetic materials like copper or lead have relative magnetic permeability higher but close to 1. Here, a common value of the relative magnetic permeability can be  $1 - 2.5 \times 10^{-5}$ .

Contrary to diamagnetic or paramagnetic materials, ferromagnetic materials have variable relative magnetic permeability that can reach values exceeding 10,000. Example of ferromagnetic materials that are inspected with EMATs are: carbon steels, structural steels, martensitic stainless steels, permalloys, nickel or cobalt-iron alloys. Figure 2.2 illustrates an example of the relationship between magnetic flux, magnetic field and relative magnetic permeability in ferromagnetic materials. In the left vertical axis of figure 2.2, the relationship between total magnetic flux and the applied magnetic field in a ferromagnetic material is shown. The right vertical axis presents the variation of the relative magnetic permeability as the applied magnetic field varies in the ferromagnetic material. The results in figure 2.2 were measure in a API 5L X52 carbon steel using the methodology presented by ASTM in [1].

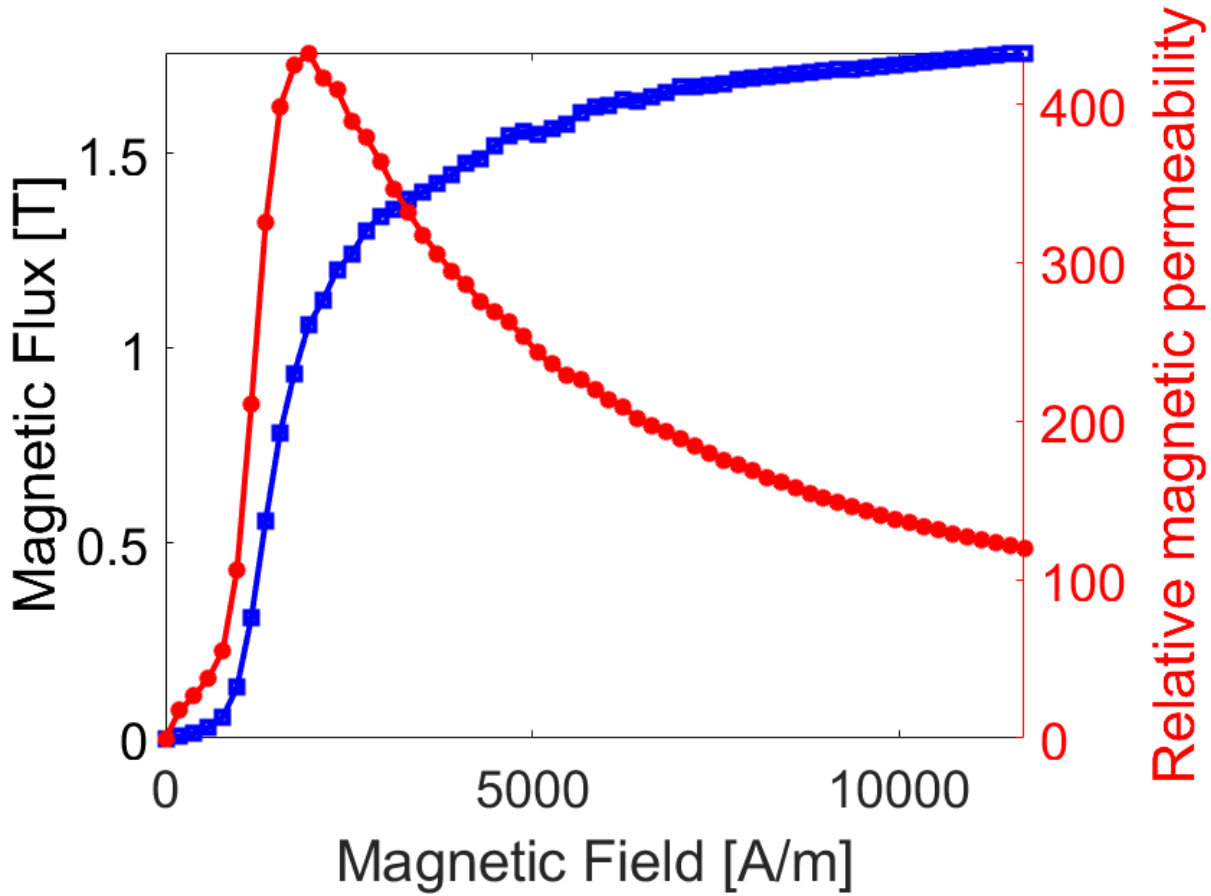


**Figure 2.2:** Magnetic flux, magnetic field and relative magnetic permeability relationship in ferromagnetic materials. The left-hand side axis corresponds to the magnetic flux data presented in a blue line with square markers. In the right-hand side axis shows the values of the relative magnetic permeability data illustrated with a red line and circular markers. The experimental data was measured in a API 5L X52 specimen using the methodology established in the ASTM standard A596/A596M - 21 [1].

The third electromagnetic property of materials that affects the transduction of EMATs is the magnetostriction response of a material. This property describes the spontaneous elongations that a material experiences when a magnetic field is applied to it [2]. Hence, it can be used to exert mechanical loads in a magnetostrictive material. The magnetostriction response of a material can be classified in terms of the elongation it induces in the material. The magnetostriction response can be classified as positive, negative, or null. When the magnetostriction response of a material is null or close to zero, i.e., in materials like aluminium, copper or carbon steels, the material experiences zero spontaneous elongation when a magnetic field is applied. The magnetostriction response of a material is classified as positive when a material exhibits a positive spontaneous elongation -material

expansion- when a magnetic field is applied to it. Some materials that present positive magnetostriction response are terfenol-D, permalloys, cobalt-steel alloys, etc. Finally, the magnetostriction response of a material is classified as negative magnetostriction when a material experiences a spontaneous contraction -negative elongation or compression- when an external magnetic field is applied to it. A material that exhibits negative magnetostriction is nickel. Nickel shrinks when an external magnetic field is applied to it. The elongation that a magnetostrictive material experience when a magnetic field is applied can be mathematically written as [2]:

$$\epsilon_m = \mu_m \mathbf{H} \quad (2.5)$$

Where the strain of a magnetostrictive material is  $\epsilon_m$  and the relationship between material elongation and applied magnetic field of a material is represented as  $\mu_m$ . In here,  $\mu_m$  is the magnetostrictive property of a material.

To illustrate the different magnetostriction responses experienced by magnetostrictive materials, figure 2.3 shows the magnetostrictive curves of three magnetostrictive materials: nickel, 70% cobalt-nickel alloy and 45 permalloy [2].

Now that the electromagnetic material properties that affect the transduction of EMATs have been presented, I will continue with the description of the three excitation mechanisms that are involve in the transduction of EMATs. These three excitation mechanisms -Lorentz force, magnetisation force and magnetostriction force- describes the transduction from electromagnetic energy to mechanical loads. The Lorentz force describes how a magnetic flux interacting with a electrodynamic field generates mechanical loadings in a material. The magnetisation force explains how an applied dynamic magnetic field interacting with a magnetised material induces mechanical loads in the magnetised material. While magnetostriction forces are the mechanical loads generated when an external magnetic field is applied to a magnetostrictive material.

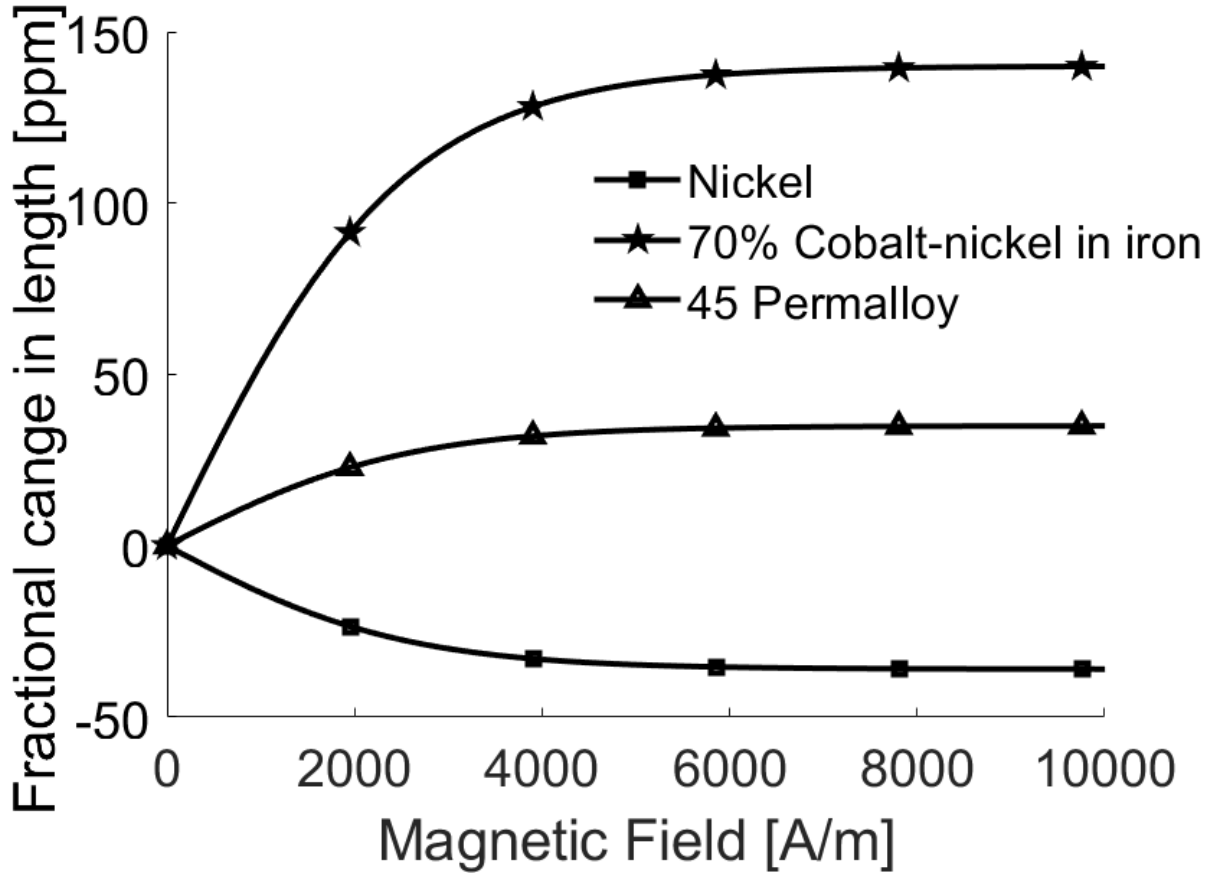


**Figure 2.3:** Magnetostriction curves of three magnetostrictive materials. Nickel has negative magnetostrictive behaviour, while 70% cobalt-nickel alloy and 45 permalloy exhibit positive magnetostrictive response. The curves were extracted from [2].

### 2.3.2 Lorentz force

Formally, the Lorentz force describes how the interaction of a charge density with an electric field or a magnetic flux with a current density can generate mechanical loads in a material. If an external electrical field is applied to a charge density, the charge density will experience an electromagnetic force on it. Similarly, if a magnetic flux is applied at a right angle to a moving charge density, the charges will experience an electromagnetic force on it. Mathematically, this relationship is described as:

$$\mathbf{LF} = \rho_c \mathbf{E} + \mathbf{J} \times \mathbf{B} \quad (2.6)$$

## 2. Principles of wave generation and wave propagation using EMATs

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Where the  $\mathbf{LF}$  is the Lorentz force,  $\rho_c$  is the charge density,  $\mathbf{E}$  represents the electric field,  $\times$  describes the vectorial cross product, and  $\mathbf{J}$  stands for current density.

An EMAT induces a magnetic flux into a metallic material with its magnetic circuit and a current density with its coil. However, an EMAT does not apply an electric field to a metallic material as it does not generate electric field. Hence, the transduction of EMATs only benefits from the second term of equation 2.6 when using the Lorentz force as an excitation mechanism. For EMATs, the Lorentz force, described in equation 2.6, can be written as:

$$\mathbf{LF} = \mathbf{J} \times \mathbf{B} \quad (2.7)$$

To take advantage of this excitation mechanism, the EMAT has to be designed with a magnetic circuit that generates magnetic flux normally oriented to the paths of the EMAT's coil. When an electric potential drop is applied to the coil of the EMAT, the coil induces a current density into an inspected material. This current density is parallel to the path of the EMAT's coil and has orthogonal orientation to the magnetic flux generated by the magnetic circuit of the EMAT. Hence, the interaction of the induced current density and the induced magnetic flux in the inspected material generates mechanical loads that are described by the Lorentz force in equation 2.7. To illustrate this concept, let's take for example the EMAT presented in figure 2.1a. When the EMAT is placed on top of a metallic material, the magnetic circuit of this EMAT induces a magnetic flux normal to the surface of the inspected material. While the coil of the EMAT induces current density in the inspected material. The induced current density is parallel to the surface of the inspected material. The interaction of the current density and the magnetic flux generates mechanical loads tangential and normal to the surface of the inspected material. The normal mechanical loads in the material are generated due to the curvature of the magnetic flux induced by the magnet. However, often, they can be ignored as their amplitude is one or two orders of magnitude smaller than the tangential loads. This phenomenon is illustrated in figure 2.4.

When the electric potential drop applied to the coil of the EMAT varies in time, the

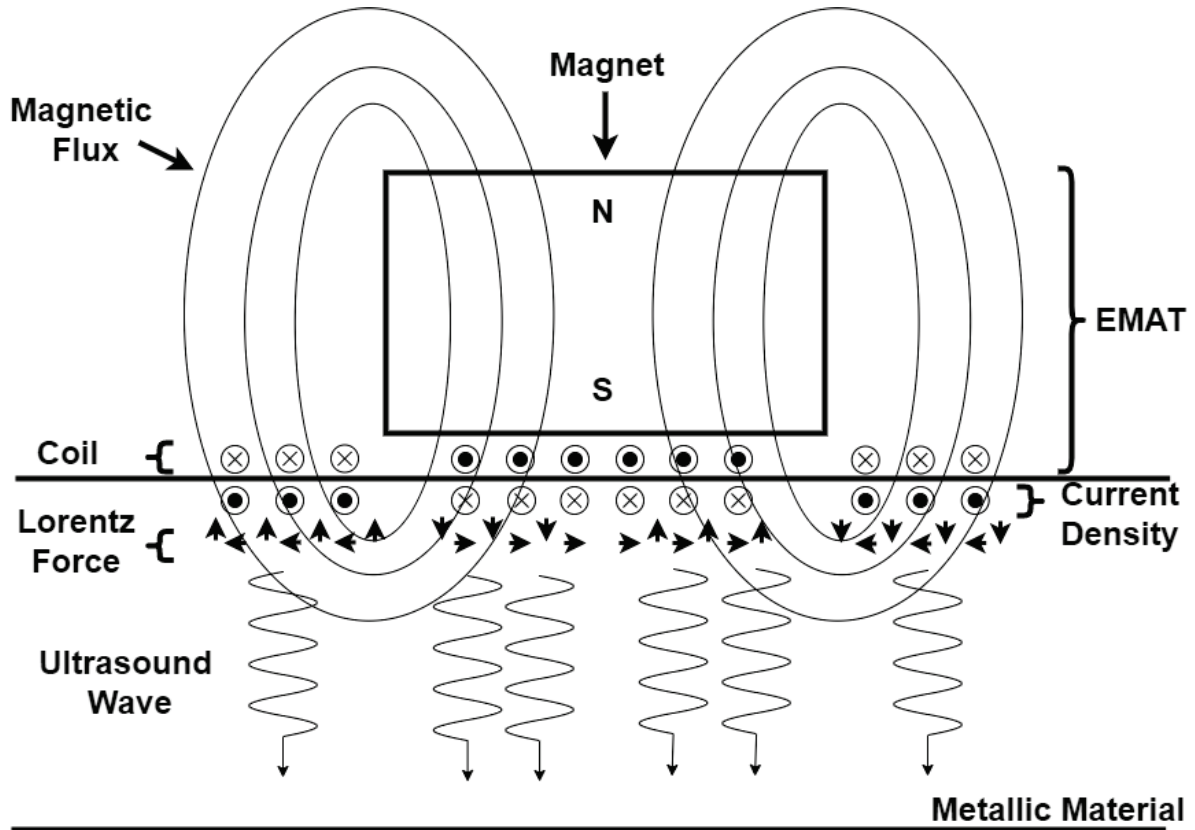


**Figure 2.4:** Schematic of the mechanical loads induced by a single magnet and butterfly coil EMAT in a metallic material when the Lorentz force is the excitation mechanism.

mechanical loads exerted by the EMAT will vary with time. The possibility of varying the strength and direction of the mechanical loads, by manipulating the applied electric potential, permits the user of EMATs to induce ultrasound waves in the inspected material. Figure 2.4 shows that a single magnet and butterfly coil EMAT induces shear vertical waves in a metallic material by means of the Lorentz force mechanism.

When a material is not magnetostrictive, the Lorentz force mechanism is the main excitation mechanism in the transduction of an EMAT. This is because the Lorentz force dominates compared to the magnetisation force mechanism.

### 2.3.3 Magnetisation force

The magnetisation force is a transduction mechanism that describes the mechanical loads generated in a magnetised material when an external magnetic field is applied to the material. When an external magnetic field is applied to a magnetised material, the magnetic

internal walls of the magnetised material reorganise following the magnetic equilibrium between the applied magnetic field and the magnetisation of the material. The displacement and reorientation of the magnetic wall in the magnetised material generates mechanical loads in the material. These mechanical loads are the results of the changes induced by the external magnetic field applied to the magnetised material. The relation that mathematically describes the mechanical loads in terms of the interaction of the changes induced by the external magnetic field and the magnetisation of the material is:

$$\mathbf{mF} = \mu_0 \cdot (\nabla \cdot \mathbf{H}) \cdot \mathbf{M} \quad (2.8)$$

Where the  $\nabla \cdot$  is the divergence operator, and  $\mathbf{mF}$  represents the magnetisation force induced by an applied magnetic field in a magnetised material.

In the case of EMATs, the magnetisation of the inspected material can be originated from two scenarios: a remanent magnetisation in the material that is inspected or induced by the static magnetic field generated by the EMAT's magnetic circuit. In the first scenario, the total magnetisation of the inspected material is the magnetic equilibrium between the remanent magnetisation and the applied magnetic field. In this scenario, the total magnetisation of the material depends on the relative magnetic permeability of the material and on whether the material presents a magnetic hysteresis loop response when a magnetic field is applied. While in the second scenario, the static magnetic field induced by an EMAT magnetises the inspected material according to equation 2.3 and 2.4. Here, the magnetisation response of the material is the difference between the total magnetic field in the material and the applied magnetic field.

Once the inspected material is magnetised by the magnetic circuit of an EMAT, an applied magnetic field can be used to induce mechanical loads by means of the magnetisation force. For EMATs with magnetic circuit, this applied magnetic field is intrinsic to its operation. When the coil of an EMAT is used for the EMAT operation, it applies a magnetic field to the inspected material. This magnetic field in combination with the magnetisation of the material generates mechanical loads. Hence, the magnetisation force mechanism is always present in the operation of an EMAT with magnetic circuit, as the usage of a magnetic

circuit and a coil is necessary for the correct implementation of an EMAT.

Comparing the magnetisation force with the magnetostriction force or Lorentz force, contrary to the other two excitation mechanisms, the magnetisation force is always present in the transduction of EMATs with magnetic circuits. However, the strength of the mechanical loads induced by the magnetisation force are several orders of magnitude inferior to the mechanical loads exerted by means of the Lorentz force or magnetostriction force. The reason for this difference is that the divergence of the magnetic field induced by the coil of an EMAT is minimal compared to the current density or magnetic field that the same coil can induce in an inspected material.

To give an idea of how the magnetisation response is generated in a metallic material, figure 2.5 shows a conceptual schematic of the mechanical loads induced by the single magnet and butterfly coil EMAT of figure 2.1a when the magnetisation force is the excitation mechanism.

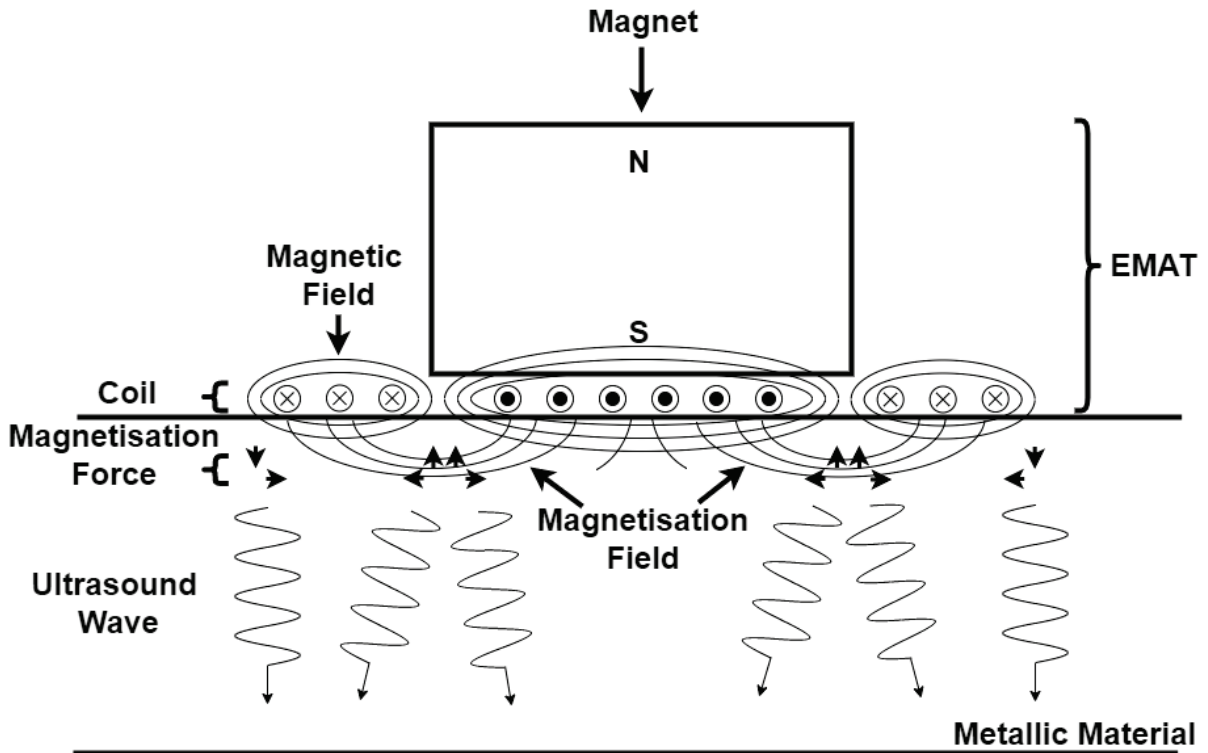


**Figure 2.5:** Schematic of the mechanical loads induced by a single magnet and butterfly coil EMAT in a metallic material when the magnetisation force is the excitation mechanism.

### 2.3.4 Magnetostriction force

The magnetostriction force is a mechanism of excitation that is material dependent. To exist the magnetostriction force, the material must be magnetostrictive. As discussed in section 2.3.1, the magnetostriction is a material property that relates the spontaneous elongation of an material with an externally applied magnetic field. Hence, the strength of the magnetostriction force is related to the magnetostrictive response of the material and to the external magnetic field that is applied to the material.

The magnetostriction force can be represented mathematically as:

$$\mathbf{MF} = C_h \cdot \epsilon_m \quad (2.9)$$

Where the  $C_h$  is the strain-stress matrix of the magnetostrictive material,  $\mathbf{MF}$  represents the mechanical loads induced by means of the magnetostriction force mechanism, and  $\epsilon_m$  is the strain experienced by the material due to an external magnetic field.  $\epsilon_m$  is described in equation 2.5.

In the case of EMATs, there are two magnetic fields that are induced: the static magnetic field coming from the magnetic circuit of an EMAT, and the dynamic magnetic field induced by the coil of an EMAT. While the first is stronger than the second and can induce mechanical loads into a magnetostrictive material, it does not intervene in the generation of ultrasound waves as its transient response is constant over time. The second, the dynamic magnetic field, can be utilised to induce ultrasound waves into a magnetostrictive material. In this scenario, the mechanical loads are induced in the material by the interaction of the dynamic magnetic field with the magnetostrictive material. To become ultrasound waves, these mechanical loads are modulated in time by manipulating the signal of the electric potential used to excite the coil of the EMAT. Hence, the ultrasound wave generation by means of the magnetostriction force mechanism, the magnetic field  $\mathbf{H}$  in equation 2.5 is the one generated with the coil of an EMAT.

To illustrate the concept of ultrasound wave generation using the magnetostriction force as a means of mechanical load excitation, figure 2.6 presents a schematic of the single

magnetic and butterfly coil EMAT, shown in figure 2.1a, inducing mechanical loads into a magnetostrictive material.

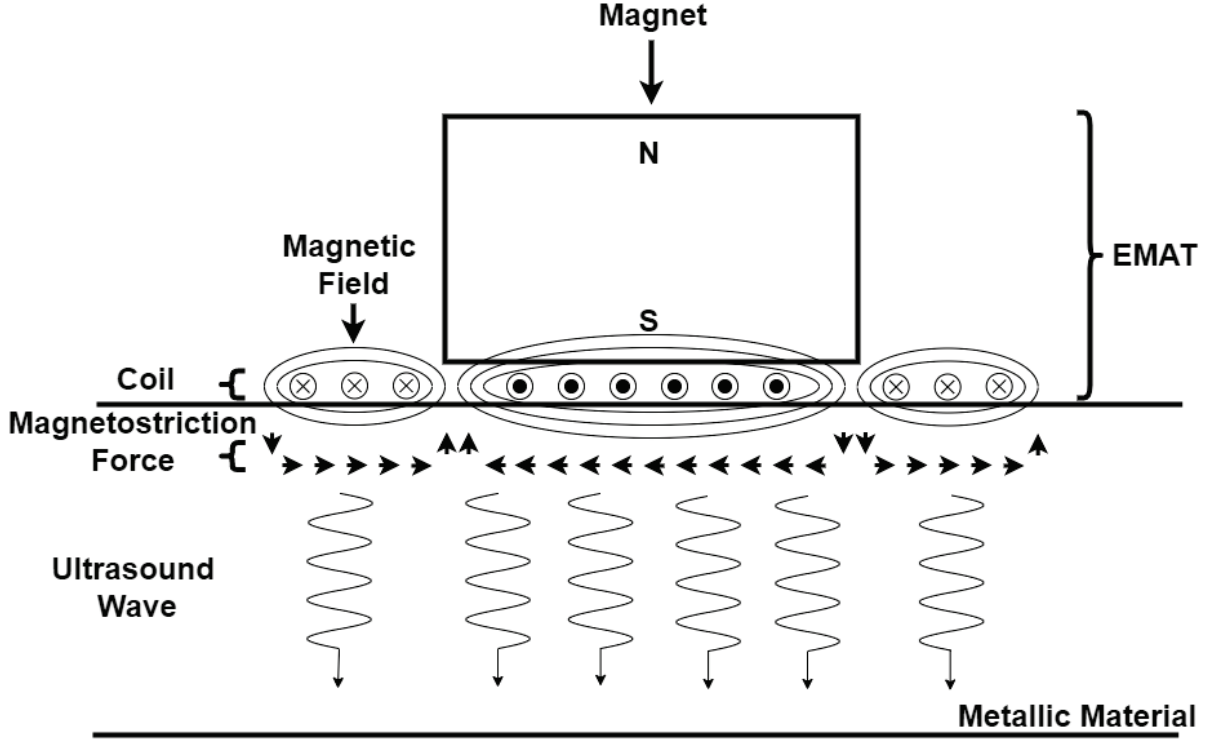


**Figure 2.6:** Schematic of the mechanical loads induced by a single magnet and butterfly coil EMAT in a magnetostrictive material when the magnetostriction force is the excitation mechanism.

## 2.4 Principles of wave propagation in elastic media

In this section, rather than presenting a fully detailed description of the wave propagation phenomenon, I attempt to give the reader a brief summary of the wave propagation principles, stating the basic tools needed to understand the wave propagation induced with EMATs in bulk media. Hence, in this section, I present the general equation of waves in infinite media and define the two wave modes that exist in bulk materials. For a detailed explanation on the principles of wave propagation on elastic media I invite the reader to consult [70, 71, 79], which are the main text sources used to write this section.

The general equation of balance of stresses for an isotropic elastic medium can be given in Cartesian coordinates as:

$$\nabla \sigma + \rho \mathbf{f} = \rho \ddot{\mathbf{u}} \quad (2.10)$$

Where  $\sigma$  represents the stress tensor,  $\rho$  is the density of the elastic medium,  $\mathbf{f}$  stands for the body force per unit mass,  $\nabla$  is the gradient operator and  $\ddot{\mathbf{u}}$  is the second derivative in time of the displacement. Equation 2.10 can be given in terms of displacements by expressing the stresses in terms of the strains, and the later in terms of displacements. This can be achieved by substituting the general Hooke's Law into equation 2.10. Then, the governing equation in terms of displacement results:

$$(\lambda + \mu) \nabla \nabla \cdot \mathbf{u} + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f} = \rho \ddot{\mathbf{u}} \quad (2.11)$$

where Hooke's Law is:

$$\sigma_{ij} = \lambda \epsilon_{kk} \delta_{ij} + 2\mu \epsilon_{ij} \quad (2.12)$$

and the relationship between strain and displacement is defined by:

$$\epsilon_{ij} = \frac{1}{2} (\mathbf{u}_{i,j} + \mathbf{u}_{j,i}) \quad (2.13)$$

Here,  $\lambda$  and  $\mu$  are the Lamé elastic constants of the medium,  $\nabla \cdot$  is the divergence operator,  $\nabla^2$  represents the Laplace operator,  $\epsilon$  represents the strain in the medium, the  $\delta$  sign indicates the mathematical Kronecker delta operator, and the subindices  $i, j, k$  stands for the spatial coordinate of the Cartesian system.

The particle displacement in a bulk elastic medium can be of two forms: dilatational or distortional. The first refers to a displacement wave that propagates in an elastic medium by compressing and dilating the particles that compose the medium. Hence, the dilatational wave refers to a wave that propagates by changing the volume of the

elastic medium, this while keeping the mass of the volume constant. the second particle displacement stands for the displacement wave that propagates in an elastic medium by the rotation of the particles that compose the media. This type of wave, also known as equivoluminal waves, propagates in the elastic media without altering the volume of the material.

To evaluate the velocity at which the dilatational wave propagates in the elastic medium, the divergence of equation 2.11 without the body forces is performed. The divergence is evaluated as the divergence operator calculates the changes in volume of a medium. hence:

$$\begin{aligned} (\lambda + \mu)\nabla\nabla \cdot \mathbf{u} + \mu\nabla^2\mathbf{u} &= \rho\ddot{\mathbf{u}} \\ (\lambda + \mu)\nabla \cdot (\nabla\nabla \cdot \mathbf{u}) + \mu\nabla \cdot (\nabla^2\mathbf{u}) &= \rho\nabla \cdot \ddot{\mathbf{u}} \end{aligned} \quad (2.14)$$

as  $\nabla \cdot \nabla = \nabla^2$ , and  $\nabla \cdot (\nabla^2\mathbf{u}) = \nabla^2(\nabla \cdot \mathbf{u})$ , then equation 2.14 can be written as:

$$\begin{aligned} (\lambda + \mu)\nabla^2\nabla \cdot \mathbf{u} + \mu\nabla^2\nabla \cdot \mathbf{u} &= \rho\nabla \cdot \ddot{\mathbf{u}} \\ (\lambda + 2\mu)\nabla^2\nabla \cdot \mathbf{u} &= \rho\nabla \cdot \ddot{\mathbf{u}} \\ \nabla^2\nabla \cdot \mathbf{u} &= \frac{1}{c_1}\nabla \cdot \ddot{\mathbf{u}} \end{aligned} \quad (2.15)$$

Here, equation 2.15 is the wave equation. hence the wave speed of the dilatational wave is:

$$c_1 = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad (2.16)$$

Similarly, the wave speed at which the distortional wave propagates in an elastic bulk medium can be calculated by evaluating the rotational operator,  $\nabla \times$ , of the governing equation 2.11 without the body forces. This operation results in:

$$\begin{aligned}
 (\lambda + \mu)\nabla\nabla \cdot \mathbf{u} + \mu\nabla^2\mathbf{u} &= \rho\ddot{\mathbf{u}} \\
 (\lambda + \mu)\nabla \times (\nabla\nabla \cdot \mathbf{u}) + \mu\nabla \times (\nabla^2\mathbf{u}) &= \rho\nabla \times \ddot{\mathbf{u}}
 \end{aligned}
 \tag{2.17}$$

since the rotational of a gradient of a scalar is zero and  $\nabla \times (\nabla^2\mathbf{u}) = \nabla^2(\nabla \times \mathbf{u})$ , equation 2.17 can be written as:

$$\begin{aligned}
 \mu\nabla^2\nabla \times \mathbf{u} &= \rho\nabla \times \ddot{\mathbf{u}} \\
 \nabla^2\nabla \times \mathbf{u} &= \frac{1}{c_2}\nabla \times \ddot{\mathbf{u}}
 \end{aligned}
 \tag{2.18}$$

Equation 2.18 represents the distortional wave in an elastic bulk material, and its wave speed is indicated by the letter  $c_2$ .  $c_2$  is mathematically written as:

$$c_2 = \sqrt{\frac{\mu}{\rho}} \tag{2.19}$$

To understand better how these two waves propagates into bulk elastic materials, and to give a better interpretation of the wave motion, lets study the wave propagation of a simple harmonic wave into the elastic material. Here, suppose that the harmonic wave is a plane wave that propagates along one of the Cartesian coordinates,  $x$ , of the system. For a harmonic plane wave, the displacement in the three Cartesian coordinates can be described as:

$$\begin{aligned}
 u_x &= \mathbf{A}_x e^{i\gamma(x-ct)} \\
 u_y &= \mathbf{A}_y e^{i\gamma(x-ct)} \\
 u_z &= \mathbf{A}_z e^{i\gamma(x-ct)}
 \end{aligned}
 \tag{2.20}$$

where the subindices  $x, y$  and  $z$  indicate the orientation of the displacement, the letter  $A$  represents the amplitude of the displacement along the axes,  $\gamma$  is the wavenumber of

the propagating wave. The wavenumber is described as the wavelength divided by  $2\pi$ .  $i$  represents the complex identity  $\sqrt{-1}$ , the wave speed of the propagating wave is written as  $c$  and the time is represented by the letter  $t$ . Substituting the displacement solution in equation 2.20 into the governing equation presented in 2.11 gives:

$$\begin{aligned}
 (\lambda + \mu)\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_y}{\partial x \partial y} + \frac{\partial^2 u_z}{\partial x \partial z}\right) + \mu\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2}\right) + \rho \mathbf{f} &= \rho \frac{\partial^2 u_x}{\partial t^2} \\
 (\lambda + \mu)\left(\frac{\partial^2 u_x}{\partial x^2}\right) + \mu\left(\frac{\partial^2 u_x}{\partial x^2}\right) &= \rho \frac{\partial^2 u_x}{\partial t^2} \\
 (\lambda + \mu)(-\gamma^2 \mathbf{A}_x e^{i\gamma(x-ct)}) + \mu(-\gamma^2 \mathbf{A}_x e^{i\gamma(x-ct)}) &= -\rho \gamma^2 c^2 \mathbf{A}_x e^{i\gamma(x-ct)} \\
 \gamma^2(\lambda + 2\mu - \rho c^2) \mathbf{A}_x &= 0
 \end{aligned} \tag{2.21}$$

$$\begin{aligned}
 (\lambda + \mu)\left(\frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_x}{\partial y \partial x} + \frac{\partial^2 u_z}{\partial y \partial z}\right) + \mu\left(\frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial z^2}\right) + \rho \mathbf{f} &= \rho \frac{\partial^2 u_y}{\partial t^2} \\
 \mu\left(\frac{\partial^2 u_y}{\partial x^2}\right) &= \rho \frac{\partial^2 u_y}{\partial t^2} \\
 \mu(-\gamma^2 \mathbf{A}_y e^{i\gamma(x-ct)}) &= -\rho \gamma^2 c^2 \mathbf{A}_y e^{i\gamma(x-ct)} \\
 \gamma^2(\mu - \rho c^2) \mathbf{A}_y &= 0
 \end{aligned} \tag{2.22}$$

$$\begin{aligned}
 (\lambda + \mu)\left(\frac{\partial^2 u_z}{\partial z^2} + \frac{\partial^2 u_z}{\partial z \partial x} + \frac{\partial^2 u_z}{\partial z \partial y}\right) + \mu\left(\frac{\partial^2 u_z}{\partial z^2} + \frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial z^2}\right) + \rho \mathbf{f} &= \rho \frac{\partial^2 u_z}{\partial t^2} \\
 \mu\left(\frac{\partial^2 u_z}{\partial x^2}\right) &= \rho \frac{\partial^2 u_z}{\partial t^2} \\
 \mu(-\gamma^2 \mathbf{A}_z e^{i\gamma(x-ct)}) &= -\rho \gamma^2 c^2 \mathbf{A}_z e^{i\gamma(x-ct)} \\
 \gamma^2(\mu - \rho c^2) \mathbf{A}_z &= 0
 \end{aligned} \tag{2.23}$$

From equations 2.21, 2.22 and 2.23, it can be concluded that when  $c$  is equal to  $c_1$ ,  $\mathbf{A}_y$

## 2. Principles of wave generation and wave propagation using EMATs

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and  $\mathbf{A}_z$  must be equal to 0 so equations 2.22 and 2.23 are satisfied. This means that when  $c$  is equal to  $c_1$ , hence the wave is dilatational, the displacement exists only along the direction of propagation of the wave, in other words, longitudinal. On the contrary, when  $c$  is equal to  $c_2$ ,  $c$  satisfies equation 2.22 and 2.23 but not equation 2.21. In this scenario,  $\mathbf{A}_x$  must be equal to 0. This case means that when  $c$  is equal to  $c_2$  -distortional wave-, the displacement is perpendicular to the direction of propagation and can be called transversal. To illustrate the motion of particle in longitudinal and transversal waves, figure 2.7 presents the two cases in the form of harmonic waves.

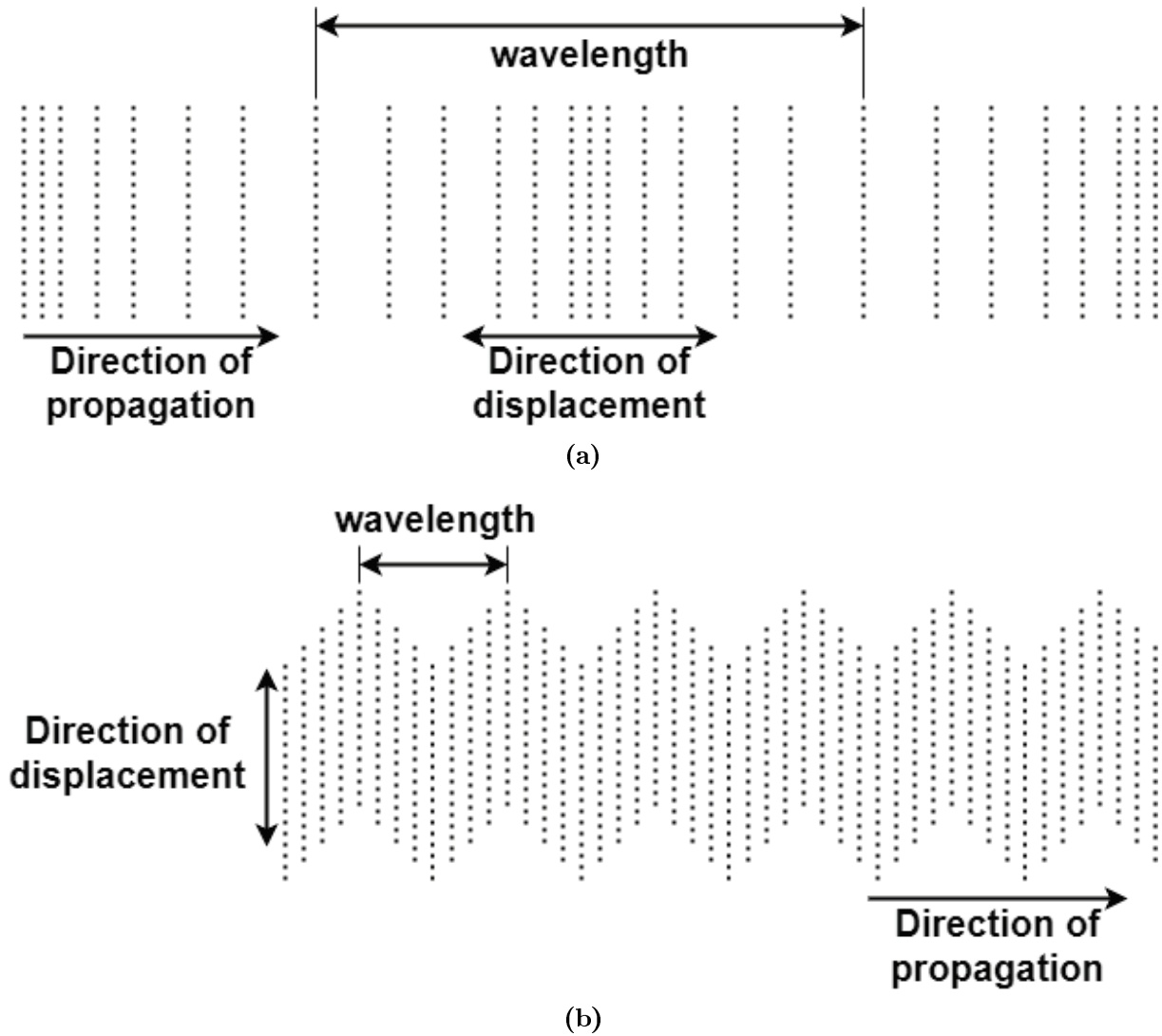


**Figure 2.7:** Examples of waves in bulk elastic media. a) illustrates the wave propagation and particle displacement of a longitudinal wave. b) shows the wave displacement and propagation of a transversal wave.

## **2.5 The effect of the wave source orientation**

This section focuses on the study of the wavefield generated by different ultrasound sources. Specifically, on ultrasound sources that differ in their mechanical load orientation i.e. tangential and normal mechanical loads to the surface of the propagating material, and single ultrasound sources or dipole ultrasound sources. The objective of this section is to relate the orientation of the mechanical loads to the longitudinal and shear wave radiation patterns that the ultrasound source generates.

The results presented in this section will later assist the reader to comprehend in greater detail the rest of the chapters of this document. However, if the reader prefers to read this chapter only, the results offered in this section, in combination with the design concepts and physical principles presented throughout this chapter, can assist the reader to understand the design of EMATs.

To study the wave radiation that an ultrasound source can generate, a Finite Element Analysis (FEA) was used. FEA is a powerful numerical tool that allows the user to compute an approximate solution for a given problem. The approximate solution often has a minimal error compared to the exact solution. For the case of ultrasound wave propagation in bulk elastic materials, it has been proven that FE software packages, such as POGO [80] or Simula Abaqus/Explicit [81], yield accurate solutions when the FE model is setup properly [82, 83]. If the reader is interested in learning more about the FE method and its application to ultrasound and NDE, I recommend the following textbooks or research papers [84, 85, 82, 83].

The FEA was carried out in a 2D model. The model was composed of a  $200mm \times 100mm$  aluminium block with free boundaries and mechanical loads located at the centre bottom boundary of the block. The mechanical properties of the aluminium block were: density of  $2700Kg/m^3$ , Young modulus of  $70.76GPa$  and Poisson's ratio of 0.3375. The mechanical load was interchanged between single and dipole loads, between tangential  $-x$ -direction in figure 2.8- and normal  $-y$ -direction in figure 2.8- loads, and between 8 single and 8 dipole load elements depending on the simulation intended. The mechanical loads were line sources of extension of  $0.4mm$ . To measure the wave radiation patterns generated by the mechanical loads, measuring points forming a semi-circle with  $50mm$  radius and

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centred at the mechanical load were placed. The receiving measuring points were placed from  $0^\circ$  to  $180^\circ$  with an angular spacing of  $1^\circ$ . A schematic of the 2D FE model is shown in figure 2.8. The excitation signal for all the mechanical loads had amplitude of  $1N$  and was a 5-cycle Hanning-windowed toneburst with centre frequency of  $1MHz$ . This yields a wavelength for a shear wave of approx.  $3.1mm$  and a wavelength for a longitudinal wave of approx.  $6.2mm$  in metals such as Aluminium and Steel.

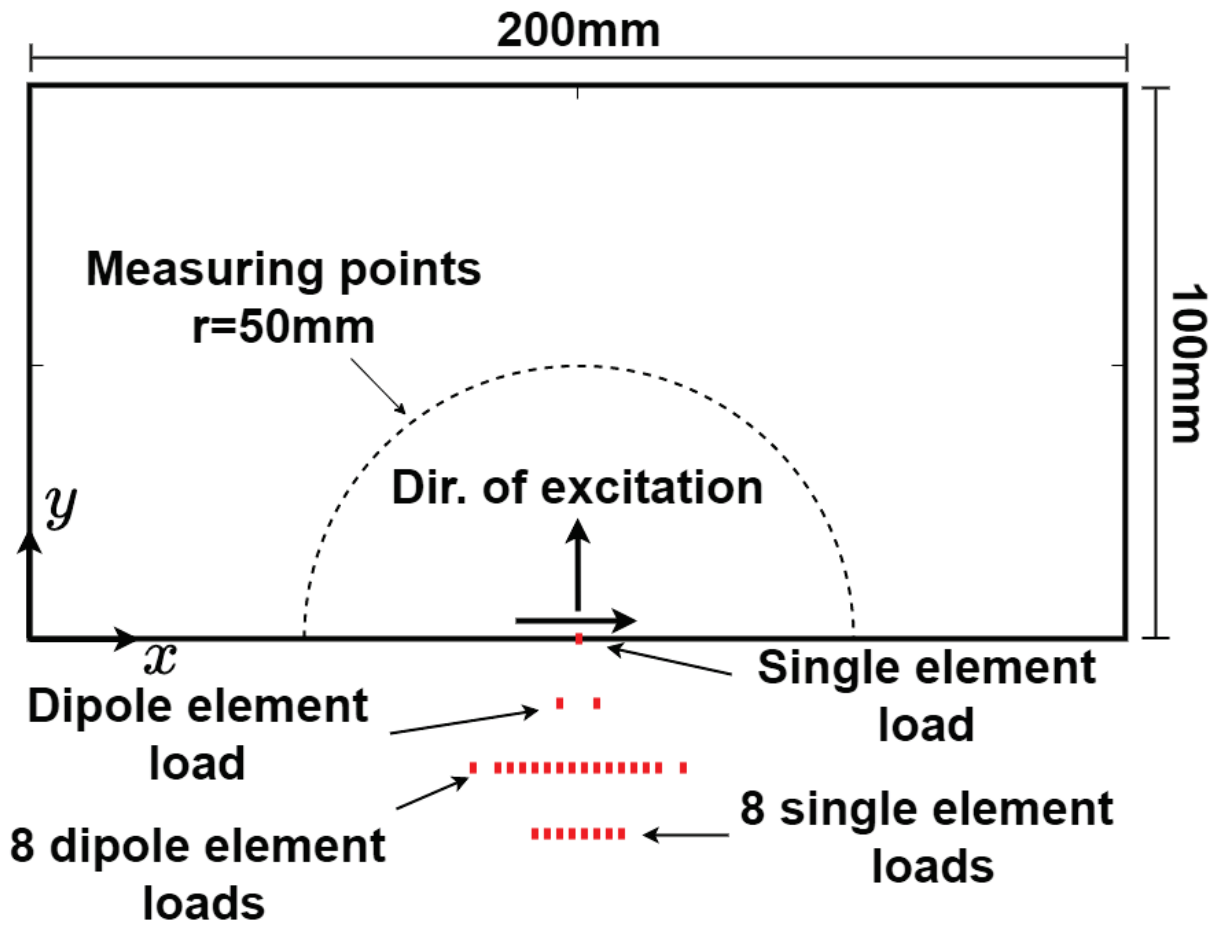


**Figure 2.8:** Schematic of the 2D finite element model. The red dots represent the mechanical loads used in the wavefield study. The mechanical loads were interchanged based on the results intended to obtain with the finite element simulation.

The mechanical load sets investigated by the FE simulations were 6 in total. Two sets of single mechanical load elements, two sets of dipole mechanical load elements, one set of 8 dipole mechanical load elements and one set 8 single mechanical load elements. The difference between each pair was the orientation of their mechanical loads. One of the pairs had mechanical loads oriented in the  $x$ -direction or tangential to the edge of the 2D

model, and the other one of the pair had mechanical loads oriented in the  $y$ -direction or normal to the edge of the 2D model.

The single mechanical load element had a single mechanical load that was aligned with the  $x$  or  $y$  direction. The dipole element consisted of two mechanical loads with the same alignment but opposite orientation, i.e., aligned with the  $x$ -direction but one of the mechanical loads is oriented in the positive direction, while the second is oriented in the negative direction. In addition to the wavefield study as a function of the source alignment, for the dipole element, the wavefield was also studied as a function of the distance between the mechanical loads that form the dipole element.

The FEA with the two sets of 8 elements were performed to study the steerability that the single mechanical load and dipole mechanical load have. The set of 8 single mechanical load elements was constructed with the use of single mechanical load elements. The single mechanical load elements were placed one next to the other a third of a wavelength apart. The distance between elements was selected so that each ultrasound source behaves similar to an ultrasound point source for the wavelength of the steered ultrasound waves. The mechanical loads of the 8 single elements had the same mechanical load alignment and orientation. In contrast, the set of the 8 dipole mechanical load elements was composed of 8 dipole elements that were partially overlayed. The overlay was a  $1/3$  of the distance of the dipole mechanical loads. The distance between mechanical loads of the dipole element was selected to be one wavelength. Hence, with the overlay, the distance between dipole elements was  $wavelength/3$ . To illustrate the overlay of the dipole element, figure 2.9 shows the configuration of the 8 dipole mechanical load elements.

To execute the steerability analysis, the ultrasound wave generated with the 8 elements were steered using the plane wave steering method. The plane wave method consists of time delaying the ultrasound wave generated by each source element, so the combination of the ultrasound waves generates a plane wave steered to a desired angle. The time delay is selecting according to the distance between source elements and the desired steering angle. Equation 2.24 describes this mathematically:

$$t_d = \frac{N_{element} \cdot D_d \cdot \cos(\theta)}{vel_{wave}} \quad (2.24)$$

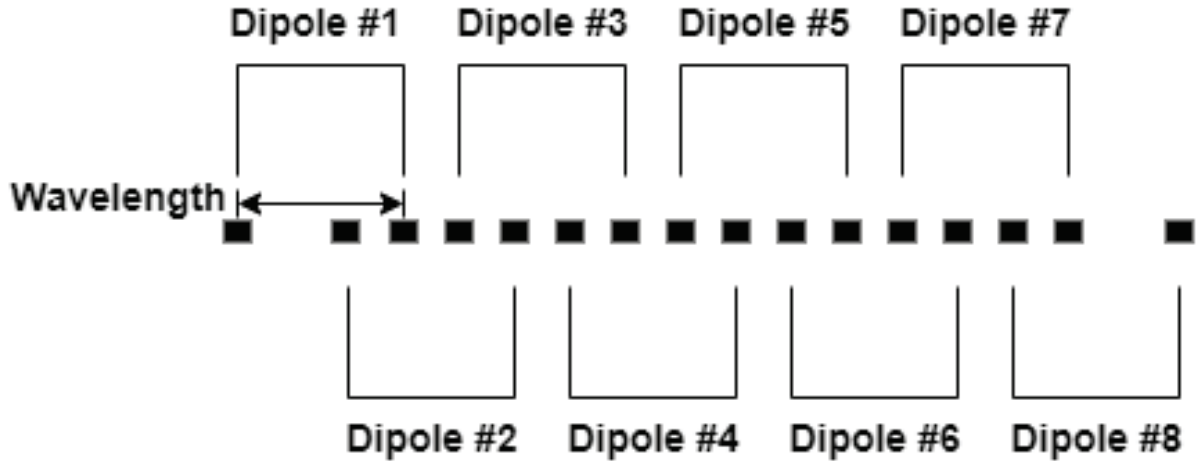


**Figure 2.9:** Schematic of the 8 dipole mechanical loads schematic.

where,  $t_d$  is the time delay applied to each element  $N_{element}$  of the array.  $D_d$  is the distance between elements of the array,  $\theta$  is the desired steering angle, and  $vel_{wave}$  corresponds to the wave speed of the wave that is intended to be steered.

The FEA was carried out using the Simula Abaqus/Explicit commercial FE package [81]. To discretise the 2D model, a structured mesh composed of piecewise bilinear square element with length size of  $0.1mm$  was used. This gives 30 elements per wavelength (assuming wavelength of  $3mm$ ). The simulation was carried out under the plane stress assumption. To discretise the simulation in time, a time step of  $1ns$  was employed [83, 82]. Hence, the 2D FE model was composed of 2 million elements and took around 35 minutes to solve on a data Cruncher with Intel Xeon(R) 32 CPU ES-2667 at  $3.4GHz$  and consumed approximately  $40Gb$  of RAM.

Figure 2.10 shows the wavefield results that were obtained with the single mechanical load element. Figure 2.10a and figure 2.10b are the results that were obtained when the mechanical load was aligned with the  $x$ -direction. While figure 2.10c and figure 2.10d are the results observed when the mechanical load was aligned with the  $y$ -direction. The displacement amplitude of the ultrasound waves recorded at the measuring points is shown in figure 2.10a and figure 2.10c. Figure 2.10b and figure 2.10d present the wave radiation pattern of a single mechanical load aligned with the  $x$ -direction and with the  $y$ -direction, respectively.

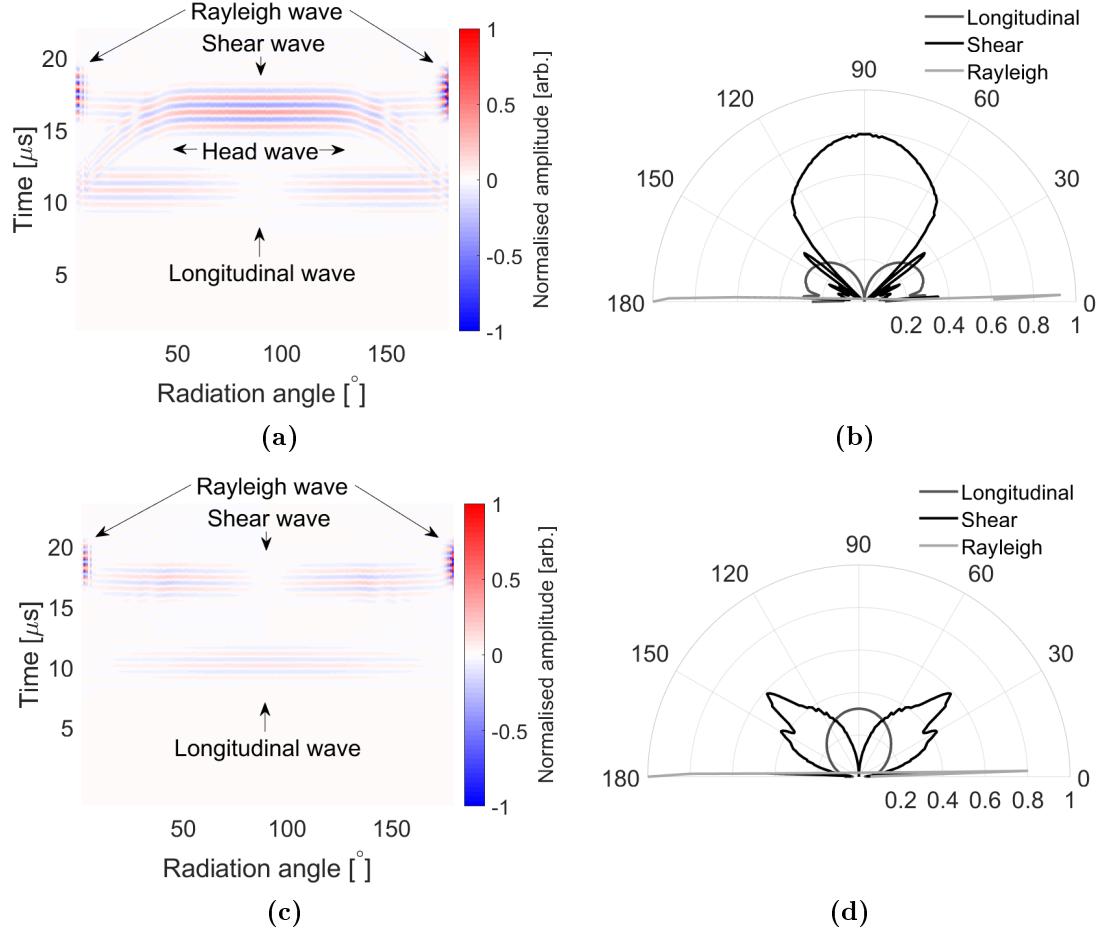


**Figure 2.10:** Wave propagation and wave radiation pattern of a single mechanical load element. a) Wave displacement recorded at 50mm away from the ultrasound source. The mechanical load was aligned with the  $x$ -direction. b) Wave radiation pattern of a single mechanical load element with mechanical load aligned with the  $x$ -direction. c) Wave displacement recorded at 50mm away from the ultrasound source. The mechanical load was aligned with the  $y$ -direction. d) Wave radiation pattern of a single mechanical load element with mechanical load aligned with the  $y$ -direction. The results shown in these four figures were obtained by means of a 2D FEA.

The wave radiation patterns of all the results presented in this section were extracted at the time at which the maximum amplitude of each excited wave was passing through the measuring points.

The results obtained with a single dipole mechanical load element are presented in figure 2.11. The results shown in figure 2.11 were obtained with mechanical loads aligned with the  $x$  or  $y$  direction. The wave amplitude of the ultrasound waves recorded at the measuring points for both orientation are shown in figures 2.11a and figure 2.11c. The wave radiation patterns that a dipole mechanical load element can generate, whether the

## 2. Principles of wave generation and wave propagation using EMATs

mechanical loads are aligned with the  $x$  or  $y$  direction, are shown in figure 2.11b and figure 2.11d.

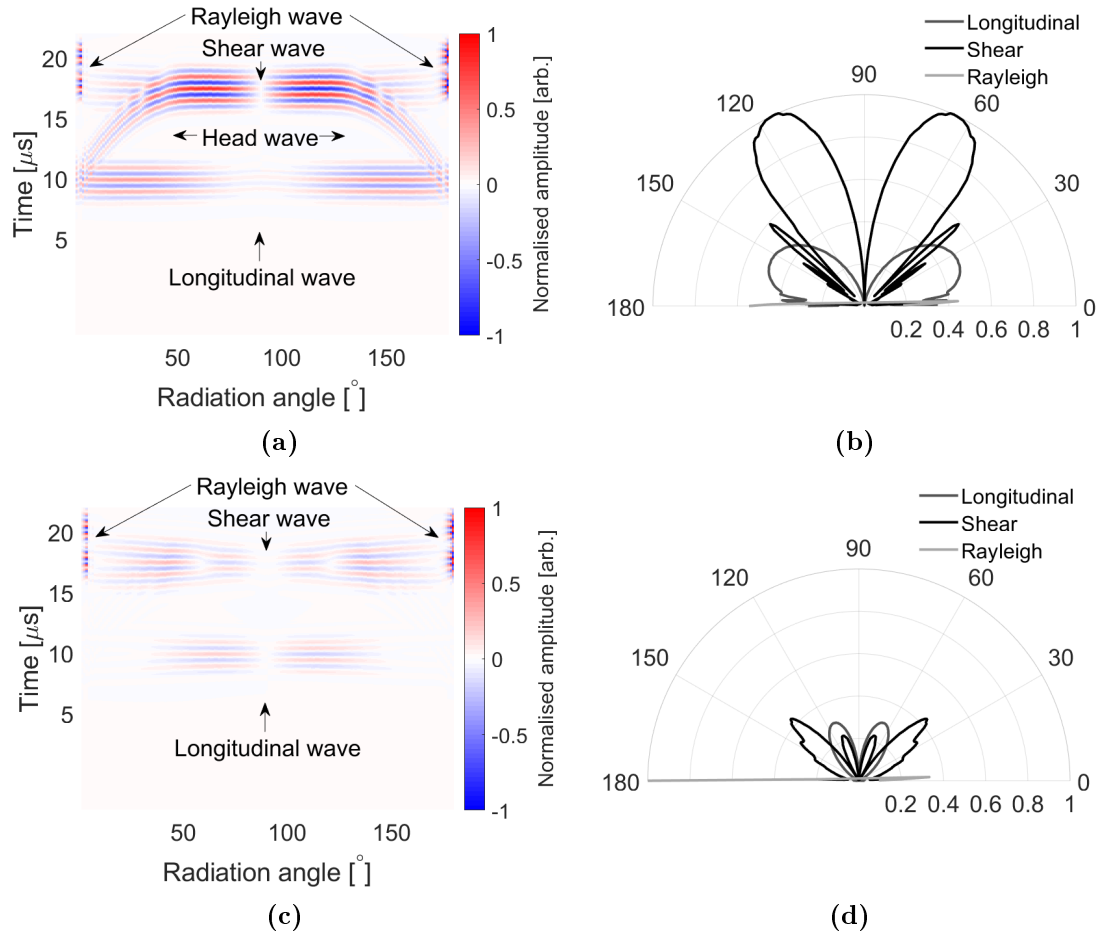


**Figure 2.11:** Wave propagation and wave radiation pattern of a dipole mechanical load element. a) Wave displacement recorded at 50mm away from the ultrasound source. The mechanical loads were aligned with the  $x$ -direction. b) Wave radiation pattern of a dipole mechanical load element with mechanical loads aligned with the  $x$ -direction. c) Wave displacement recorded at 50mm away from the ultrasound source. The mechanical loads were aligned with the  $y$ -direction. d) Wave radiation pattern of a dipole mechanical load element with mechanical loads aligned with the  $y$ -direction. The results shown in these four figures were obtained by means of a 2D FEA. The distance between poles was 1/3 of the wavelength.

The FE results of the wavefield analysis as a function of the distance between the mechanical loads of the dipole element are presented in figure 2.12. Figure 2.12a and figure 2.12b show the results obtained when the mechanical loads were aligned with the  $x$ -direction, while figure 2.12c and figure 2.12d display the wavefield outcome when the mechanical loads were oriented parallel to the  $y$ -direction.

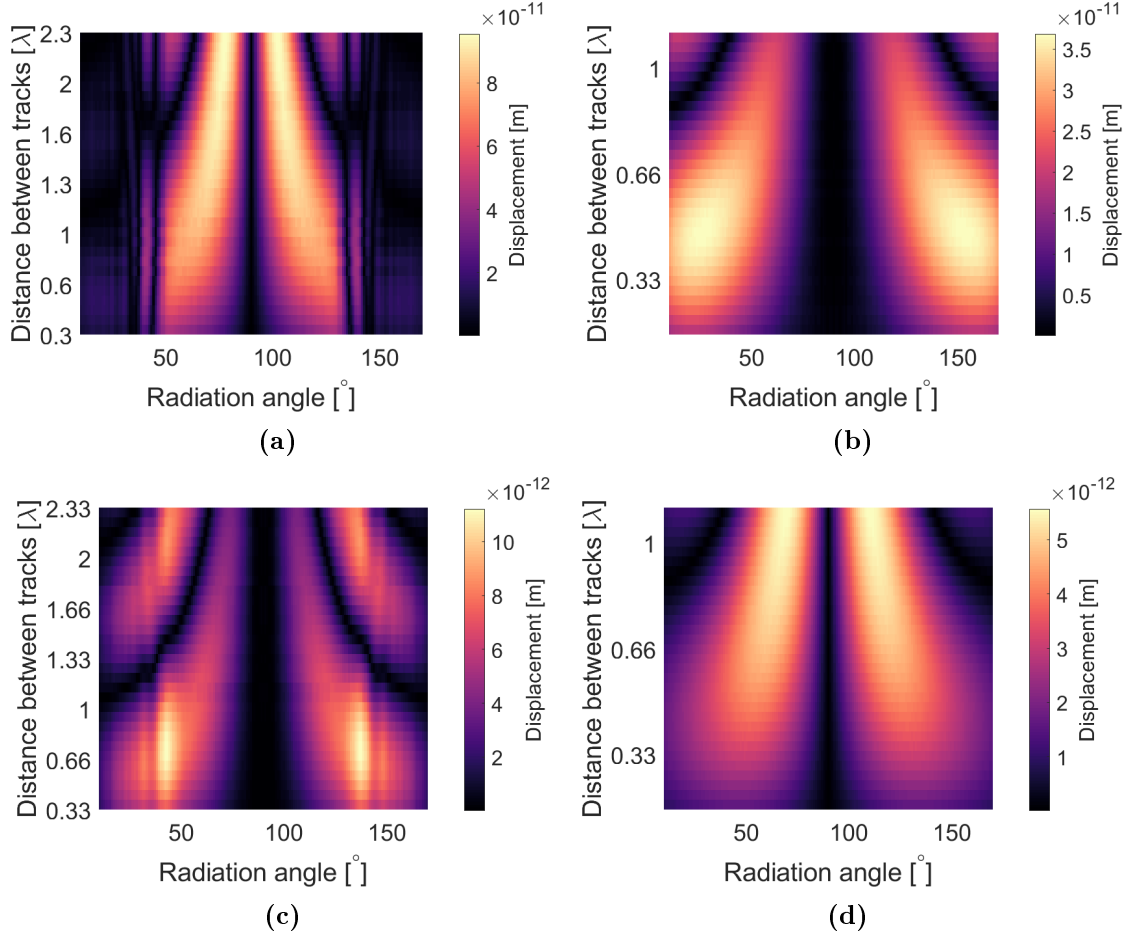


**Figure 2.12:** Wave radiation pattern of a dipole mechanical load element as a function of the distance between mechanical loads. a) Wave radiation pattern of the shear wave generated by the dipole element as a function of the distance between mechanical loads. The mechanical loads were aligned with the  $x$ -direction. The distance between mechanical loads is given in terms of the wavelength of the shear wave in aluminium ( $\lambda$ ) b) Wave radiation pattern of the longitudinal wave generated by the dipole element as a function of the distance between mechanical loads. The mechanical loads were aligned with the  $x$ -direction. The distance between mechanical loads is given in terms of the wavelength of the longitudinal wave in aluminium ( $\lambda$ ) c) Wave radiation pattern of the shear wave generated by the dipole element as a function of the distance between mechanical loads. The mechanical loads were aligned with the  $y$ -direction. The distance between mechanical loads is given in terms of the wavelength of the shear wave in aluminium ( $\lambda$ ) d) Wave radiation pattern of the longitudinal wave generated by the dipole element as a function of the distance between mechanical loads. The mechanical loads were aligned with the  $y$ -direction. The distance between mechanical loads is given in terms of the wavelength of the longitudinal wave in aluminium ( $\lambda$ ). The results shown in these four figures were obtained by means of a 2D FEA.

Figure 2.13 shows the steerability results obtained when the 8 single mechanical load elements were used to excite an ultrasound wave in the 2D model. To summarise the wave steerability of the set into one figure, each of the wave radiation patterns obtained

## 2. Principles of wave generation and wave propagation using EMATs

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when the ultrasound waves were steered at a given angle were stacked one next to the other to form a steerability map. Hence, the figures in figure 2.13 display the radiation relationship between the intended steering angle and the amplitude displacement at a measured angle. Figure 2.13a and figure 2.13b present the results achieved when the mechanical loads of the 8 single elements were aligned with the  $y$ -direction. Figure 2.13a displays the steerability map of shear waves obtained when the longitudinal waves were steered. Figure 2.13b presents the steerability map obtained when the longitudinal waves were steered.

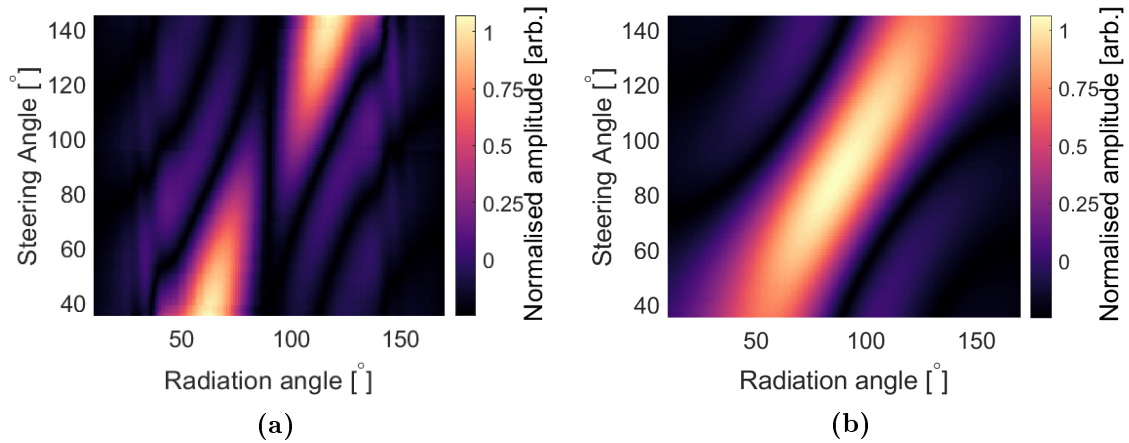


**Figure 2.13:** Steerability map of a 8 single mechanical load elements with mechanical load aligned with the  $y$ -direction. a) Steerability map obtained when steering the shear waves generated with the 8 elements. b) Steerability map of the longitudinal waves generated with the 8 elements. The results shown in these two figures were obtained by means of a 2D FEA.

Finally, the steerability maps when the 8 dipole mechanical load elements were used to steer ultrasound waves is presented in figure 2.14. The mechanical loads of the 8 dipole elements were aligned with the  $x$ -direction of the 2D model. Figure 2.14a is the steerability map obtained when steering the shear waves generated with the 8 dipole elements. While figure 2.14b presents the steerability map of longitudinal waves when the shear waves were steered.

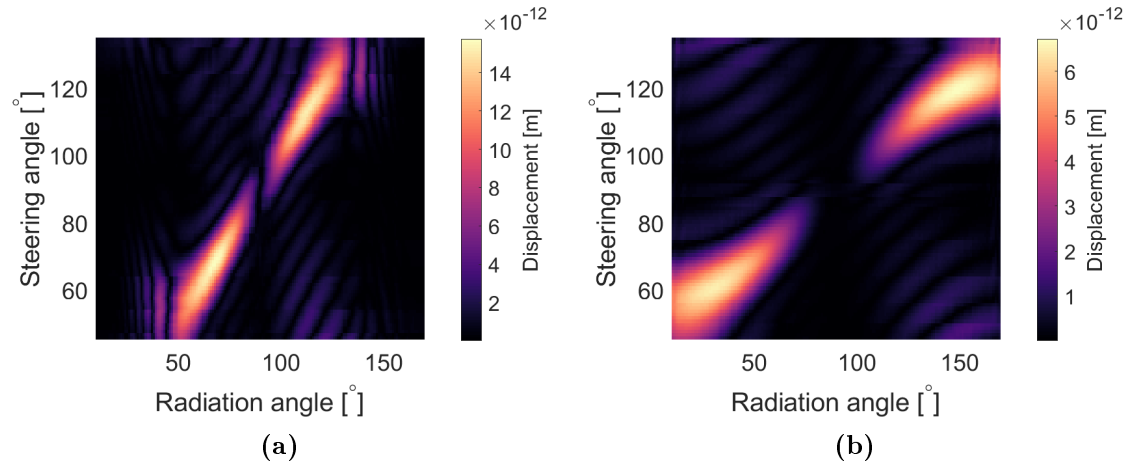


**Figure 2.14:** Steerability map of a 8 single mechanical load elements with mechanical load aligned with the  $y$ -direction. a) Steerability map obtained when steering the shear waves generated with the 8 elements. b) Steerability map of the longitudinal waves generated with the 8 elements. The results shown in these two figures were obtained by means of a 2D FEA.

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## Chapter 3

# Orthogonal and Co-located Shear Wave EMAT

This chapter summarised the findings obtained when two co-located shear waves with orthogonal and linear polarisation are used for thickness gauging and defect detection simultaneously. The results presented here were obtained by me with the supervision of Dr Frederic Cegla and with the advice of Dr Pouyan Khalili. Most of the material in this chapter was taken with minor alterations from [P1] (with permission from NDT & E International).

### 3.1 Introduction

Pulse-echo mode thickness measurements are one of the most commonly employed ultrasound non-destructive evaluation (NDE) techniques. The procedure consists in exciting waves normal to the inspected surface using an ultrasound transducer (UT). These waves propagate into the material that is to be inspected at an angle that is normal to the surface and reflect from the back-wall of the inspected component before returning to the transducer. The series of wave reflections and their time of flight (ToF) can be used to determine the thickness of the material at the specific spot where the UT is located [67, 86]. Example applications where UTs are frequently used to inspect metallic materials are: manual thickness measurements [87, 54, 88], corrosion mapping [66, 89] inline

inspection (ILI) with e.g. pipeline inspection gauges (PIGs) [90, 91] and permanently installed devices for thickness gauging [92, 64, 32, 65].

The effectiveness of the thickness measurements depends on the quality of the returning signals. Severe surface roughness and non-uniformity can result in low signal to noise ratio (SNR) [93] and poor thickness measurements [55]. At the same time, ToF calculations of normal incidence wave reflections are relatively insensitive to small defects and crack-like defects because they reflect very little energy back and do not influence the arrival time of back-wall reflections [94]. These effects on the signal are, in some cases, comparable to the changes induced by surface roughness and therefore normal incidence waves are usually unsuitable for crack detection.

A different setup is used to perform crack detection with ultrasound [11]. An angled beam is sent into the inspected component; which is usually achieved by installing a piezo-electric UT onto an angled wedge [95]. The inspection consists in generating an ultrasound pulse that travels through the wedge and refracts at the wedge-specimen interface, resulting in an obliquely travelling wave in the material that is being inspected. The presence of a defect in the travel path of the wave can result in partial or complete reflection (depending on the geometry of the defect) of the ultrasound wave which reflects back to the transducer; therefore a defect is detected when a reflected signal is received [96, 95]. Applications of these type of UT probe are: crack detection on plates, pipes or welds [11, 95, 96], NDE inspection of train wheels [97] among others.

The above shows that two different setups are required to perform thickness measurements and crack detection. This can be practically inconvenient to implement. Therefore, to overcome these impracticalities, in this work I investigated if both measurements can be combined by performing two simultaneous pulse-echo tests. The concept is to use a pair of orthogonal and linearly polarised shear waves emitted by the same transducer. This enables thickness gauging and crack-like defect detection with the same setup.

The UT probe that is presented in this chapter consists of an electromagnetic acoustic transducer (EMAT) that contains two orthogonal co-located butterfly coils. The EMAT can excite a pair of perpendicular and linearly polarised shear waves propagating into the inspected material at  $90^\circ$  relative with its surface. The generated waves travel through the metallic material and bounce back from the back-wall to the transducer. The re-

ceived back-wall reflections are analysed to quantify the thickness of the material and to determine the presence of a crack-like defect.

Thickness gauging is performed, using an orthogonal co-located coil (OCLC) EMAT, by calculating the ToF of the received back-wall reflections. While the presence of crack-like defects is detected by comparing the amplitudes of the two orthogonal and linearly polarised shear wave reflections. This is possible as the amplitude of the reflected shear waves is strongly dependent on the relative orientation of a crack-like defect with respect to the polarisation direction of the incident shear wave.

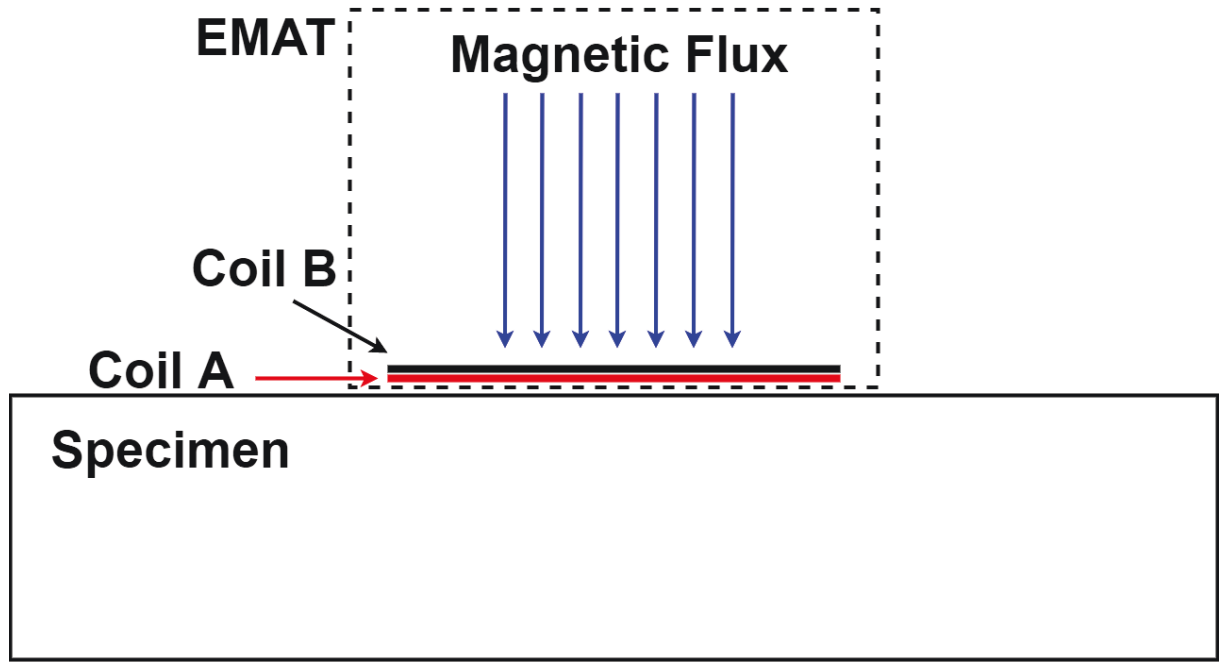
There has been prior work aimed at understanding how linearly polarised shear waves interact with crack-like defects. For instance, S. K. Datta et al. [53] investigated how shear horizontal waves are diffracted when interacting with surface-breaking defects at different angles. Their experimental results indicated that SH waves propagating at  $0^\circ$  can be used to detect surface-breaking defects. A. H. Harker [98] analysed in-plane shear waves interacting with surface-breaking cracks at different incident angles. He concluded that in-plane incident shear waves split their energy into other waves after interacting with the defect. Howard [94] described qualitatively how the back-wall reflections of bulk waves are affected by the width of surface-breaking defects with respect to the UT aperture. In industry, for example, it is a well-established procedure to measure the arrival time of several oblique angle shear vertical wave reflections to size a crack-like defect [11]. However, there is no methodology that utilises relative changes in amplitude between orthogonal polarised shear waves to detect and characterise the presence of a crack-like defect. I believe that the lack of this methodology is a result of the absence of a device capable to record the amplitude of two orthogonal shear waves simultaneously, and because there are no studies that relate the amplitude of shear wave reflections to the size of crack-like defects. Therefore, this is what I set out to present in this chapter.

To understand how both normal incidence shear waves interact with back-wall cracks and how crack-like defects affect the reflected waves; 3D Finite Element (FE) simulations of the waves interacting with different crack-like defects were performed. An experimental setup that mimics the 3D-FE model was then built to validate the FE simulation results. The simulation and experimental results were compared, and their agreement was verified. This chapter is organised as follows: in section 2, the OCLC EMAT layout is described.

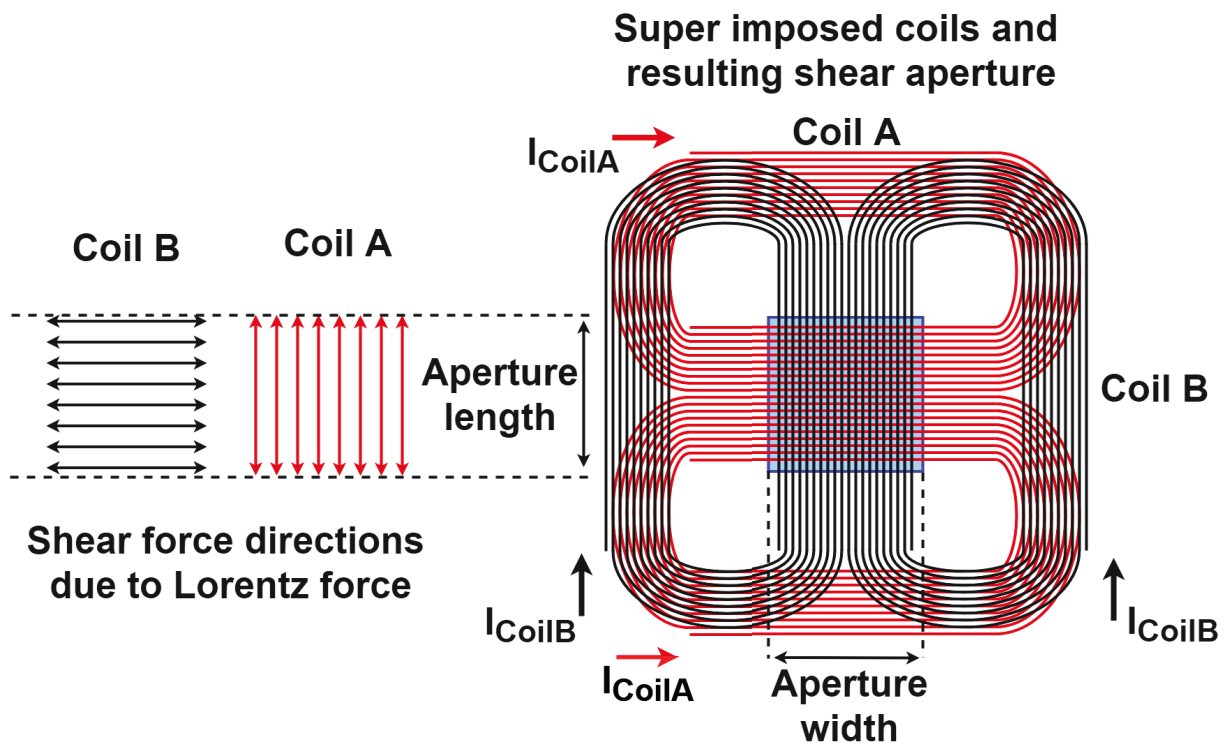
In section, 3 I present the FE model used to study the interaction of the EMAT wavefield with notches of different sizes and orientations. In section 4, I explain the behaviour of the reflected waves when the EMAT wavefield interacts with crack-like defects and then we illustrate the concept of crack-like defect detection with FE simulation results. In section 5, the experimental design and setup is presented. In section 6 I compare the FE simulation results with their equivalent experimental measurement results. Section 7 discusses the presented work and its conclusion.

## 3.2 The orthogonal co-located coils (OCLC) EMAT

In this chapter I am proposing to use an EMAT that contains a pair of orthogonal co-located coils (schematic concept of the magnetic flux orientation, the orthogonal coil design and the directions of the generated shear forces are shown in figure 3.1a and 3.1b). The design of the proposed EMAT is based on the results presented by Isla and Cegla [32]. The EMAT that they designed maximised the bias magnetic field, so that, in combination with one butterfly coil (20 turns, 0.25mm track width and 0.25mm gap between tracks), it generates a linearly polarised normal incidence shear wave by means of the Lorentz force mechanism [30]. The OCLC EMAT its composed of the same magnetic circuit and coil introduced by Isla and Cegla [32] plus a second identical butterfly coil that is placed on top and rotated at 90° relative to the first EMAT coil. Both coils are placed at the bottom of the EMAT. Therefore, the description of the magnetic field and the ultrasound wave generation of the OCLC EMAT is the same to the one described by Isla and Cegla [32]. But with the difference that an additional ultrasound shear wave with perpendicular polarisation direction is generated by the second coil. Therefore, the active aperture of the OCLC EMAT is a square area at its centre (marked in blue in figure 3.1b) [94] where the vertical and horizontal tracks of the coils cross. It is in this area where the magnetic flux is applied and hence where the Lorentz force will exert a surface traction on the specimen.



(a)



(b)

**Figure 3.1:** Schematic of the orthogonal co-located EMAT coils. a) Schematic side view of the OCLC EMAT. b) Top view layout showing the two coils that are identical but rotated by  $90^\circ$  and placed on top of each other, as well as the active aperture area and the shearing direction resulting from the two coils.  $I_{CoilA}$  and  $I_{CoilB}$  indicate the current direction in the coils.

## 3.3 Finite element simulation of interaction of shear horizontal waves with notches/cracks in isotropic materials

In order to assess the interaction of the two orthogonal and linearly polarised shear waves with crack-like defects of various depths, widths and orientations, FE analysis was employed. FE is a versatile and powerful tool that allows the investigation of a large number of defect shapes/sizes which would be very costly to fully examine experimentally.

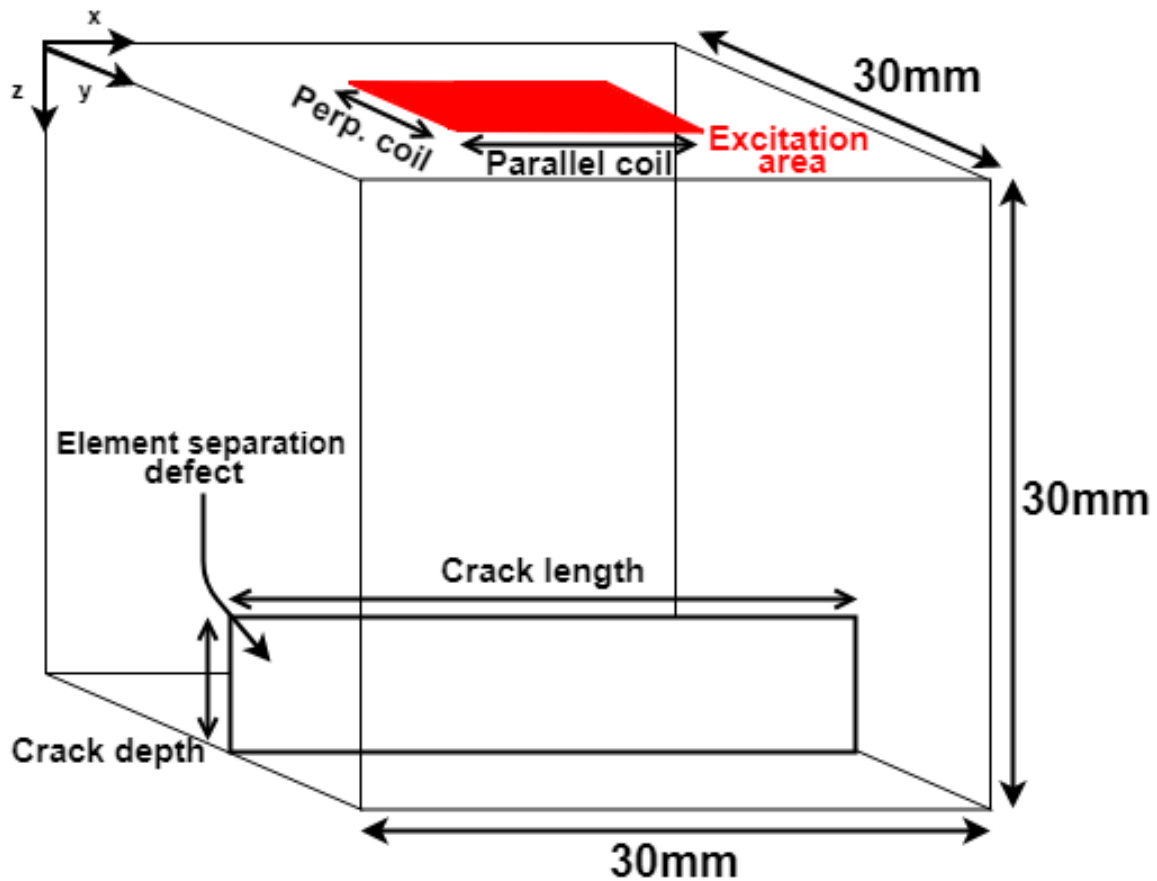


**Figure 3.2:** Schematic of the FE setup. The red area represents the equivalent OCLC EMAT excitation/reception area (aperture).

The predictions were performed in a pulse-echo setup at 2 MHz centre frequency, which in an aluminium ( $\rho = 2700\text{kg/m}^3$ ,  $E = 70.76\text{GPa}$ ,  $\nu = 0.3375$ ) structure corresponds to a wavelength of around  $1.6\text{mm}$ . The full 3D FE simulations were carried out with

the Pogo Software package [80, 82]. In order to ensure the accuracy and stability of the simulations, linear cubic elements with side lengths of  $0.05mm$  and a time step of  $6.34ns$  were used. This gives 30 elements per wavelength (assuming a wavelength of  $1.5mm$ ) and more than 5 simulation time steps before the shear wave travels from one element to the next. Parameters that are more conservative than the commonly suggested [83, 82]. To ensure the simulations use the least possible computation resources, a small section of a block was modelled. The geometry investigated throughout the simulations is shown in Figure 3.2. Here, a typical model had around 648 million degrees of freedom and took approximately one hour and half to run on a data Muncher with 8 Nvidia Quadro RTX 8000 GPU cards.

Figure 3.2 displays the general FE setup used throughout this study. In order to mimic the OCLC EMAT active area, an excitation area of  $12mm \times 12mm$  [94] was placed on the top surface of a  $30mm$  thick aluminium block where polarised shear waves were generated via tangential surface tractions; the excitation signal consisted of a 5-cycle Hanning-windowed toneburst at  $2MHz$  centre frequency with maximum amplitude of 1, (I am assuming that the wave propagation of the shear waves is a linear problem and am only interested in relative amplitude changes of the waves. Therefore, the absolute values of the surface tractions in the simulations are not relevant for the results of this study). The preference of using a 5-cycle Hanning-windowed toneburst rather than a single pulse as an excitation signal is due to its well-defined frequency bandwidth compared to single pulse signals. The surface defect was placed on the opposite surface of the aluminium block. By simply changing the geometry of the defect, the effect of various parameters such as defect depth, width, and orientation on the reflection of the shear waves can be studied.

To simulate a pulse-echo measurement, the reflection was recorded via the same nodes used for the excitation (red area in Figure 3.2) where the OCLC EMAT reception was simulated by summing and then normalising the surface displacement components oriented along the corresponding coil direction.

In order to understand the behaviour of the polarised shear waves when interacting with surface crack-like defects, an one-element-wide notch defect was placed at the middle of the block, as is shown in figure 3.2. The defect was created by disconnecting the set of nodes at the location of the discontinuity. With this configuration, the displacement

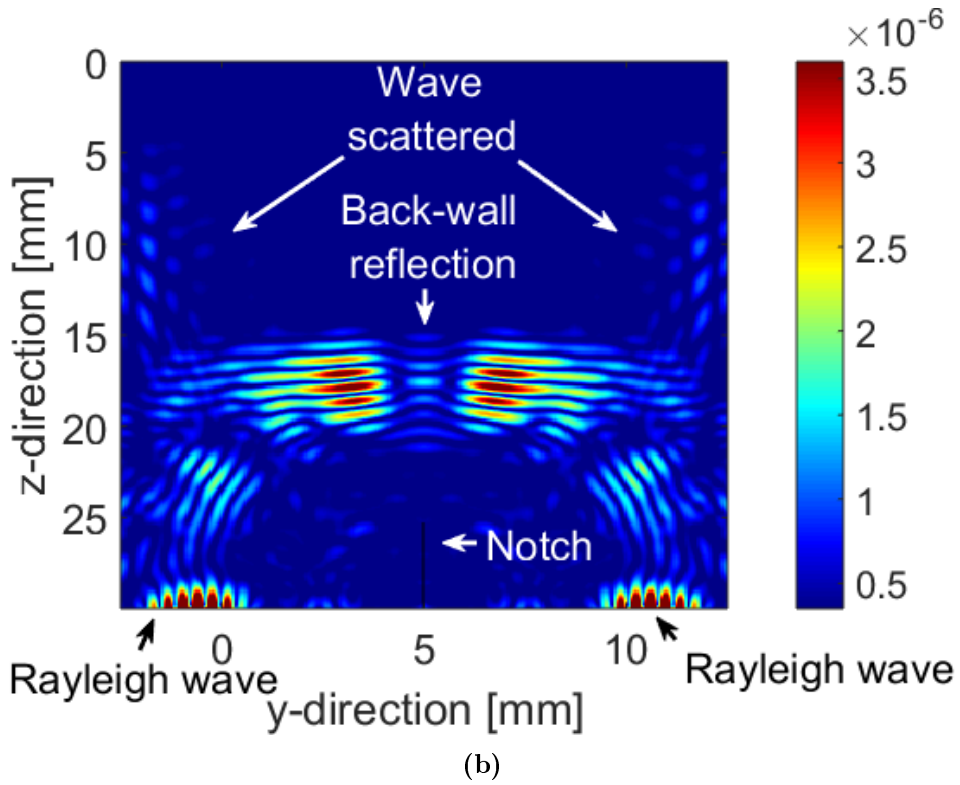
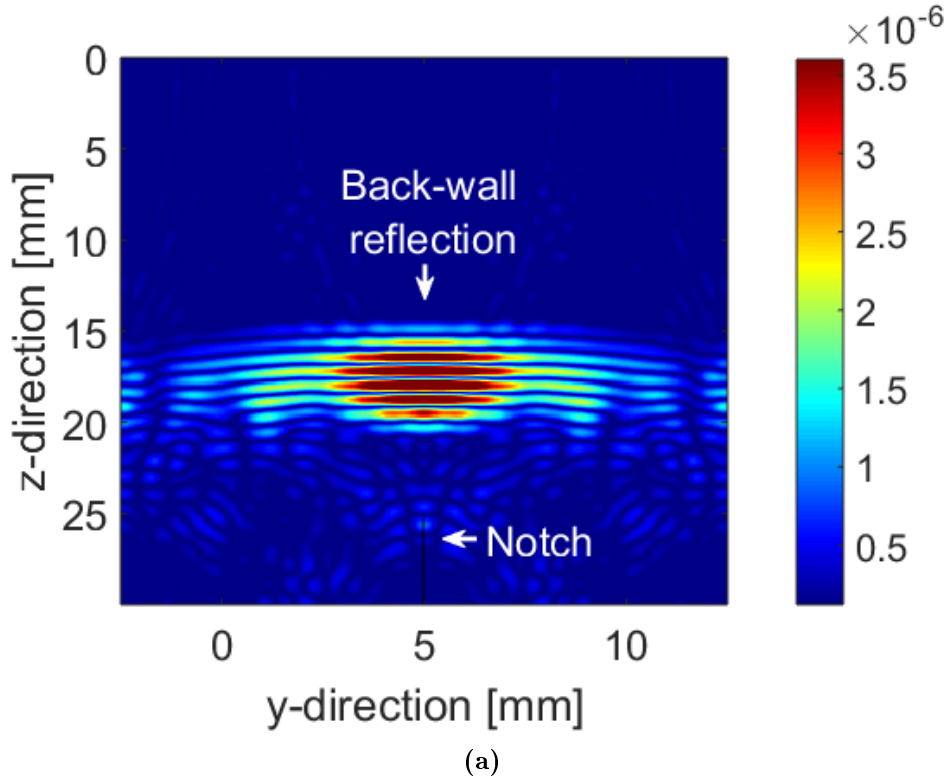
coming from the left-hand side of the defect is not transferred to the right-hand side and vice versa, simulating the effect of a surface-breaking defect. Then, simulations of the wave propagation were carried out with various defect depths (0.05, 0.3, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10mm) as well as for different normalised (to transducer size) defect lengths of 5%, 10%, 20%, 40%, 60%, 80% and 100% and at different orientations (0°, 10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80° and 90°).

## 3.4 Measurement concept

The procedure of measuring the thickness of a metallic material consists in generating an ultrasound wave at the material surface, and then recording the reflections of the emitted wave from the back-wall of the material. By determining the ToF between consecutive back-wall reflections and multiplying this with the wave speed, the thickness of the material is estimated.

Moreover, to detect the presence of crack-like defects, the relative amplitude of the reflection of two orthogonal and linearly polarised shear waves that are co-located is proposed. This is possible because the reflected amplitude of a transmitted linearly polarised shear wave through an area of material containing a crack-like defect is strongly dependent on the relative orientation of the defect and the incident shear wave polarisation. Figure 3.3 illustrates how the shear waves are affected by the presence of a crack-like defect. The FE simulation results were obtained for a notch of 0.05mm width, 5mm depth and 30mm length. Figure 3.3a shows how an incident shear wave that has a polarisation direction parallel to the defect face is almost unaffected by the presence of the notch, while figure 3.3b illustrates how an incident shear wave with polarisation perpendicular to the notch scatters at the defect's tip and mode converts into compression and Rayleigh waves. Figure 3.3c shows the amplitude of the signals recorded when the incident shear wave is parallel or perpendicular to the notch orientation. The time-traces show the excitation signal used for the pulse-echo tests, the received L+S wave which is the resultant wave of the mode conversion of the longitudinal wave that is excited at the edges of the OCLC EMAT's aperture and then mode converted to shear waves at the back-wall surface of the specimen [32] and the 1<sup>st</sup> back-wall reflection recorded at the aperture area. The amp-

litute difference between both 1<sup>st</sup> back-wall reflections is due to the relative orientation of the shear waves with respect to the notch.



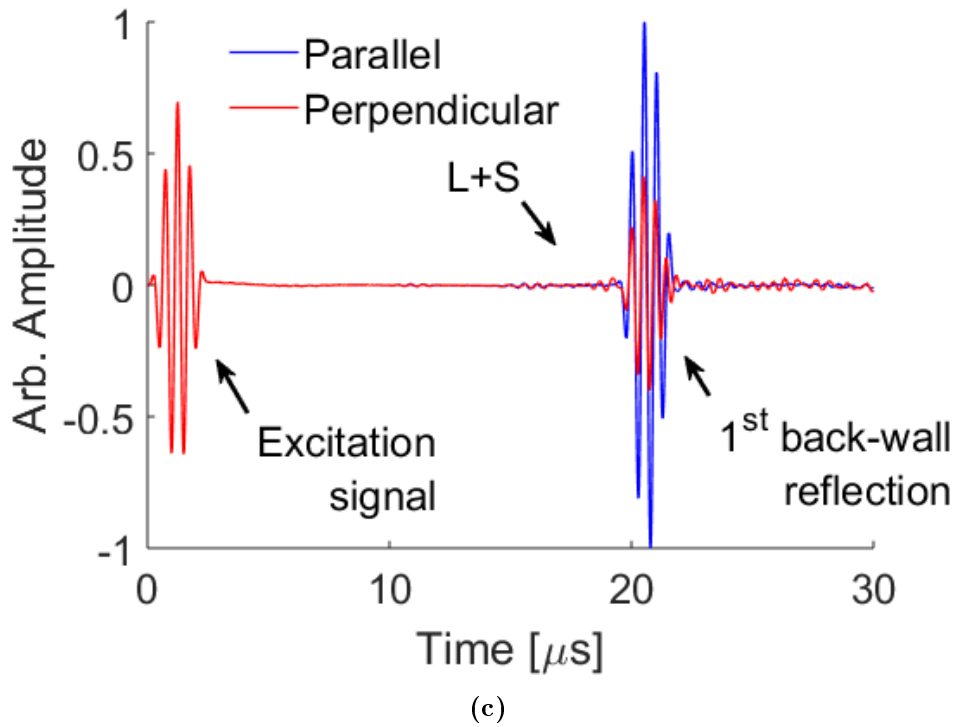


**Figure 3.3:** FE results of two orthogonal and linearly polarised shear waves (2MHz, 5-cycle Hanning-windowed) interacting with a notch defect of 0.05mm width and 5mm depth across the back surface of the material. a) Displacement magnitude of the shear wave with polarisation aligned parallel. b) Displacement magnitude of the shear wave with polarisation aligned perpendicular. c) Normalised time-trace of the incident and reflected shear waves when the back-wall has a notch in it.

The amplitude of a reflected shear wave when interacting with a crack-like defect also depends on the relative length of the defect with respect of the transducer aperture. If the crack-like defect is shorter/smaller than the transducer aperture, part of the incident wave will not interact with the defect, leaving the reflected wave from that area unaffected by the presence of the defect. Figure 3.4 shows the back-wall reflection amplitude drop of the shear wave perpendicular to the defect as a function of the crack depth and aperture. The results show that the amplitude drop increases for deeper and/or longer defects.

The amplitude drop is also dependent on the width of the defect/notch as additional scattering occurs due to the reflection from the top side of the defect; hence higher amplitude is observed as the width of the defect is increased. Figure 3.5 displays the effect of the crack-like defect (notch) width on the amplitude drop of back-wall reflections. The FE results show the percentage of amplitude drop of the perpendicular and parallel (relative

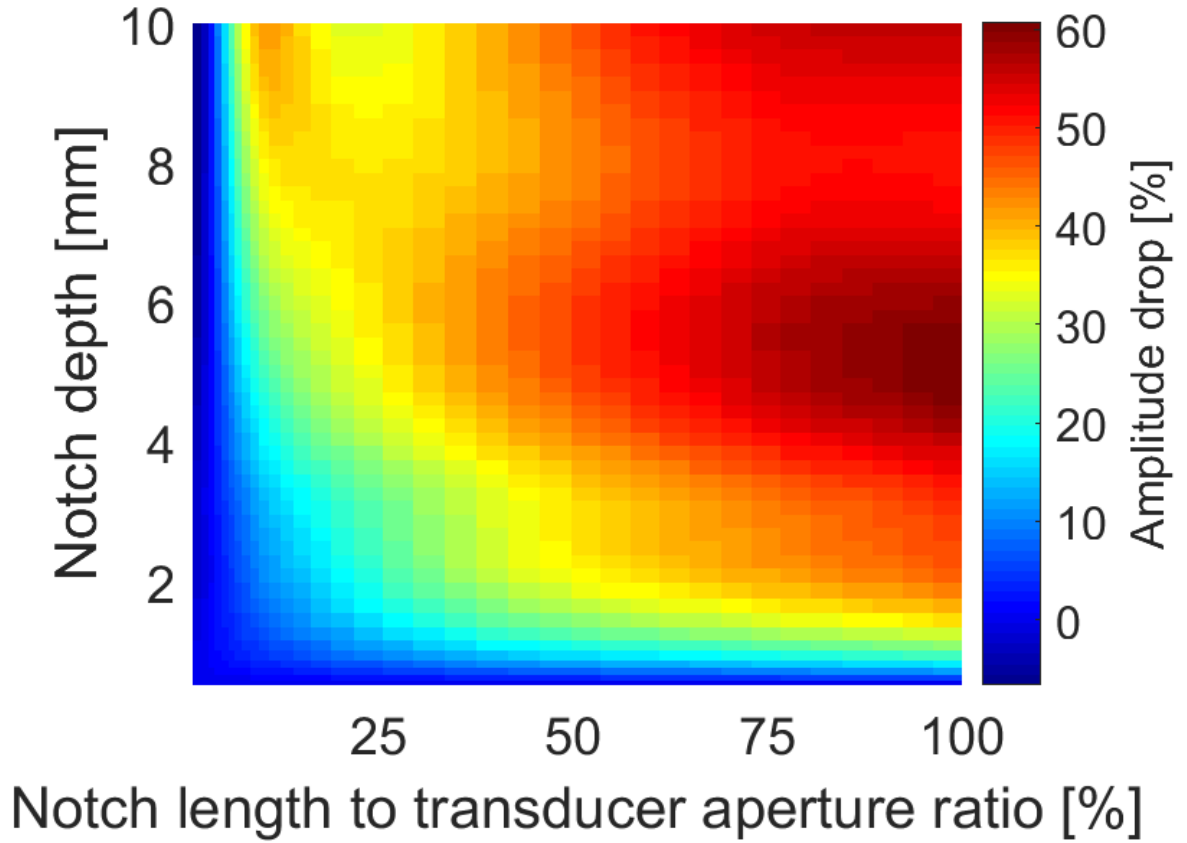


**Figure 3.4:** FE simulation predictions of the amplitude drop of the perpendicularly (with respect to defect face) and linearly polarised shear wave relative to the parallel polarised shear wave as a function of crack depth and crack length. The results were obtained for a  $30\text{mm}$  thick aluminium block at a centre frequency of  $2\text{MHz}$ .

to the defect face) shear waves as a function of the defect/notch width ranging from 0 to  $1\text{ mm}$ .

The OCLC EMAT, in pulse-echo mode, is proposed to be used to measure the thickness of a metallic material and detect the presence of a crack-like defect in the same material by exciting two orthogonal and linearly polarised shear waves simultaneously. The two generated shear waves will interact with the material back-wall surface and reflect towards the OCLC EMAT. The thickness of the material is proposed to be measured by calculating the ToF using one of the signals recorded with the coils. To detect the presence of a crack like defect, the amplitudes of the two reflected waves could be recorded and compared to each other. If there is an amplitude drop in one of the waves relative to the other, then it has been detected that one of the incident waves has scattered more energy away due

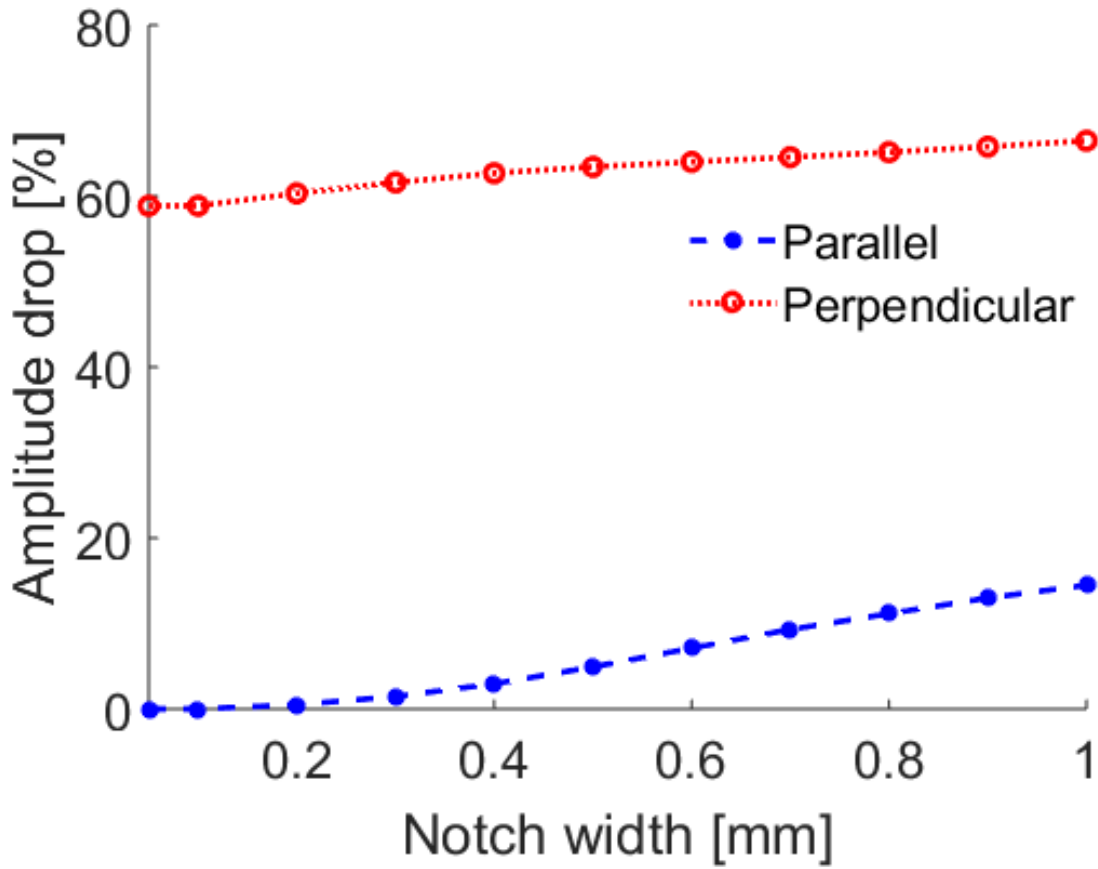


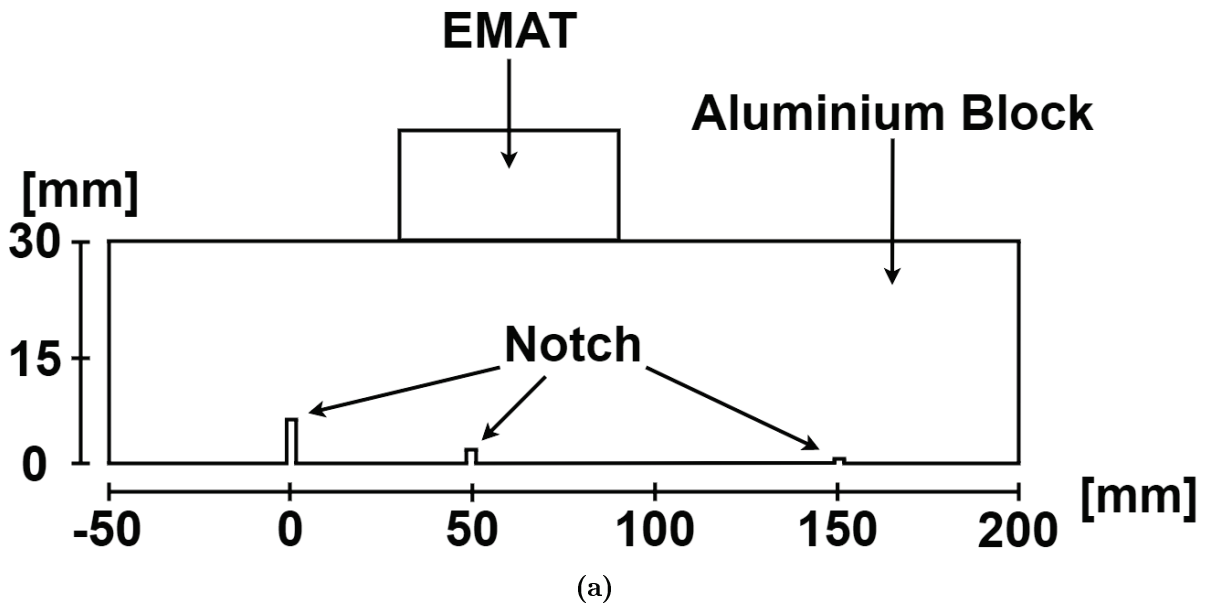
**Figure 3.5:** FE simulation results of the notch width effect in the percentage amplitude drop of linearly polarised shear wave back-wall reflections. The notches simulated were 30mm long and 5mm depth.

to the presence of an anomaly in the material.

### 3.5 Experimental design and setup

To verify the FE predictions, an OCLC EMAT with 12mm active aperture was built and placed on a 30mm thick, 250mm long and 100mm wide aluminium block. Three notches with different depths (0.3, 1 and 5mm or 1/5, 2/3 and 10/3 of the wavelength as shown in figure 3.6a) were machined into the back-wall of the block. The notches were 0.3mm wide and spanned the whole width of the specimen. Then, four different experiments were carried out by performing several pulse-echo tests on the aluminium block. The first experiment, which consisted in a pulse-echo test executed in a defect free region (OCLC EMAT placed at 100mm as shown in figure 3.6a), was carried out to get the

baseline amplitude of the reflected shear waves and the wave propagation velocity of the excited shear waves. The second experiment consisted of a pulse-echo test over the three different notches (where one of the linearly polarised shear waves was aligned parallel with the notch orientation), the purpose of this experiment was to measure the effect of defect depth in the amplitude of the reflected shear waves. The results obtained in the first and second experiment were analysed to extract the back-wall reflection amplitude drop due to the presence of the notches and the estimated thickness of the material when a defect is present. The third experiment was performed to investigate the effect of the transducer offset relative to the defect position. The experiment was conducted by varying the relative offset between the 5mm-depth notch and the centre of the OCLC EMAT. The relative offset was varied from  $-10$  to  $10\text{mm}$  with a  $1\text{mm}$  step. The last experiment was performed to measure the amplitude drop when the relative orientation of the OCLC EMAT with respect to the defect is varied. The experiment was executed by rotating the OCLC EMAT in  $10^\circ$  steps from  $90^\circ$  position to the  $0^\circ$  position. For the four experiments both coils were used in pulse-echo mode; and the coils were excited simultaneously. Figure 3.6a depicts the geometrical setup of the first three experiments and figure 3.6b shows the geometrical setup of the last measurement.



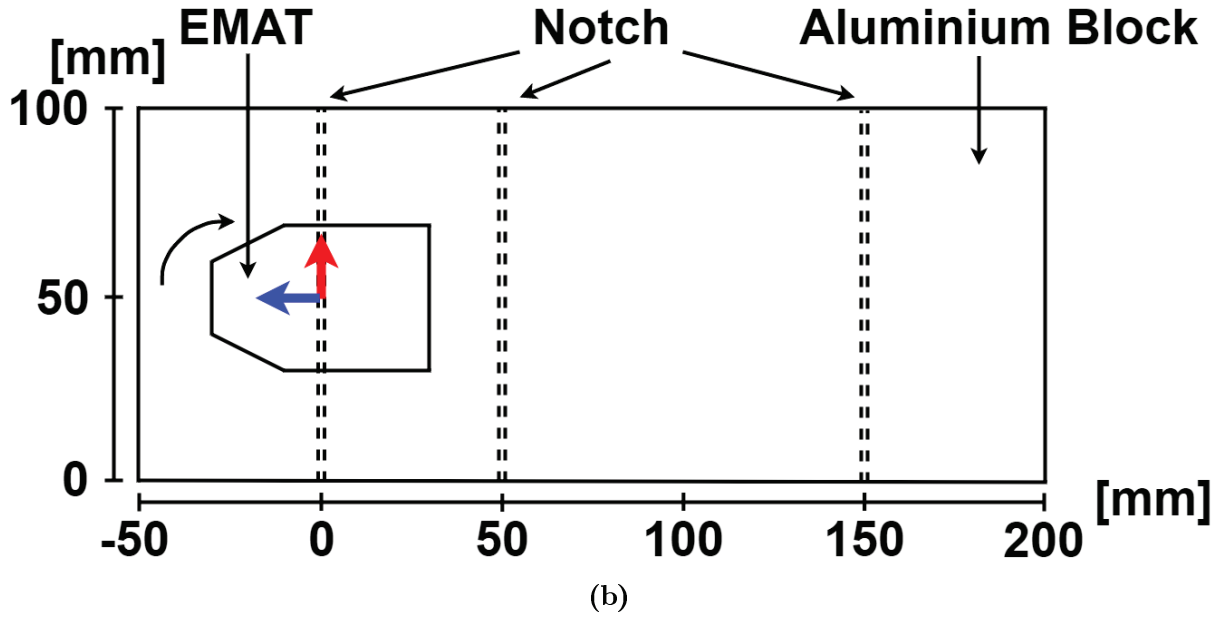
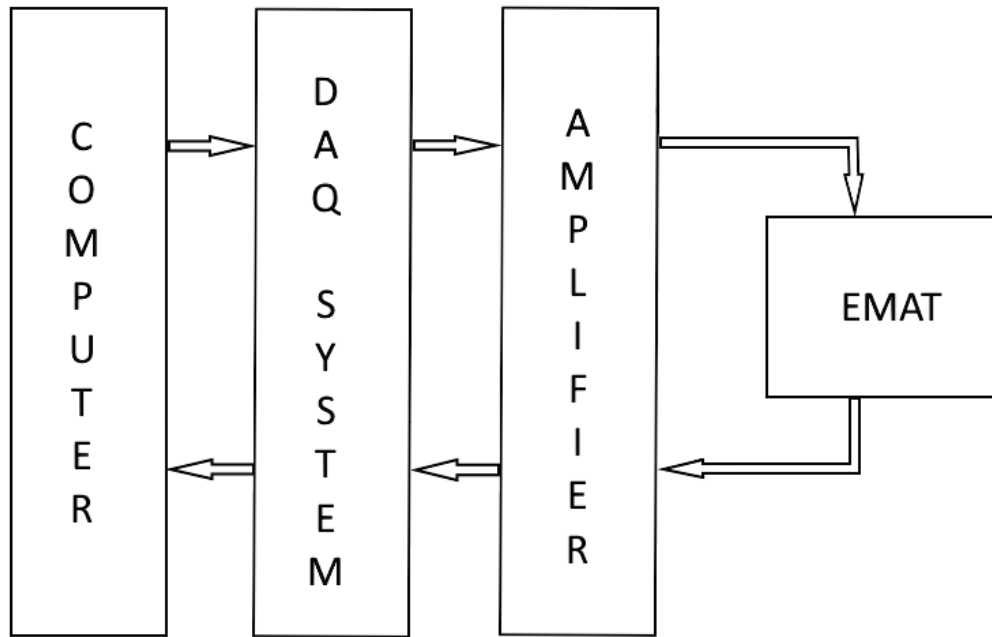


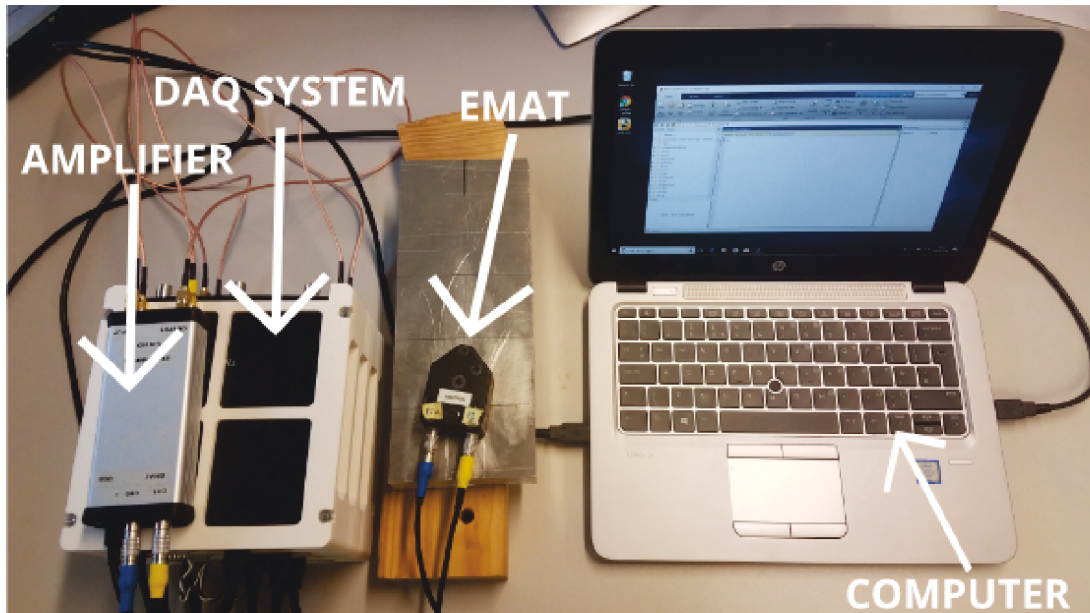
**Figure 3.6:** Schematic of the measurement setup and geometrical orientation of the OCLC EMAT. a) Front view. b) Top view. Arrows indicates the coils orientation when the OCLC EMAT has an angle rotation of  $0^\circ$  with respect of the notch. Blue arrow represents coil A orientation and red arrow indicates coil B orientation.

A schematic of the experimental setup used to perform the experiments is shown in figure 3.7a. The measurement setup consists of a computer, a data acquisition system (DAQ) containing two synchronised Handyscope-5 (HS5) with arbitrary function generator (AWG) and oscilloscopes, an Amplification System (AS) developed in-house and the OCLC EMAT. A picture of the full system is shown in figure 3.7b.

The computer, which controlled the experiment, executed a Matlab [99] routine that used two synchronised HS5 devices to send and receive signals to/from each coil. In between the HS5s and the OCLC EMAT the AS was connected. The purpose-built amplifier was used to enhance the excitation and receive signals of the transducer. The AS contains a buffer amplifier on the transmitting side, an isolation switch to interchange between transmitter and a 60 dB receiver amplifier.



(a)



(b)

**Figure 3.7:** Measurement setup. a) Schematic. b) Picture of the full acquisition system including Laptop, HS5, Amplifier, specimen and OCLC EMAT.

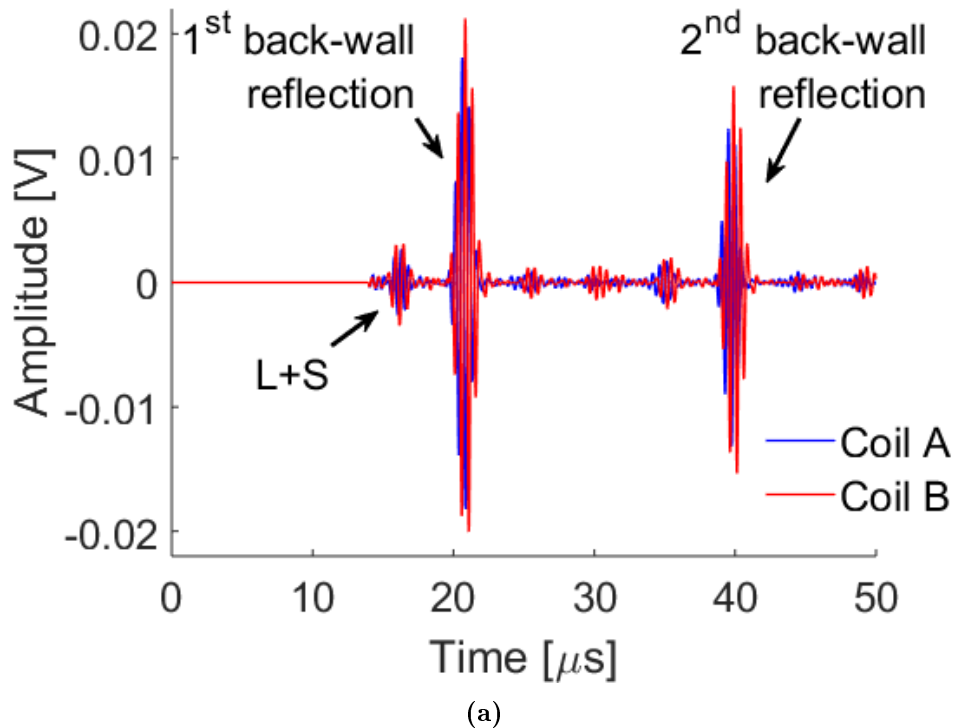
### 3. Orthogonal and Co-located Shear Wave EMAT

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Ultrasound data could be acquired rapidly and simultaneously from both OCLC EMAT coils by employing the use of coded sequences to excite each coil [100]. The signal encoded was a 5-cycle Hanning-windowed toneburst at  $2MHz$  centre frequency with an amplitude of  $24V_{pp}$  from the AWG. Then, the signal was amplified by the AS and transmitted to the OCLC EMAT, which induced the tangential traction at the surface of the aluminium block. Once the ultrasound signal has been excited and travelled through the material, its reflections from the back-wall of the material were measured by the OCLC EMAT and sent to the AS, which amplified the received signal to be recorded by the HS5 devices.

## 3.6 Finite elements and experimental results

The results of two pulse-echo tests on the aluminium block, using the OCLC EMAT, are shown in figure 3.8. The time-traces shown in figure 3.8a are the results of the inspection when the OCLC EMAT is placed on top of the undamaged area of the aluminium block and figure 3.8b shows the results of the inspection when the OCLC EMAT is placed on top of the  $5mm$ -depth notch.



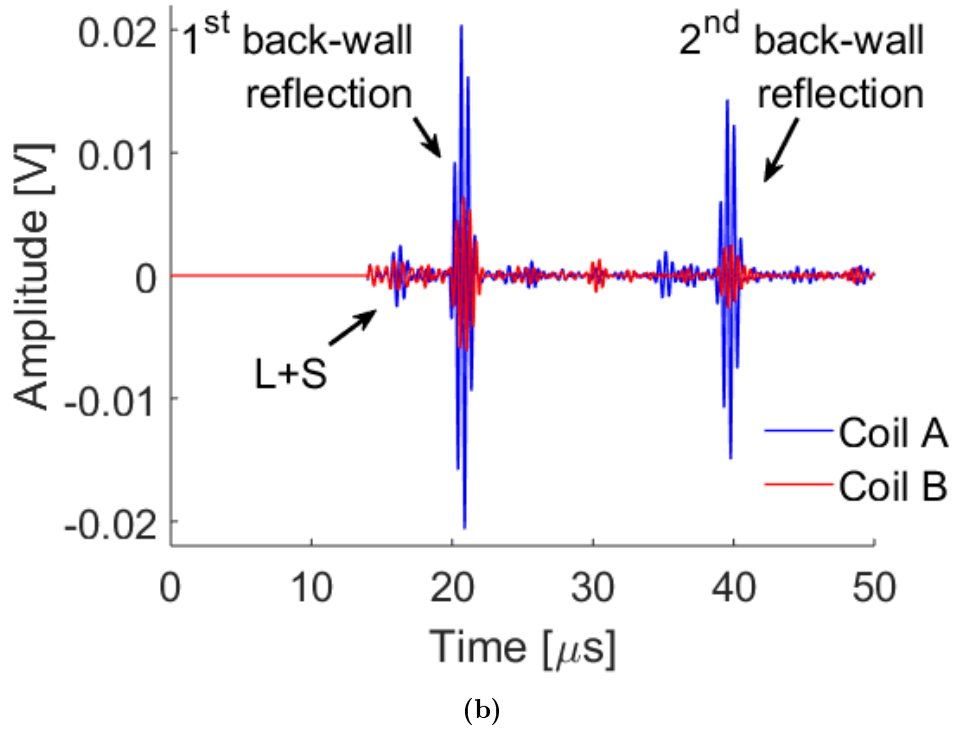


**Figure 3.8:** Back-wall reflection recorded with the OCLC EMAT coils. a) Back-wall reflection from an undamaged back surface. b) Back-wall reflection when a 5mm depth, 0.3mm width and 100mm long notch is present.

The ToFs shown in table 3.1 were calculated by measuring the time difference among maximum absolute values of the 1<sup>st</sup> and 2<sup>nd</sup> back-wall reflection of the same time-trace. The ToF calculated, when the back-wall is undamaged, were used to estimate the reference values of the shear wave propagation velocities in the aluminium block at the direction of each coil. The velocities were calculated by dividing the distance that the shear waves travelled in the aluminium block by the ToF.

Once the shear wave propagation velocities in the aluminium block were estimated, the calculated ToFs when the notch is present were used to measure the thickness of the aluminium block. The thickness was measured by multiplying the ToFs with the shear wave propagation velocities in aluminium and then divide the result by the times that the wave travelled through the material from the 1<sup>st</sup> to 2<sup>nd</sup> back-wall reflection. The estimated velocities and thicknesses using the calculated ToFs when the back-wall of the aluminium block is undamaged and when the notch is present are shown in table 3.1.

### 3. Orthogonal and Co-located Shear Wave EMAT

| Thickness measurement |             |              |               |
|-----------------------|-------------|--------------|---------------|
|                       |             | Undamaged    | Notch present |
| Coil A                | ToF         | $18.88\mu s$ | $19.04\mu s$  |
|                       | SW velocity | $3178m/s$    | $3178m/s$     |
|                       | Thickness   | $30mm$       | $30.03mm$     |
| Coil B                | ToF         | $18.9\mu s$  | $19.06\mu s$  |
|                       | SW velocity | $3151m/s$    | $3151m/s$     |
|                       | Thickness   | $30mm$       | $30.03mm$     |

**Table 3.1:** Estimated velocity and thickness using the OCLC EMAT.

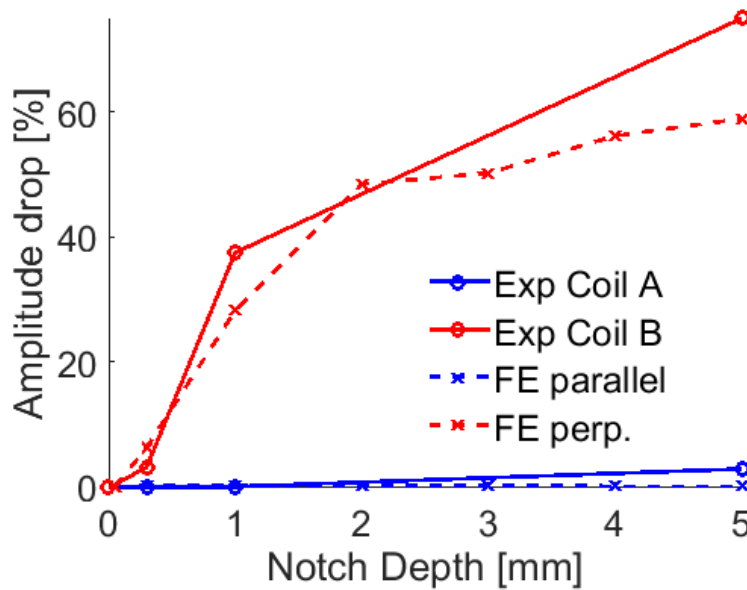


**Figure 3.9:** Maximum amplitude drop of the back-wall reflection vs the depth of a notch. The experimental results are the result of the shear waves interacting with different  $0.3mm$ -width notches, while for the FE, the results are from the interaction with different  $0.05mm$ -width notches. The amplitude drop percentage was calculated by comparing the results when the defect is present and absent.

The results of the second, third and last experiments with their equivalent FE results are shown in figures 3.9, 3.10 and 3.11 respectively. The FE results in figures 3.9, 3.10 and 3.11 were obtained for  $0.05mm$ -width notches, while the experimental results were obtained for  $0.3mm$ -width notches. The rest of the geometrical dimensions of the notches

were the same for both cases.

Figure 3.9 shows the maximum amplitude drop of the shear waves as a result of their interaction with notches of different depth. Figure 3.10 shows the relative amplitude drop from each coil as a function of OCLC EMAT offset relative to the notch ( $0\text{mm}$  value offset signifies that the OCLC EMAT is directly over the defect). Figure 3.11 shows the results acquired in the fourth experiment. The normalised maximum amplitude recorded on both coils is plotted for each angular position in which it was taken. The amplitude drop percentage for figures 3.9 and 3.10 were calculated by comparing the results to those obtained from the undamaged section of the specimen.

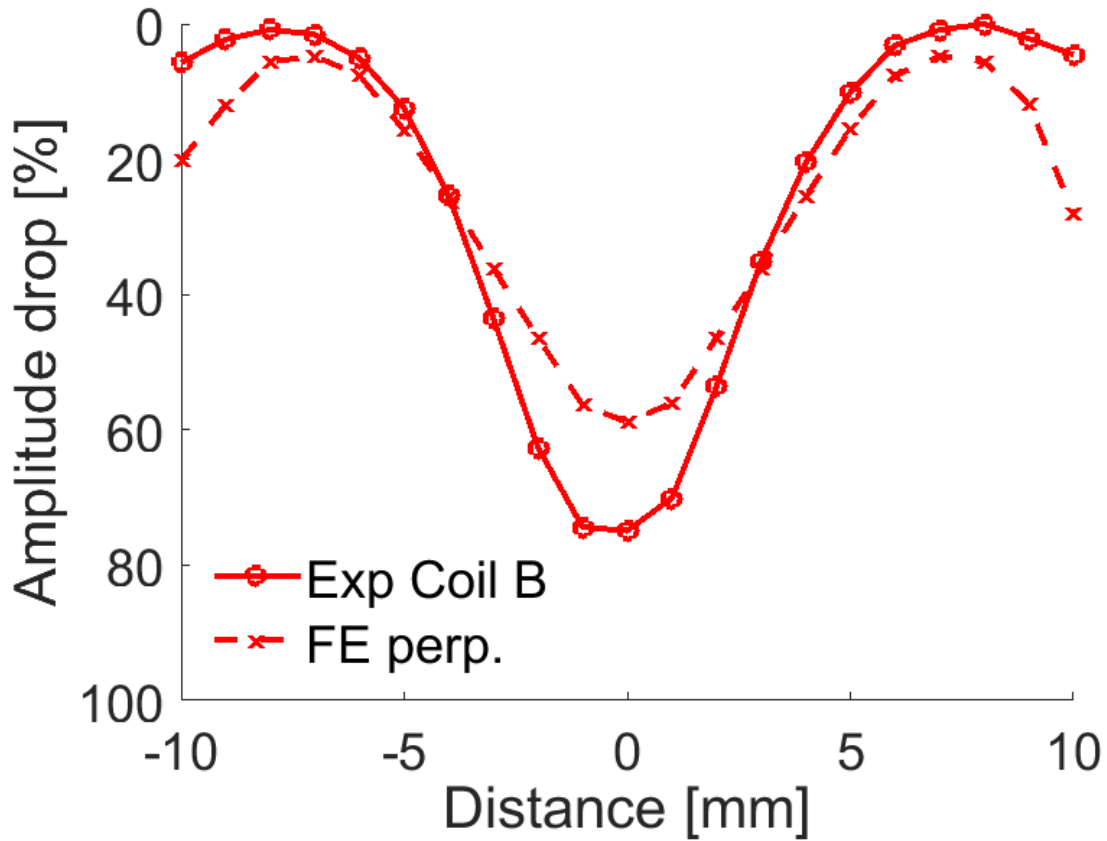


**Figure 3.10:** Maximum amplitude drop of the back-wall reflection vs offset distance between notch and OCLC EMAT. The experimental results are the result of the shear waves interacting with the  $5\text{mm}$ -depth notch, while for the FE, the results are from the interaction with a  $0.05\text{mm}$ -width and  $5\text{mm}$ -depth notch. The amplitude drop percentage was calculated by comparing the results when the defect is present and absent.

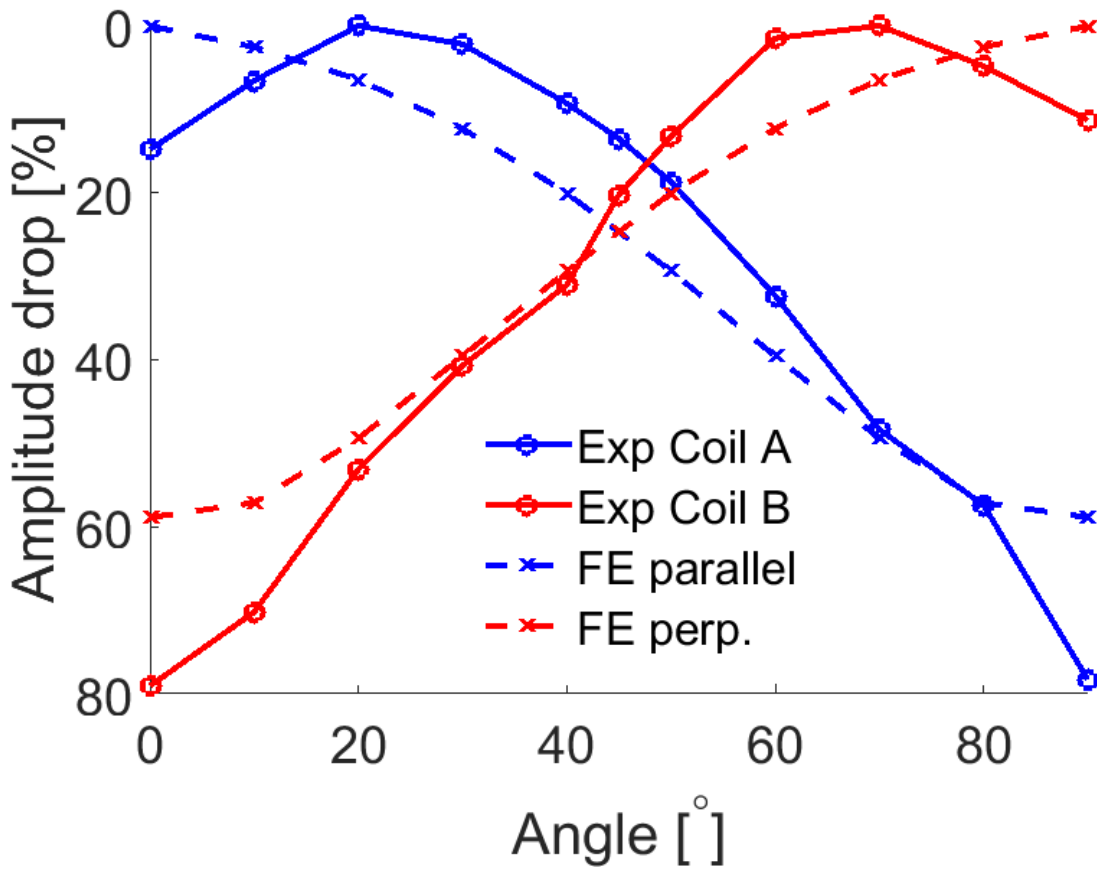


**Figure 3.11:** Maximum amplitude of the back-wall reflection vs relative angle of the  $5mm$ -depth notch with the OCLC EMAT. The experimental results are the result of the shear waves interacting with the notch, while for the FE, the results are from the interaction with a  $0.05mm$ -width notch. The amplitude drop percentage was calculated by measuring how much each amplitude data point has decreased compare with the maximum value in the experiment.

### 3.7 Discussion

The possibility of using the OCLC EMAT to detect and characterise crack-like defects was studied by establishing the forward relationship between the ultrasound shear waves that the OCLC EMAT excites and crack-like defects present in metals. The FE results used to understand the interaction of the ultrasound shear waves with crack-like defects were compared to their experimental counterpart. The results showed that a direct relationship between the amplitude of the ultrasound signal and crack-like defect exists. Hence, the amplitude of the ultrasound signals can be used to detect and estimate the size of a crack-like defect. It should be noted, however, that the majority of the FE results had

lower amplitude drops compared with the experimental measurements. I believe that this discrepancy is the combination of several geometry factors, i.e., the difference in notch width, and notch tip shape used in the simulations when compared to the ones used in the experiments. The FE results were obtained for  $0.05mm$ -width notches, while in the experiments, the notches had a width of  $0.3mm$ . In figure 3.5, it is shown that this difference in notch width can lead to an extra 9% amplitude drop. Other experimental factors such as surface roughness associated with the notch faces and not flat bottom surface of the notch tip are thought to further enhance the amplitude drop recorded in experiments.

The amplitude drop percentage recorded with the OCLC EMAT depends on the relative position and orientation of the coils with respect to the crack-like defect; and therefore, the highest chance to detect the presence of the defect occurs when one is positioned directly above the defect and oriented perpendicular to the defect. However, if the relative orientation of both coils with respect of the defect is similar (close to  $45^\circ$ ), then the amplitude drop of each coil will be similar, complicating the detection of the defect. In such cases, the presence of the defect would not be verified. However, by rotating the transducer  $45^\circ$  in the same position, defects with height of  $1/2$  of the wavelength or higher could be detected due to stronger contrast between the amplitude drops recorded by each OCLC EMAT coil.

The capability to perform thickness measurements using the OCLC EMAT was verified by estimating the thickness of an aluminium block when the back-wall surface was undamaged and when a crack-like defect was present. The experimental results of thickness measurement are presented in table 3.1 and figure 3.8. The results, for each coil, show similar estimation values for both cases; showing that the thickness measurement can be performed irrespective to the presence of a crack-like defect. However, slight difference between the ToFs recorded by each of the coils was found to be due to the material anisotropy of the tested aluminium block, resulting in wave velocity variation of around 1%. This discrepancy can be compensated for by comparing the ToFs recorded by each coil when obtained on an undamaged section of the specimen.

Moreover, there is a  $0.02\mu s$  difference among ToFs measured with the same coil (when the notch is present and when back-wall surface is undamaged). This difference corresponds

to a position change of the maximum peak of the back-wall reflections of 1 sample, at the sampling frequency of  $50MHz$ , and is therefore not believed to be significant as slight changes in amplitude and noise can push the peak into the next digital sample point.

While the topic of this chapter is the forward interaction of linearly polarised orthogonal shear waves with crack like defects, the inverse problem is the topic of the next chapter. In chapter 5, it is explained how the signals obtained with the OCLC-EMAT can be used to estimate the presence of crack-like defects. In there, it is also explained how the signals obtained with the OCLC-EMAT can be used to characterise anisotropic materials.

## 3.8 Conclusion

This chapter has demonstrated that EMATs containing orthogonal co-located coils can be used to excite two perpendicular and linearly polarised shear waves. The two perpendicularly oriented shear waves interact very differently with crack-like defects and the resulting amplitude difference of the received signals can be used as a reliable indicator for the presence of a defect in metallic materials. The results obtained with the OCLC EMAT show that crack-like defects with depth  $0.3mm$  ( $0.2\lambda$ ) or higher can be detected by placing one of the shear waves parallel to the defect face and comparing the maximum amplitude difference between the signals that are measured with both coils. However, the received signal amplitude drop plateaus at a crack depth of roughly  $2\lambda$ , meaning the amplitude drop value cannot be used to estimate the size of defects of  $3mm$ -depth or larger. Additionally, the amplitude drop of the recorded back-wall reflections depends on the relative orientation and position of the OCLC EMAT with respect to the crack-like defect. The chance to detect the presence of a crack-like defect decreases when the OCLC EMAT is not on top nor aligned with the direction of the defect.

To investigate how the amplitude of the received signals can be used to determine the presence of a defect, FE simulations of the two orthogonal and linearly polarised shear waves interacting with different crack-like defects were performed and validated with experimental results. The FE and the experimental results show good agreement. The discrepancies resulted because the FE simulations were performed for  $0.05mm$ -width notches while the experiments were implemented on notches with a  $0.3mm$  width.

The NDE technique introduced in this chapter is a new concept that can be used for thickness measurements and crack-like defect detection. The advantage of this technique with respect of conventional NDE techniques is that one single setup allows to perform both measurements simultaneously.

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## Chapter 4

# Evaluating anisotropy and cracks in metals using the OCLC EMAT

This chapter summarised the findings obtained when two co-located shear waves with orthogonal and linear polarisation are used for defect detection and anisotropy characterisation. The results presented here were obtained by me with the supervision of Dr Frederic Cegla and with the advice of Dr Bo Lan. Most of the material in this chapter was taken with minor alterations from [P2] (with permission from NDT & E International).

### 4.1 Introduction

Shear waves are important in Non-Destructive Evaluation (NDE) for assessing material microstructure [101–103], detecting and sizing crack defects [104–108], or even measuring residual stresses [109–111], due to their higher sensitivity to these features compared to longitudinal waves. The elastic anisotropy (i.e. direction-dependence) of materials, which is a general phenomenon in metals and minerals alike, strongly affects the propagation of shear waves [72] by causing the so-called wave splitting: a shear wave with an arbitrary polarisation/shear direction would split into two partial shear waves with polarisation along the two principal shear directions (PSDs) of the material, and the partial waves then travel into the material at different wave speeds [112].

Shear splitting greatly complicates the inspections in anisotropic materials, since both

time-domain signals and amplitude drops now need to be carefully handled for defect detection and sizing [53, 11, 113–115]. Whereas in an isotropic material these factors only depend on the source position and the defect, in an anisotropic material there is also a dependence on the relative orientation with respect to the PSDs. These PSDs can be arbitrarily oriented with respect to surfaces of the component that is being tested, which further complicates the detection procedure.

In chapter 3, it was presented a method for simultaneous crack detection and thickness measurement in a metallic material [P1]. The proposed methodology utilised two orthogonal shear waves with linear polarisation to inspect the material. The thickness of the material was estimated by calculating the product of Time-of-Flight (ToF) of the back-wall echoes and the shear wave speed in the material. The presence of a crack-like defect was determined by comparing the amplitude of the first back-wall echoes of the two orthogonal shear waves. The study focused on the interaction of the two shear waves of different polarisation with a crack-like defect in an aluminium block. The previous work relied on two assumptions: 1) the material that is being inspected is isotropic 2) any signal amplitude difference is the result of the presence of a defect. However, both assumptions are usually violated. Even aluminium, which is normally considered an isotropic material, exhibits weakly anisotropic behaviour [116]; and in anisotropic materials, the wave splitting phenomenon introduces signal amplitude drops that could be comparable to those obtained when a defect is present in an isotropic material. However, the amplitude drop in the anisotropic material appears due to the wave speed difference among PSD, the distance that the split waves travel in the anisotropic material, and the incident shear wave orientation with respect to the PSD. While the amplitude drop due to the presence of a defect depends on other factors such as the geometry of the defect, the type of incident wave and the angle form between the incident wave and the defect.

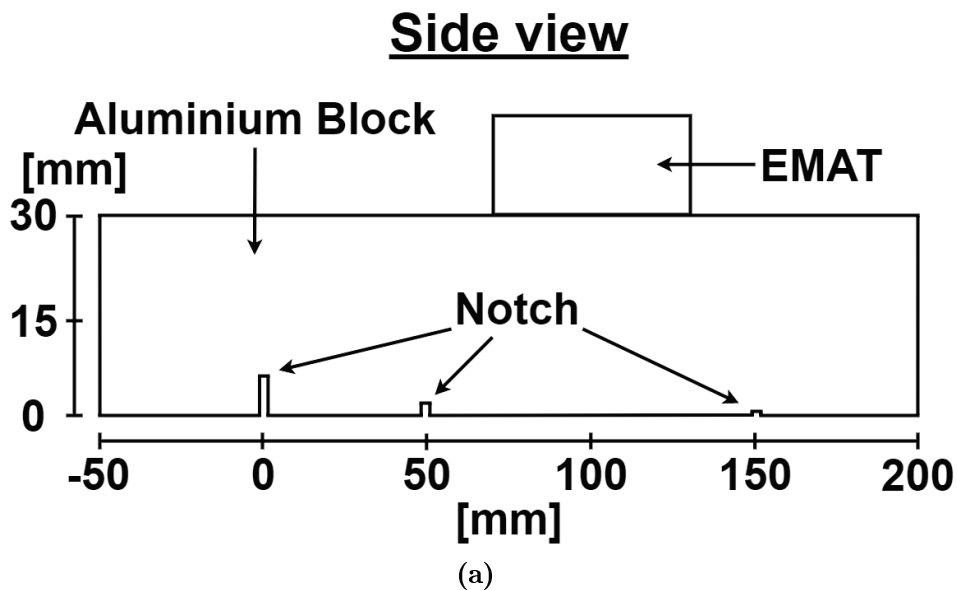
The wave propagation physics to address these considerations are presented in this chapter. The study will explain how two orthogonal and linearly polarised shear waves propagate in anisotropic materials and how their signal amplitude is affected by the presence of a crack-like defect. It will be demonstrated a convenient and accurate way to identify the PSDs of an anisotropic material, using an electro-magnetic acoustic transducer (EMAT) with a pair of co-located and orthogonally aligned coils known as the orthogonal co-located coils

EMAT or OCLC-EMAT. With the four time-domain signals obtained from the transducer, a shear wave with pure polarisation (along one of the PSD) can be generated, and indeed the shear waves excited with any arbitrary polarisation can be reconstructed (called in this thesis electrical steering). It will then be shown that, with the PSDs known, it can not only detect the presence of a crack-like defect in an anisotropic material, but also accurately and reliably evaluate the orientation of the crack.

### 4.2 Background and context

The experiments in this chapter were executed with the same setup as described in chapter 3 [P1]. In this setup, the OCLC-EMAT is used to excite two orthogonal and linearly polarised shear waves, at the same location in space. The transducer is composed of a magnetic circuit and two butterfly coils, one on top of the other, at the same location. However, one of the coils is rotated by  $90^\circ$  with respect to the other.

The main advantage of the OCLC-EMAT is the orientation of its butterfly coils. Their orientations permit the induction of two orthogonal and independent eddy currents in the surface of a conductive material. In combination with the bias magnetic field, the OCLC-EMAT can simultaneously excite two linearly polarised surface loads in orthogonal directions at the same spatial location via the Lorentz force [32].



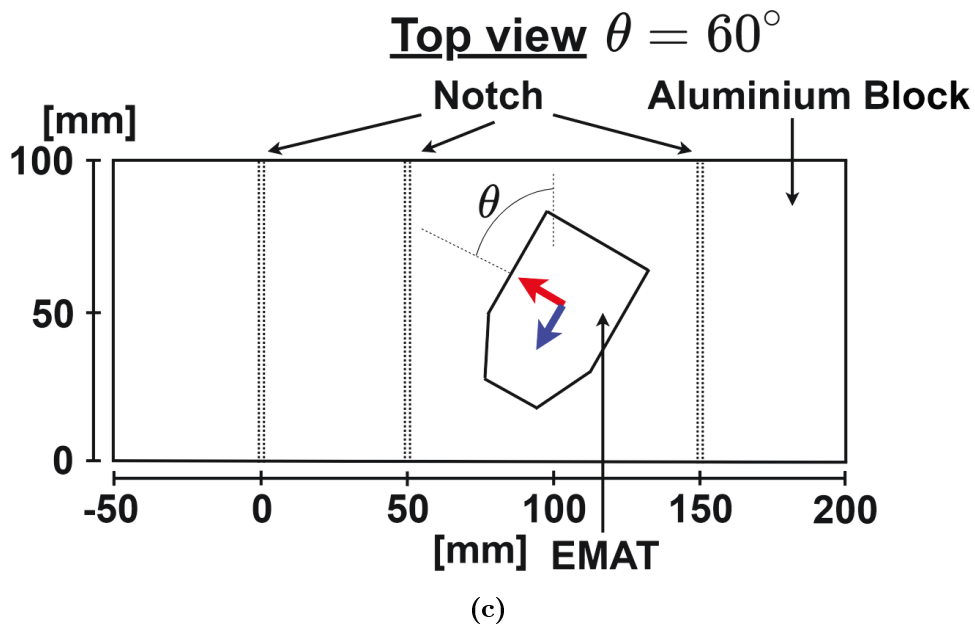
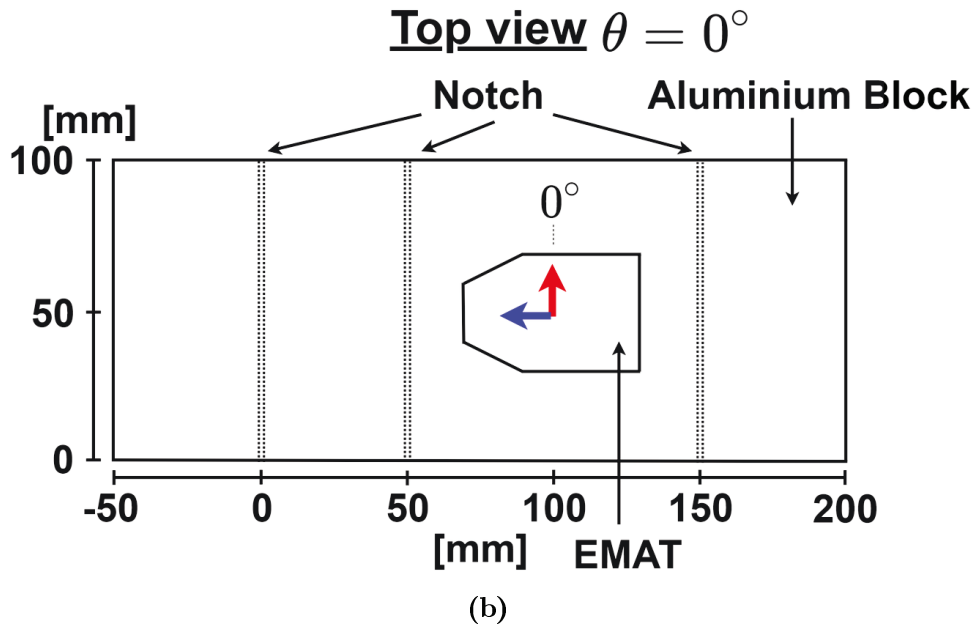
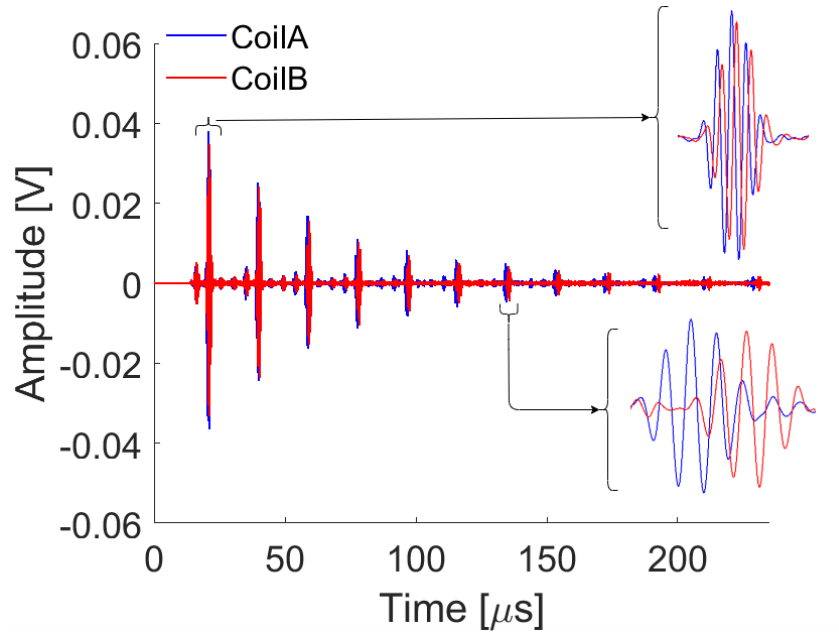
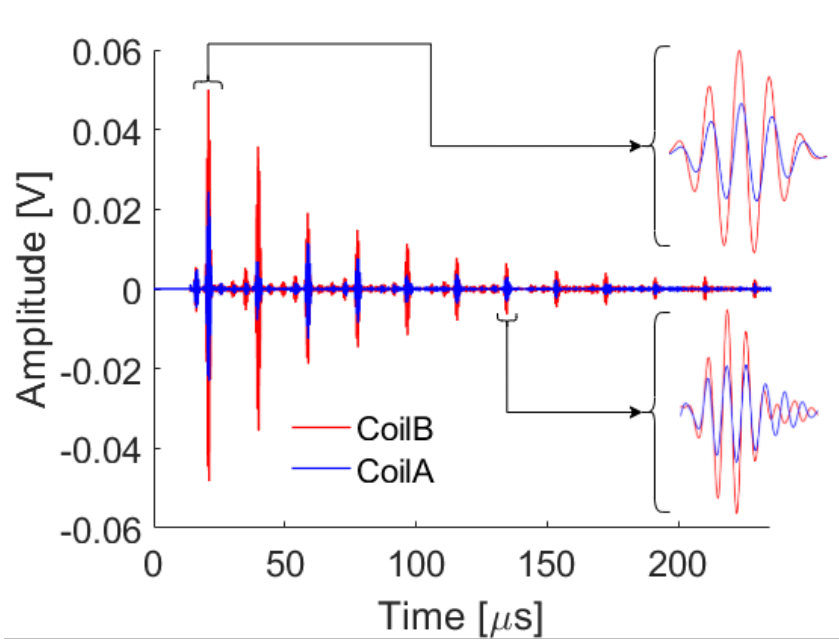


**Figure 4.1:** Schematic of the orthogonal co-located coils EMAT positioning on the aluminium block. a) Side view schematic of the OCLC EMAT on top of the aluminium block. The notches are 0.3mm width, and 0.3, 1 and 5mm height (1/5, 2/3 and 10/3 of the wavelength) b) Top view schematic of the OCLC EMAT on top of the aluminium block. c) Top view schematic of the OCLC EMAT 60° rotated on top of the aluminium block. The  $\theta$  indicates the rotated angle of the EMAT's coils with respect of the principal shear directions. The blue and red arrows indicate the shear polarisation of coil A and coil B, respectively. The 60° indicates the alignment with the principal shear directions of the material.



(a)



(b)

**Figure 4.2:** Back-wall reflections measured with the coils at different OCLC-EMAT orientation. The A-scans were obtained by placing the OCLC-EMAT coils at  $\theta = 0^\circ$  and  $\theta = 60^\circ$  with respect to the principal shear directions. a) A-scans excited and measured with the OCLC-EMAT coil at  $\theta = 0^\circ$ . b) A-scans excited and measured with the OCLC-EMAT coils at  $\theta = 60^\circ$ .

The previous work, shown in chapter 3 [P1], assumed that the inspected aluminium block was an isotropic material. However, the ToFs of the two orthogonal shear waves showed

that the waves travelled at different wave speeds. The difference of wave velocity was reported to be  $27\text{m/s}$  for the aluminium block that was used. The OCLC-EMAT was used to excite two shear waves with orthogonal orientation on top of the aluminium block, as shown in figure 4.1a and figure 4.1b.

The difference of wave speed is hardly noticeable on the first back-wall echo. However, when the time-traces of several back-wall echoes are plotted, the difference in speed becomes noticeable. To illustrate this, figure 4.2a shows two newly acquired time-traces of 12 back-wall echoes obtained at the same location, including a close up view of the 1<sup>st</sup> and 7<sup>th</sup> pair of back-wall echoes excited with the OCLC-EMAT. These two close up views show the difference in arrival time of the back-wall echoes increasing as the time passes.

In chapter 3, the relative signal amplitude of the two back-wall echoes was used to deduce the presence of a crack and to estimate its size. The existence of a signal amplitude difference among the two back-wall echoes was assumed to be induced only by the presence of the defect. However, the amplitude of the back-wall echoes when two orthogonal shear waves interact with a crack-like defect depends on the morphology of the defect and the relative angle between the polarisation direction of the excitation sources and the PSDs of the material [117]. When the relative angle between the PSDs and the transducers is  $0^\circ$ , the interaction of the two orthogonal shear waves with a crack-like defect behaves as if the material was isotropic and, therefore the method proposed previously [P1] can be used to detect and estimate the defect. However, when the angle is different to  $0^\circ$ , the back-wall signal amplitude depends not only on the morphology of the crack but also on the orientation of the transducer with respect to the PSDs. The effect of the angle between the excitation polarisation and the PSDs can be seen by comparing the time-traces obtained when the polarisation direction of excitation is changed with respect to the PSDs. Figures 4.2a and 4.2b illustrate the effect of having a source oriented at an angle of  $0^\circ$  and  $60^\circ$ , respectively (the second source orientation was selected arbitrarily). Figure 4.1c displays a schematic of the OCLC-EMAT coils rotated by  $60^\circ$  with respect to the PSDs and figure 4.2b shows the time-traces obtained when the OCLC-EMAT is rotated by  $60^\circ$ . The amplitudes of the echoes have considerably changed, especially those of coil A. The experimental results shown in figure 4.2b were obtained at the same location as those in figure 4.2a, only the transducer orientation was changed. During both tests

the shear waves were excited simultaneously.

These observations highlight that the transducer orientation relative to the PSDs influences the back-wall echo amplitudes as much as the presence of a crack. While the orientation of the PSDs can be determined by carefully rotating a transducer on the surface to find the maximum reflection amplitude, it is tedious to do this by hand consistently. In the next sections, I will explore how the orientation of the probe relative to the PSDs can be determined without needing to physically rotate the transducer, how to use this information to electrically steer a shear wave, how to detect the presence of a crack and how to characterise the crack orientation in the material.

### 4.3 Transmission and measurement of orthogonal shear waves in anisotropic materials.

When a shear wave starts propagating in an anisotropic material, the strain of the wave splits into two different strain components [72]. These strain components travel with polarisation along the principal shear directions of the material. The strain are orthogonal and independent of each other. Their displacement produces two different shear waves travelling along the direction of propagation of the initial shear wave, as shown in figure 4.3. Figure 4.3 illustrates the wave splitting phenomenon of an excited shear wave with arbitrary polarisation propagating in an anisotropic material. The shear wave was assumed to be excited with the OCLC-EMAT.

The split waves can have different amplitude and wave speed, depending on the properties of the material [118] and the polarisation direction of the incident shear wave. The material characteristics affect the wave speed at which the two waves travel in the material. The polarisation direction determines how the energy of the incident wave splits across the two PSDs. To illustrate the effect of the polarisation angle on a shear wave propagating in an anisotropic material, two different pulse-echo tests were performed on the same area of an aluminium block. The location used was the same as the one used for the results of figure 4.2. The first pulse-echo test was carried out by using the OCLC-EMAT coil B to generate a shear load at the surface of the aluminium block. The surface load was

#### 4. Evaluating anisotropy and cracks in metals using the OCLC EMAT

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polarised along the principal shear direction 1 ( $\theta = 0^\circ$ , orientation shown in figure 4.1b). The second pulse-echo test was performed by exciting one surface load with the OCLC-EMAT coil B at an angle of  $60^\circ$  from principal shear direction 1 ( $\theta = 60^\circ$ , orientation shown in figure 4.1c). The back-wall echoes of the two pulse-echo tests were recorded using both coils of the OCLC-EMAT. The results of the two pulse-echo tests are displayed in figure 4.4.

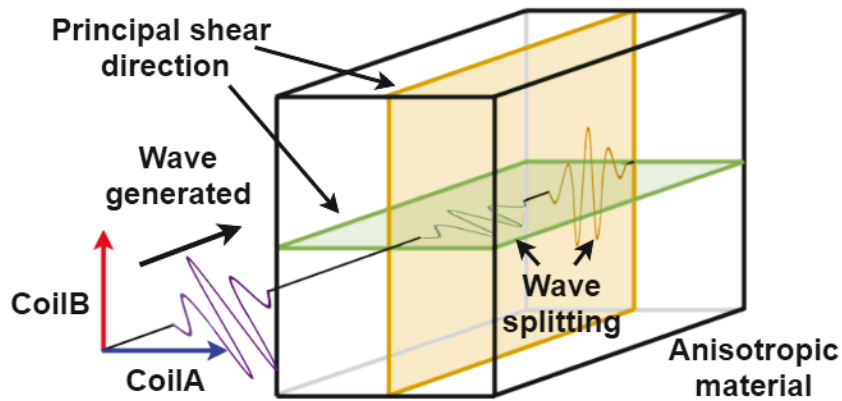


**Figure 4.3:** Wave splitting into two shear waves when travelling through an anisotropic medium. The new shear waves will travel aligned with the principal shear directions. The blue and red arrows indicate the direction of forcing that coil A and B, respectively, will induce on the specimen.

In figure 4.4a, it can be observed that the back-wall echoes of the incident shear wave were recorded by coil B, only. The reason for this is that the excited wave was polarised along the principal shear direction 1 of the material. Therefore, its back-wall echoes were measured with the coil aligned with this PSD. While in figure 4.4b it is observed that the back-wall echoes of the generated shear wave were recorded with the two coils of the OCLC-EMAT. This phenomenon can be explained by wave splitting in an anisotropic material. The strain of the shear wave that coil B generated was polarised  $60^\circ$  with respect to PSD 1, so when the wave started to propagate in the material, the strain of the incident wave split into two strain components, which are polarised along the principal shear directions. When these two waves bounced back from the back-wall to the OCLC-EMAT their strain components generate particle displacement in the material that can be measured by both coils of the EMAT.

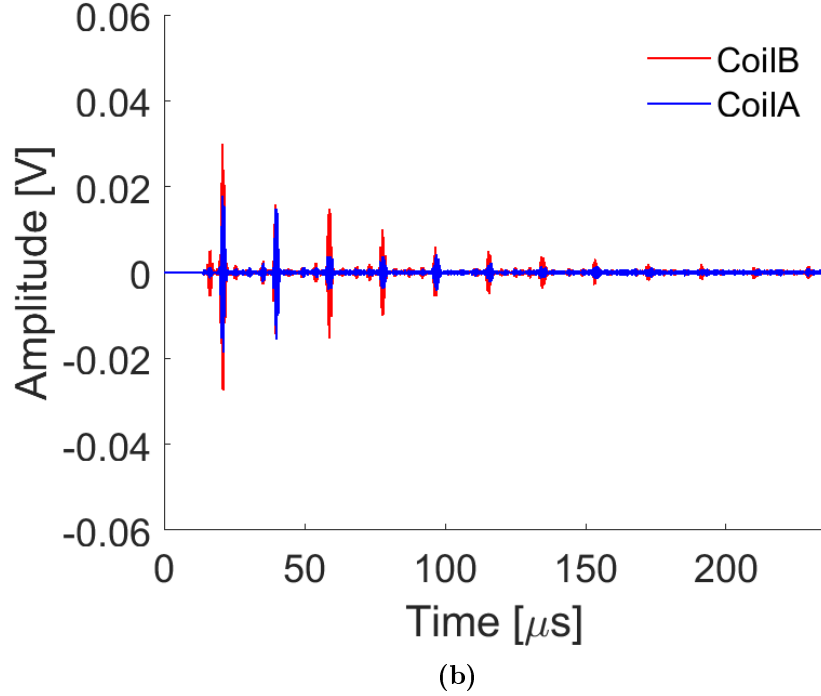
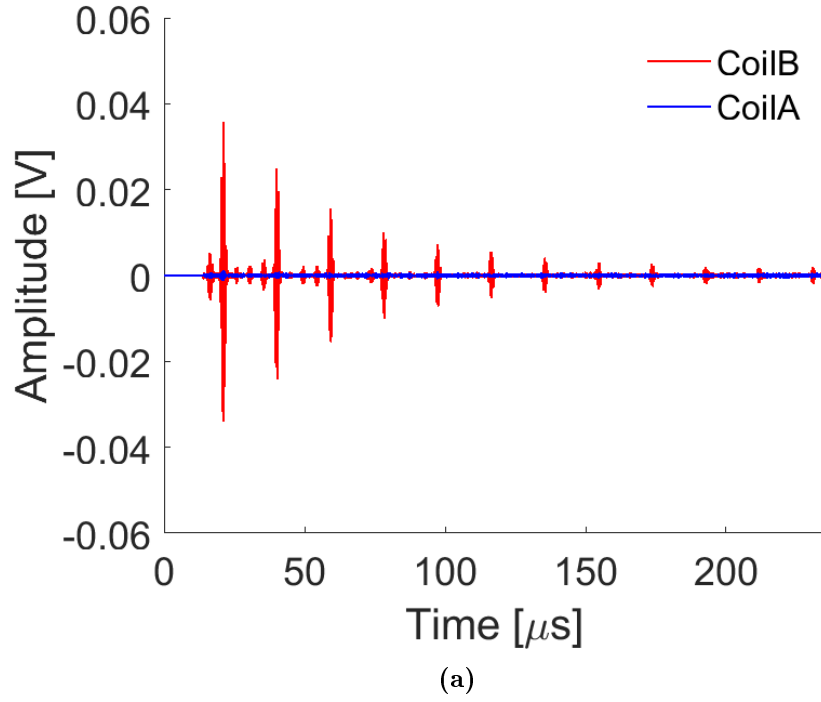


**Figure 4.4:** Back-wall reflections obtained by exciting solely Coil B of the OCLC-EMAT. a) A-scans measured when the OCLC-EMAT is align with the principal shear directions. b) A-scans measured when the OCLC-EMAT coils are  $60^\circ$  rotated with respect to the principal shear directions.

### 4.3.1 Physics of shear waves propagation in anisotropic media

To understand how two orthogonal shear waves travel through an anisotropic material, the phenomenon of the waves propagating in the material is treated as strain vectors projecting onto two orthogonal systems of coordinates. The two orthogonal systems of coordinates indicate the PSDs of the material and the excitation source and/or wave receivers. A shear wave can have one or two strain components depending on its orientation with respect to the anisotropic material. The projection of the strain vectors of the orthogonal shear sources onto the PSDs dictated how the strain of each source splits into the material. Then the projection of the strain onto the axes of the measurement system represents how the two orthogonal shear waves are recorded by the receivers. Therefore, the polarisation directions and amplitudes of the split partial waves obey the rules of vector addition/projection, and can be treated by relatively simple vector operations, where the signal detected by the coils are the projections of the partial waves along the coil orientations.

Figure 4.5 shows the phenomenon of one shear wave with linear polarisation generated by coil B of the OCLC-EMAT propagating into an anisotropic material. The propagation of the shear wave and its back-wall echoes are represented as vector quantities projected onto two orthogonal systems, one represents the PSDs and the other the OCLC-EMAT coils. The strain vectors represent the shear wave strain at its maximum amplitude. Additionally, the labels Coil B and Coil A orientation indicate the orientation of the force generated by the coils.  $\theta$  indicates the angle between the two orthogonal systems. Figure 4.5a presents the strain generated by coil B on top of the anisotropic material as a vector quantity. The strain vector is aligned with the force orientation generated by coil B. Figure 4.5b shows how the strain generated by coil B is split onto the PSDs. These strains then travel as two independent shear waves polarised along the PSDs into the material. Figure 4.5c illustrates the projections of the strain components of the returning shear waves onto the orientation of the coils of the OCLC-EMAT at the surface of the material. Figure 4.5d shows the vector quantities of the strain components that are measured by the coils of the OCLC-EMAT at the first back-wall echo of the excited shear wave in figure 4.5a.  $V$  indicates the wave speed of each strain vector. The sub-indices 1 and 2 are used to

indicate the velocity of waves that travel with polarisations corresponding to each of the PSDs.

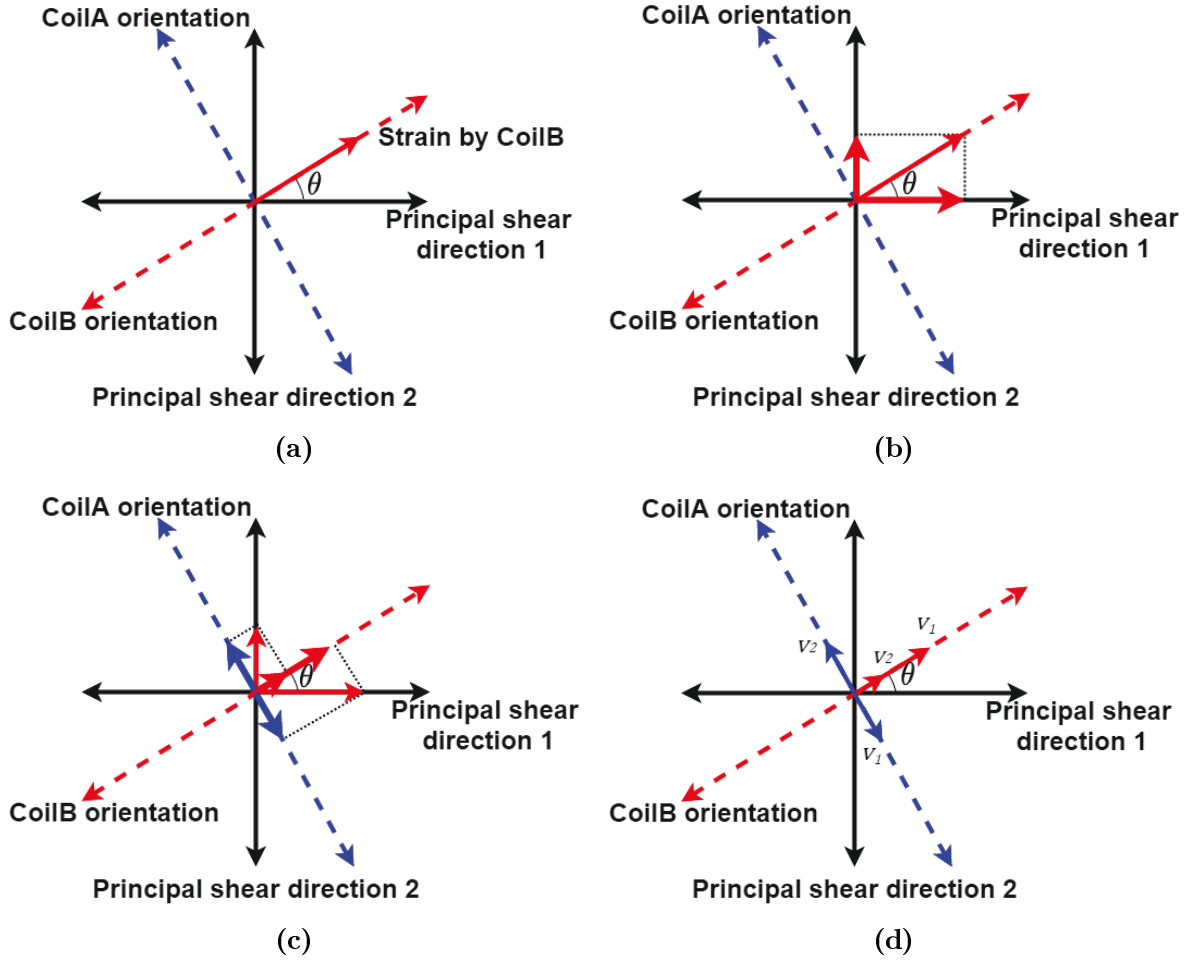


**Figure 4.5:** Wave splitting phenomenon represented as vector quantities. a) Strain generated by the OCLC-EMAT coil B. b) The strain generated by the OCLC-EMAT coil B splitting into the two principal shear directions. c) The strain travelling on the principal shear directions projected onto the OCLC-EMAT coils. d) The shear waves measured by the OCLC-EMAT coils. The bold arrows indicate the resulting shear strain vector at each step.  $v_1$  and  $v_2$  indicate the wave speed of the vector component. the sub-indices 1 and 2 correspond to the wave speed of the different principal directions.

Based on the strain vector representation of a shear wave propagating through the anisotropic material shown in figure 4.5, the maximum amplitude of the back-wall echoes measured by the OCLC-EMAT coils can be described as:

$$S_{coilB \rightarrow coilB} = A * [\cos^2(\theta) + \sin^2(\theta) * e^{(i\omega\delta t)}] \quad (4.1)$$

$$S_{coilB \rightarrow coilA} = A * [-\sin(\theta) * \cos(\theta) + \sin(\theta) * \cos(\theta) * e^{(i\omega\delta t)}] \quad (4.2)$$

$$S_{coilA \rightarrow coilB} = A * [-\sin(\theta) * \cos(\theta) + \sin(\theta) * \cos(\theta) * e^{(i\omega\delta t)}] \quad (4.3)$$

$$S_{coilA \rightarrow coilA} = A * [\sin^2(\theta) + \cos^2(\theta) * e^{(i\omega\delta t)}] \quad (4.4)$$

Where variables  $S_{coilB \rightarrow coilB}$  and  $S_{coilB \rightarrow coilA}$  represent the signal amplitude of the back-wall echoes received by the OCLC-EMAT coils when coil B is used to excite a shear load in an anisotropic material and its back-wall echoes are measured by coil B and coil A, respectively.  $S_{coilA \rightarrow coilB}$  and  $S_{coilA \rightarrow coilA}$  are the back-wall signals measured by coil B and coil A when coil A is used to generate a shear load in an anisotropic material.  $A$  indicates the maximum amplitude of the strain components that the OCLC-EMAT coils excite on the surface of the anisotropic material. For coil A and coil B, the strain components generated on top of the material are assumed to be equal in magnitude. The difference in wave speed among the two shear waves propagating along the PSDs is accounted for by  $e^{(i\omega\delta t)}$ ; where  $\omega$  is the angular frequency of the shear waves,  $\delta t$  is the time difference between arrivals of waves travelling along the two different PSDs and  $i$  is  $\sqrt{-1}$ .

### 4.3.2 Detection of the principal shear directions using two orthogonal and co-located shear transducers.

The splitting of shear loads into two orthogonal shear waves can be used to determine the orientation of the principal shear components in an anisotropic material. The angle between the two orthogonal systems, defined as  $\theta$ , can be estimated from equations 4.1,

4.2, 4.3 and 4.4. first subtract equation 4.4 from equation 4.1:

$$\begin{aligned} C &= S_{coilB \rightarrow coilB} - S_{coilA \rightarrow coilA} \\ C &= A * [\cos(2\theta) - \cos(2\theta) * e^{(i\omega\delta t)}] \end{aligned} \tag{4.5}$$

then sum equation 4.2 and equation 4.3:

$$\begin{aligned} D &= S_{coilB \rightarrow coilA} + S_{coilA \rightarrow coilB} \\ D &= A * [-\sin(2\theta) + \sin(2\theta) * e^{(i\omega\delta t)}] \end{aligned} \tag{4.6}$$

The angle can be estimated as:

$$\begin{aligned} -\tan(2\theta) &= D/C = \max(D)/\max(C) \\ -\theta &= \frac{\tan^{-1}(\max(D)/\max(C))}{2} \end{aligned} \tag{4.7}$$

Where  $\max$  indicates the maximum absolute value of the first back-wall echo of the measured signals.

### **4.3.3 Exciting a shear wave polarised along one PSD and general electrical steering.**

For conventional measurements, one normally needs to rotate the transducer to find the PSDs, and then align the transducer with the PSDs to excite a shear wave polarised along one of the PSDs. it has been shown in section 4.3.2 that with the OCLC-EMAT one can find the PSDs simply from one set of signals, and now it will be demonstrated that this same set of signals can be used to reconstruct a pure shear wave polarised along the PSDs without needing to physically rotate the transducer. This is called, in this thesis, electrical steering (of the polarisation).

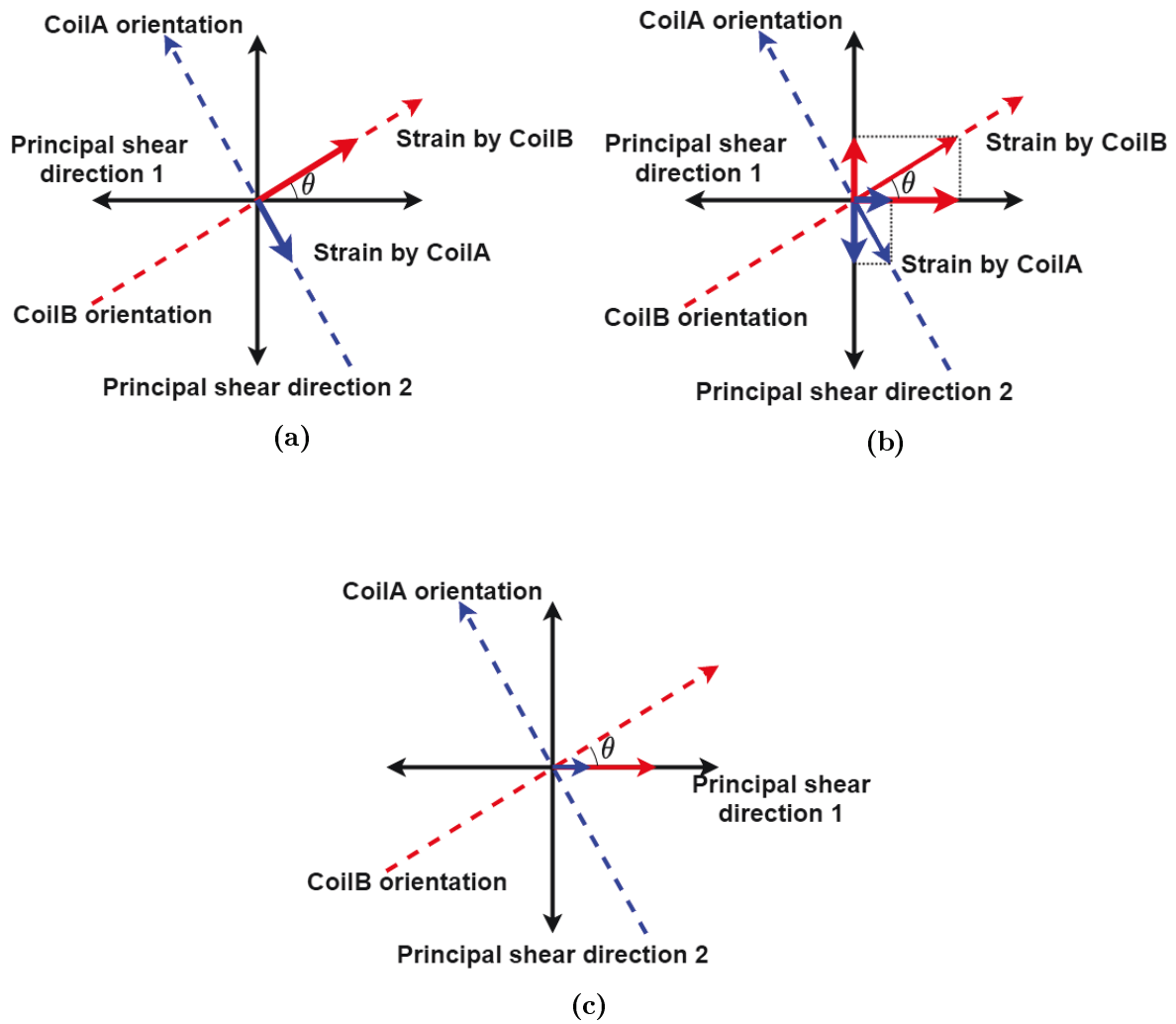


**Figure 4.6:** Combining excitation on coil A and B to result in a pure strain aligned with the principal shear direction 1. The bold arrows indicate the resulting shear strain vector at each step. a) Strain generated by the OCLC-EMAT coils. b) The strain generated by the OCLC-EMAT coils splitting into the two principal shear directions. c) The resulting strain excited with both coils aligned with one of the principal shear directions.

Two tangential loads with linear polarisation and placed on the same location can be used to generate a pure shear wave polarised along only one of the principal directions in an anisotropic material. The two orthogonal shear loads can be at any angle with respect to the PSDs. However, they must be excited simultaneously and of the right relative amplitude to obtain a shear wave that propagates with a pure strain component along the PSDs. Once the two orthogonal and amplitude modulated shear loads are excited on top of the material, their strain components split across the two PSDs instantly. This generates two new strain components aligned with the principal directions. However,

due the opposite sign of the split components along one principal direction, one of the resultant strain components is cancelled. Figure 4.6 illustrates the concept.

Figure 4.6a shows the strain components of the two orthogonal shear loads excited at the surface of the anisotropic material. Their amplitudes are proportional to the generated shear waves. The two shear wave strain components are oriented at an arbitrary angle  $\theta$ . Figure 4.6b shows the strain components of the orthogonal shear loads splitting onto the PSDs of the material. Figure 4.6c displays the final result of the interaction of the strain components. The resultant strain is aligned solely with one of the two PSDs. The relationship of the resultant wave with respect to the excitation signals can be written as simple vector summations:

$$\begin{aligned} S_{comb \rightarrow PSD1} &= \vec{CoilB} * \cos(\theta) - \vec{CoilA} * \sin(\theta) \\ S_{comb \rightarrow PSD2} &= \vec{CoilB} * \sin(\theta) + \vec{CoilA} * \cos(\theta) \end{aligned} \tag{4.8}$$

Where  $S_{comb \rightarrow PSD1}$  and  $S_{comb \rightarrow PSD2}$  are the pure shear waves travelling along one of the PSDs. The sub-indices  $comb \rightarrow PSD1$  and  $comb \rightarrow PSD2$  identify on which PSD each wave is polarised.  $\vec{CoilB}$  and  $\vec{CoilA}$  represents the signals applied on the coils for the excitation. The  $\cos(\theta)$ ,  $\sin(\theta)$  and the  $+$  and  $-$  signs are the amplitude modulation needed to obtain a shear wave purely polarised along one of the PSDs. The combination of the shear waves  $S_{comb \rightarrow PSD1}$  and  $S_{comb \rightarrow PSD2}$  can replicate physical excitation along any arbitrary direction on the surface of the material, hence electrical steering.

#### 4.3.4 Crack detection using two orthogonal and co-located transducers

The presence of a defect can be detected using a two-step procedure: first, the shear waves strain components are aligned with the PSDs of the material. The reason for this is to isolate the interaction of the two shear waves with a defect from the effects induced by the source/receiver misalignment with the PSDs of the material. Then, in the second step, the recorded back-wall echoes are analysed and the presence of a defect in the anisotropic material is identified.

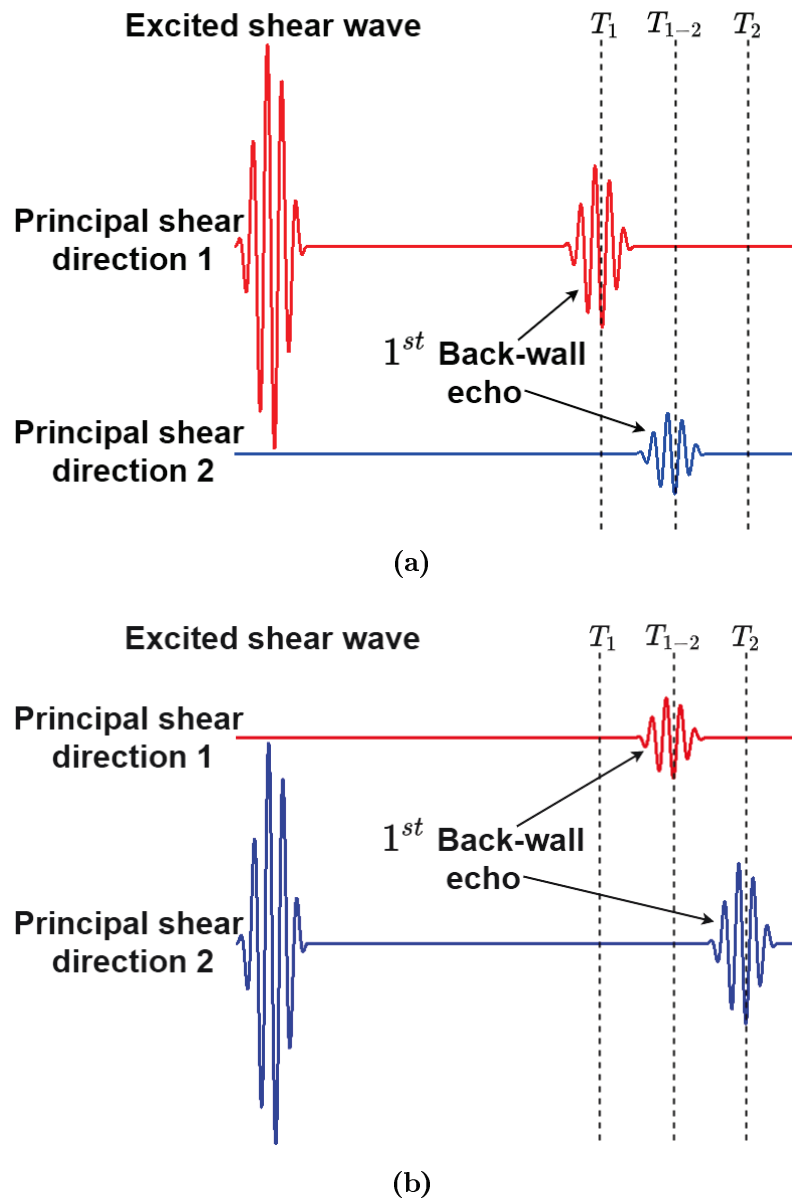


**Figure 4.7:** shear wave splitting into two shear waves after interaction with a crack in an anisotropic medium. The new shear wave will travel aligned with the principal shear direction. a) Shear wave excited along principal shear direction 1 and back-wall reflections measured along the two principal directions. b) Shear wave excited along principal shear direction 2 and back-wall reflections measured along the two principal directions.  $T_1$  and  $T_2$  indicate the arrival time at where a back-wall echo will arrive if it is travelling along the principal shear direction 1 or 2, respectively.  $T_{1-2}$  refers at the arrival time of the back-wall echo received at the principal shear direction 2 after a wave travelling along the principal shear direction 1 splits due to the presence of the crack.

In the first step, two co-located transducers that act as shear load sources and as back-wall echo recorders are aligned with the PSDs of the material. The alignment of the

transducers can be achieved by estimating the angular position of the transducers with respect to the PSDs of the anisotropic material, see section 4.3.2, and then rotating the transducers by the calculated angle so they are in the direction of the principal directions. By doing this, the changes on the back-wall echoes resulting from the sources/receivers misaligned with the PSDs is minimised.

The second step consists of using the co-located transducers, already aligned in the first step, to perform a pulse-echo test in the anisotropic material. The pulse-echo test is performed by using one of the transducers as the source and the two transducers as receivers. The active transducer generates a time varying shear load along one of the principal directions. Due to the shear load polarisation's alignment with one of the PSDs, the particle displacement of the excited shear wave occurs along the same principal direction. Therefore, no shear wave with displacement polarised along the other PSD is generated. This implies that the back-wall echoes of the generated shear wave are received only by the shear load generating transducer. However, if a crack-like defect is present, the particle displacement of the generated shear wave splits into two particle displacements along the principal shear directions once it gets in contact with the defect. The two new particle displacements generate two shear waves with polarisation direction along each PSDs. The two new shear waves bounce back to the transducers from the back-wall of the material. Therefore, when a crack-like defect is present, the back-wall echoes of the generated shear wave can be measured with the two orthogonal co-located transducers, as is shown in figure 4.7. This contrasts with when the crack-like defect is not present, where the back-wall echoes of the excited shear wave is measured only by the same transducer used to generate the wave.

### 4.3.5 Estimating the crack orientation using orthogonal and co-located shear transducers.

To estimate the orientation of a crack-like defect in an anisotropic material an analysis based on the signal amplitude of the first back-wall echo of two orthogonal shear waves is proposed. The idea here is to study the problem using the vector representation of the superposition of two consecutive wave interactions: 1) the shear wave interacting with a

tilted crack in an isotropic material and, 2) the shear wave splitting into two shear waves polarised along the PSDs. Decomposing this phenomenon into two consecutive shear wave interactions is possible when using an incident shear wave with polarisation along one of the PSDs only, and therefore the shear wave does not split due to the material, but only splits due to the presence of the crack.

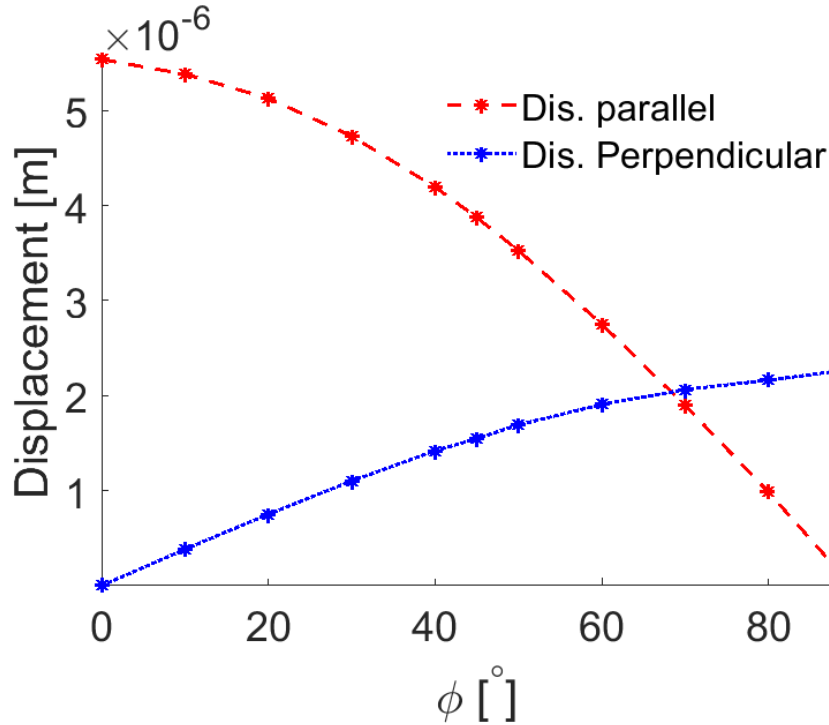


**Figure 4.8:** Maximum amplitude of the 1<sup>st</sup> back-wall reflection measured parallel and perpendicular to the crack versus the angle of the polarisation of the incident shear wave. The results were obtained in the simulation described in chapter 3 [P1], where the material is isotropic.

The effect of the first part of the superposition study on the shear wave propagating can be explained as follows: in an isotropic medium, the amplitude signal of the first back-wall reflection, which is received after a shear wave interacted with a back-wall crack, depends on the angle formed between the shear wave source and the orientation of the crack in the material [P1] [98]. This relationship can be represented as the amplitude of the first back-wall echo measured with the receiver parallel and perpendicular to the crack [P1] and it is shown in figure 4.8.

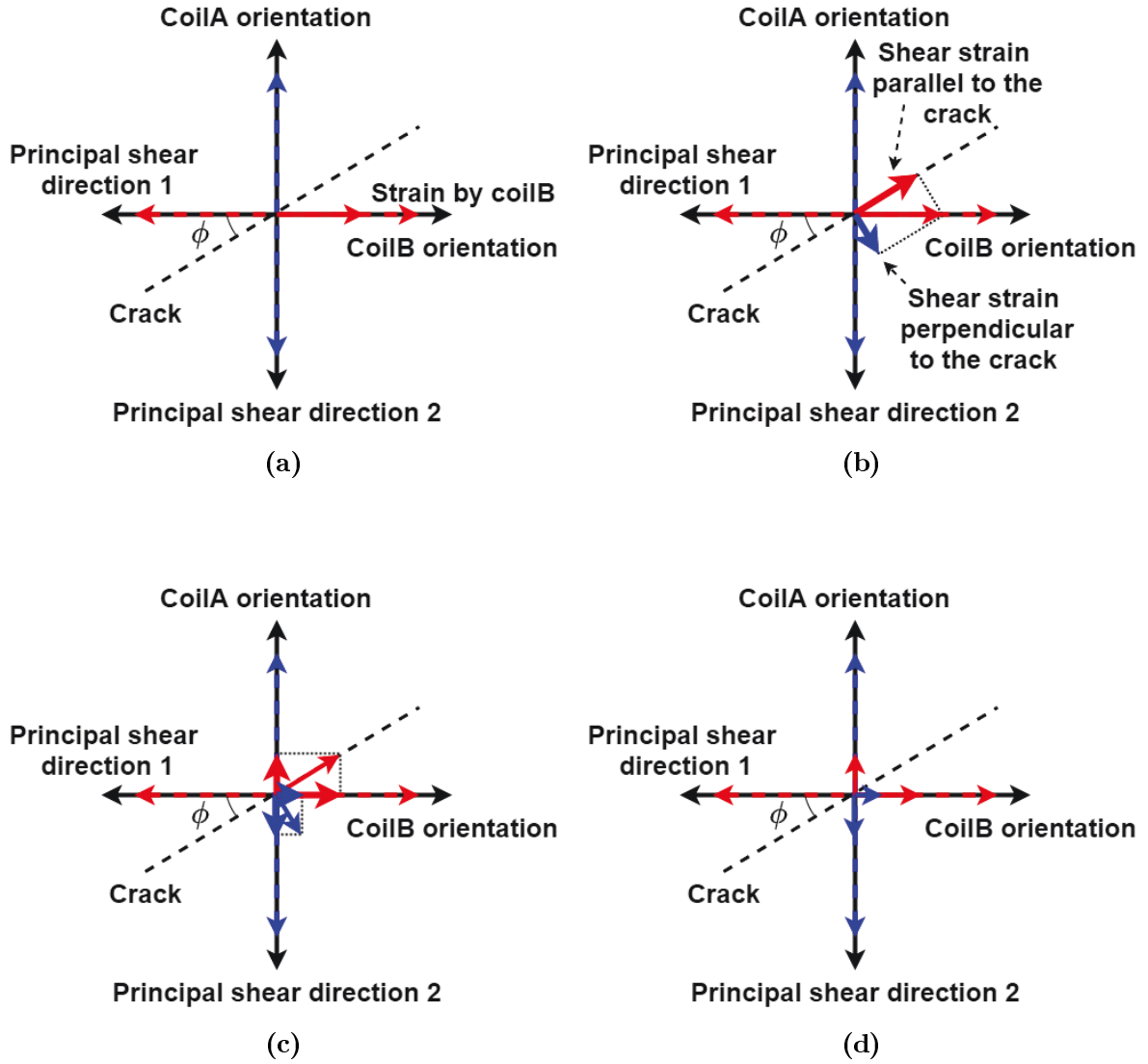


**Figure 4.9:** Vector representation of the shear wave interacting with the crack as the superposition of two wave interactions: the amplitude of the back-wall reflection in an isotropic material and the shear wave splitting in an anisotropic material. The bold arrows indicate the resulting shear strain vector at each step. a) Strain generated by coil B of the OCLC-EMAT. b) Strain components generated at the crack after the shear wave propagating along the principal shear direction 1 interacts with the defect. c) Projection of the shear strain components generated at the crack onto the principal shear directions of the anisotropic material. d) The strain measured by the coils of the OCLC-EMAT.

The consecutive second part of the superposition analysis can be explained as continues: the amplitude of the first back-wall echo, after mode conversion, of the incident shear wave is estimated as the projection of the amplitude of the back-wall reflection parallel and perpendicular to the crack onto the principal shear directions of the anisotropic material as is shown in figure 4.9. Figure 4.9 illustrates the vector representation of

the superposition analysis of the shear wave interacting with a crack in an anisotropic media. For illustration purposes, the OCLC-EMAT is used as the shear load source and wave receiver. The shear load is applied by coil B of the OCLC-EMAT and the first back-wall echo is received with both coils. Figure 4.9a shows the strain component of the excited shear wave polarised along the PSD 1. Additionally, it represents the strain component of the excited shear wave propagating in the material while it is unperturbed by the defect. Figure 4.9b displays the strain component of the excited shear wave once it gets in contact with the crack. These strain components are estimated as the back-wall reflections measured normal to and along the tilted crack in an isotropic material. Figure 4.9c illustrates how the strain components generated after the incident shear wave interacts with the crack splits into two shear waves polarised along the two PSDs of the material. In figure 4.9d, the strain components of the first back-wall echo measured by the coils of the OCLC-EMAT are shown.

The signals recorded with the two coils, during the pulse-echo test illustrated in figure 4.9, can be expressed as the transmission of a shear wave from coil B and measured with coil B and coil A. The expression of the two transmissions can be written as:

$$CoilB \rightarrow CoilB = A_1 * \cos^2(\phi) + A_2 * \sin^2(\phi) \quad (4.9)$$

$$CoilB \rightarrow CoilA = A_1 * \cos(\phi) * \sin(\phi) + A_2 * \sin(\phi) * \cos(\phi) \quad (4.10)$$

Where  $CoilB \rightarrow CoilB$  and  $CoilB \rightarrow CoilA$  symbolise the shear wave transmission from coil B and its reception with coil B and coil A, respectively.  $\phi$  is the angle formed between the crack surface and the excitation source.  $A_1$  and  $A_2$  Are the signal amplitude of the back-wall echoes obtained when the incident shear wave is oriented parallel and perpendicular to the crack in an isotropic material (or align with one of the principal shear directions in an anisotropic material).  $A_1$  is the maximum amplitude of the back-wall echoes when excited along the crack with unit input and  $A_2$  is the maximum

amplitude of the back-wall echoes when excited perpendicular to the defect with a unit input. Similar to the pulse-echo test illustrated in figure 4.9, the second pulse-echo test can be indicated as the transmission of a shear wave from coil A to coil B and coil A. The transmission/reception of the shear wave can be written as:

$$CoilA \rightarrow CoilB = A_1 * \cos(\phi) * \sin(\phi) + A_2 * \cos(\phi) * \sin(\phi) \quad (4.11)$$

$$CoilA \rightarrow CoilA = A_1 * \sin^2(\phi) + A_2 * \cos^2(\phi) \quad (4.12)$$

Where  $CoilA \rightarrow CoilB$  and  $CoilA \rightarrow CoilA$  represent the signal measured when a shear wave is transmitted from coil A and received with coil B and coil A, respectively. The orientation of the crack-like defect, illustrated in figure 4.9, can be estimated from equations 4.9 and 4.12 as follows:

$$\phi = \tan^{-1} \sqrt{\frac{1 - A_2/A_1 * \frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB}}{\frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB} - A_2/A_1}} \quad (4.13)$$

The steps followed in order to obtain equation 4.13 are shown in section 6.3. Equation 4.13 assumes that the amplitude of the strain components applied at the principal directions are equal. In case, that strain components are not equal, the amplitude signal of the back-wall echoes,  $CoilA \rightarrow CoilA$ , needs to be normalised with respect to  $coilB$ . The normalisation can be carried out by multiplying  $CoilA \rightarrow CoilA$  with  $\frac{CoilB \rightarrow CoilA}{CoilA \rightarrow CoilB}$ .

Additionally, prior information of the values  $A_1$  and  $A_2$  are required in order to calculate the crack orientation. For the work presented in this chapter,  $A_1$  and  $A_2$  were obtained from the experimental results shown in chapter 3 [P1].

### 4.4 Experimental results

The results presented in this section were obtained from experiments that mimic the theory presented in section 4.3.

The experimental setup used to perform the experiments was similar to the one described in section 3 [P1]; but with the difference that the orientation of the notches machined, in the aluminium blocks, were changed. The orientation ( $\phi$ ) of the inspected notches were  $0^\circ$ ,  $20^\circ$ ,  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$ ,  $70^\circ$  and  $90^\circ$ . In total, 4 different samples were inspected. On each one a single notch was machined. The notches were machined on the back-wall of the blocks. The notch dimensions were  $5\text{mm}$  by  $0.3\text{mm}$  (depth, width) and they ran across the whole specimen (aluminium block) as indicated in figure 4.10. The results obtained with notches oriented at  $60^\circ$ ,  $70^\circ$  and  $90^\circ$  were achieved on the same blocks as for notches oriented at  $30^\circ$ ,  $20^\circ$  and  $0^\circ$ , respectively; but with the OCLC-EMAT rotated  $90^\circ$  with respect to the position used on the experiments for  $30^\circ$ ,  $20^\circ$  and  $0^\circ$ . Figure 4.10 is a schematic top view of the experiments carried out to estimate the notch orientation in an anisotropic material.

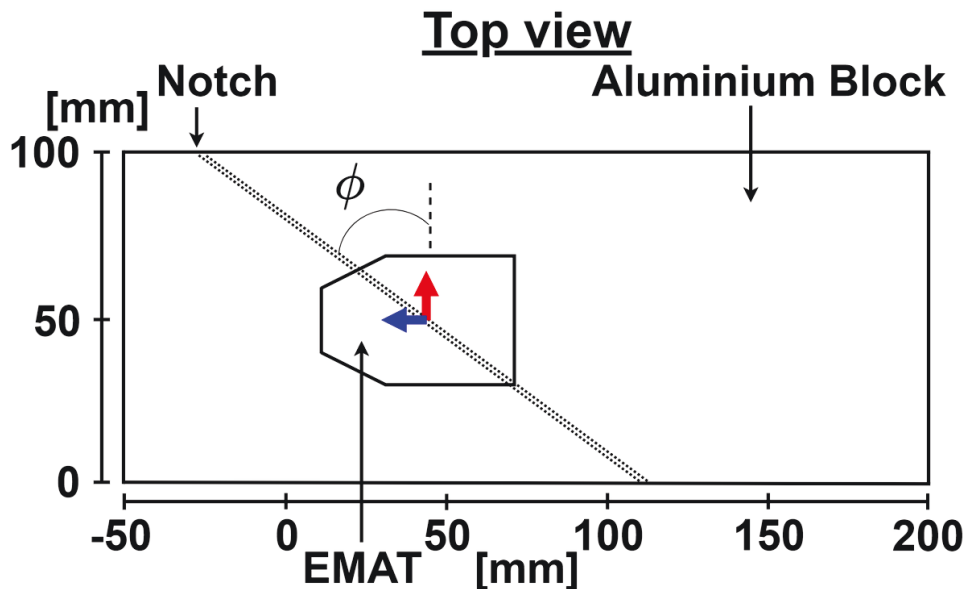


**Figure 4.10:** Schematic Top view of the test carried out to characterise the notch orientation.

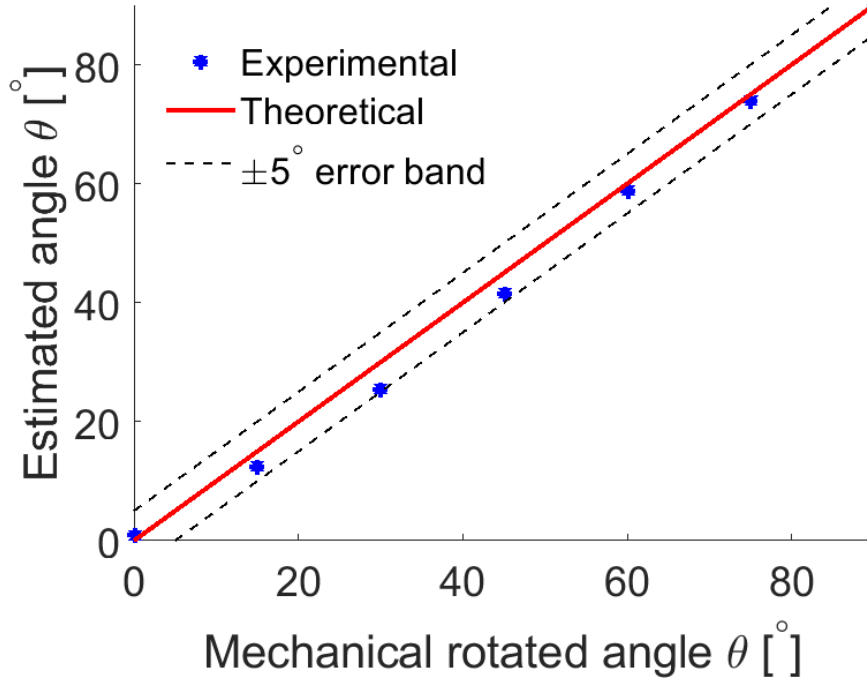


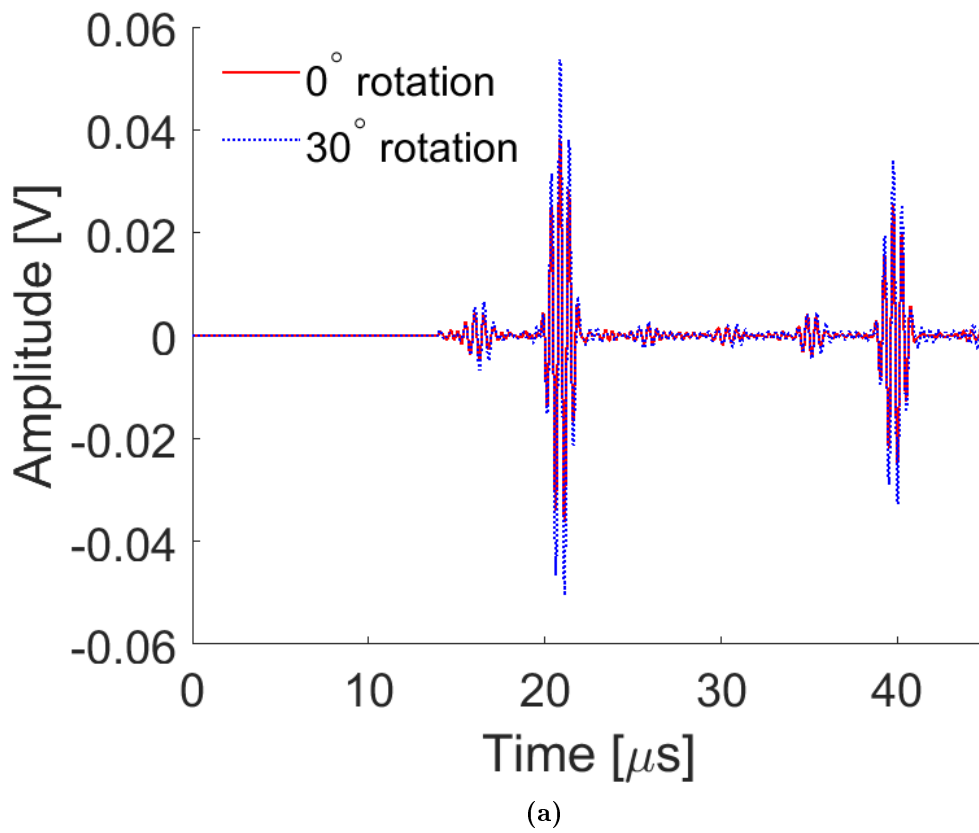
**Figure 4.11:** Estimated orientation of principal shear directions of an anisotropic material (aluminium) with respect to the OCLC-EMAT coils.

As is shown in figure 4.10, the notches were machined on the left side of the aluminium block, leaving the right side of the block as the test zone used to characterise the orientation of the principal shear directions of the material.

Figure 4.11 shows the estimated orientation of the PSDs of the material as the OCLC-EMAT is rotating on top of the aluminium block.  $\theta$  is the existing angle formed by the OCLC-EMAT coils with the principal directions. The red line indicates the angle form by the physical position of the OCLC-EMAT coils and the PSDs, the blue dots are the estimated angle formed by the OCLC-EMAT coils with the principal shear directions and the black dashed line are the 5° upper and lower error band. Fourteen pulse-echo tests were performed in total.

Figure 4.12 displays the results obtained when two orthogonal shear loads were used to excite a single shear wave polarised along one of the principal shear directions. The pulse-echo tests were carried out on an area where the notches were not present. Figure 4.12a shows a comparison of two different pulse-echo tests, when the OCLC-EMAT was physically at  $\theta$  equal to 0° and 30°. To excite one shear wave polarised along the first

principal direction, when  $\theta$  is  $30^\circ$ , the signal amplitude of the shear loads were modulated according to equation 4.8. The back-wall echoes of the excited shear wave are recorded using the two coils of the OCLC-EMAT. The time-traces plotted in figure 4.12a are the sum of the signal measured with both coils during a single pulse-echo test. Figure 4.12b shows the calculated ToF of the back-wall echoes obtained when the shear wave is excited along the principal shear directions. The shear wave was excited using two orthogonal shear loads. The tractions were excited at different angles with respect to the PSDs. The different angles were obtained by rotating the OCLC-EMAT on top of the aluminium block. The black line indicates the wave speed measured when the shear surface tractions were polarised along the principal shear directions 1 and 2. the blue circles are the measured wave velocity of the shear wave polarised along the PSD 1 at different  $\theta$ . the red dots are the calculated wave speed of the shear wave polarised along PSD 2 for different  $\theta$  angles and the dashed black line are the 0.5% upper and lower error band of the wave speed. Sixteen pulse-echo tests were performed in total.



In figure 4.13, the time-traces obtained after one pulse-echo test are shown to indicate the

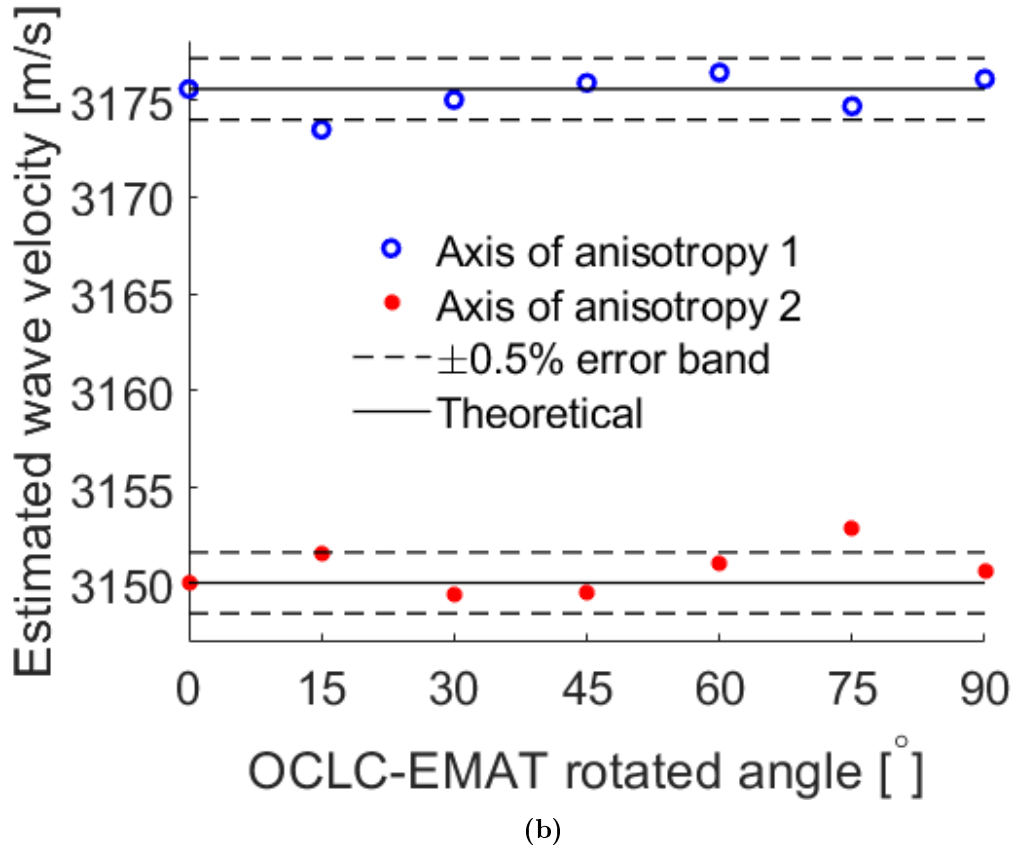


**Figure 4.12:** Experimental results of shear waves oriented along the principal shear directions. The shear waves were excited using two orthogonal shear loads. The results were obtained with different OCLC-EMAT angular positions. a) A-scans of excited shear wave travelling aligned with the principal shear direction 1. b) Wave speed estimation of the excited shear waves travelling along the principal shear directions of the anisotropic material.

presence of a notch. the signals displayed are the result of a shear wave interacting with a notch present in an anisotropic material. The defect was oriented  $20^\circ$  with respect to the principal shear direction 1 of the material. The pulse-echo test was carried out with the OCLC-EMAT coils aligned with the PSDs. The shear wave was excited with coil B of the OCLC-EMAT and its back-wall echoes were recorded with both coils. As mentioned in section 4.3.4, when the defect is not present in the area where the pulse-echo test is carried out, the received back-wall echoes are only measured with one coil, as shown in figure 4.4a. while, when the defect is present, the back-wall echoes received after the interaction of the shear wave with the notch are recorded with both coils of the OCLC-EMAT, as is shown in figure 4.13. One pulse-echo test was performed to obtain the results shown in figure 4.13.

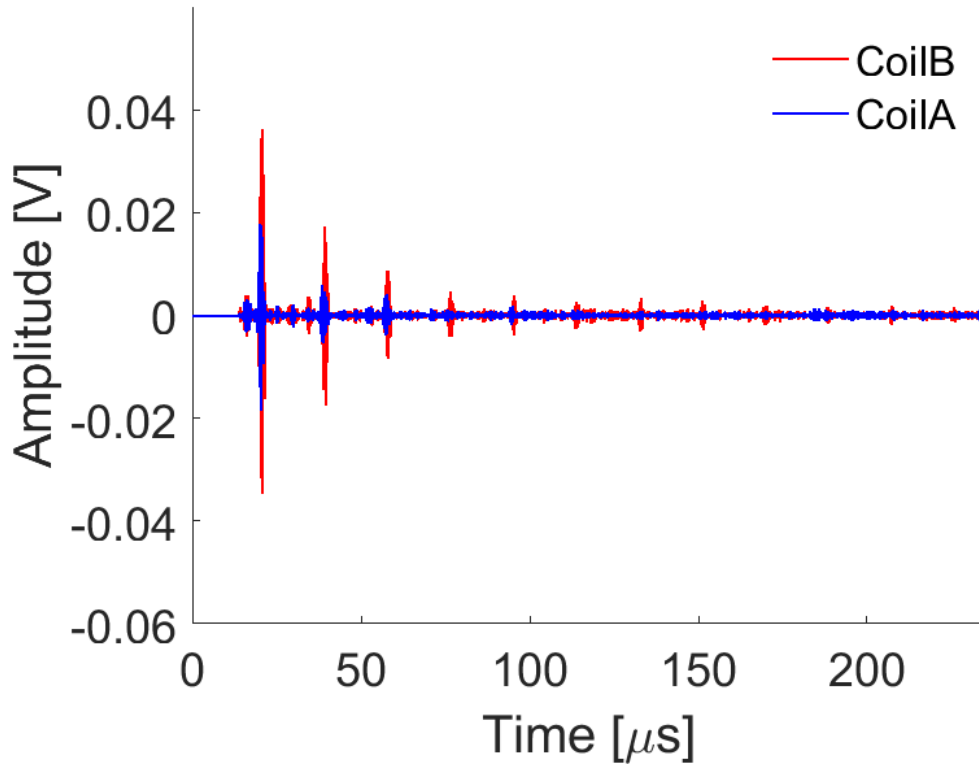


**Figure 4.13:** Experimental results of notch detection based on back-wall reflection. The notch was oriented  $20^\circ$  away from the first principal direction of the material. The results obtained, in contrast to the signals shown in figure 4.4a, display an amplitude and shape change among the recorded signals. The back-wall echoes are received with both coils of the OCLC-EMAT.

Figure 4.14 displays the results obtained after the inspection of an anisotropic material with notches machined at different angles. The results were obtained by using an OCLC-EMAT on top of the area where the notch was present. The transducer's coils were placed with orientation along the principal shear directions of the material. The inspection of each crack-like defect was carried out by mimicking the steps described in section 4.3.5. Figure 4.10 shows the schematic top view of the inspection. The OCLC-EMAT is placed on top of the aluminium block and aligned with the PSDs on an area where the defect is present. Figure 4.14 summarises the estimated notch angles. The results were obtained by performing pulse-echo tests in the inspected material. The red line in the plot indicates the orientation on which the notches were machined with respect to first principal shear direction, while the blue dots are the estimated notch orientation, and the dashed black line are the  $5^\circ$  upper and lower error band of the estimation. Fourteen pulse-echo tests were performed in total, two for each estimated notch orientation.

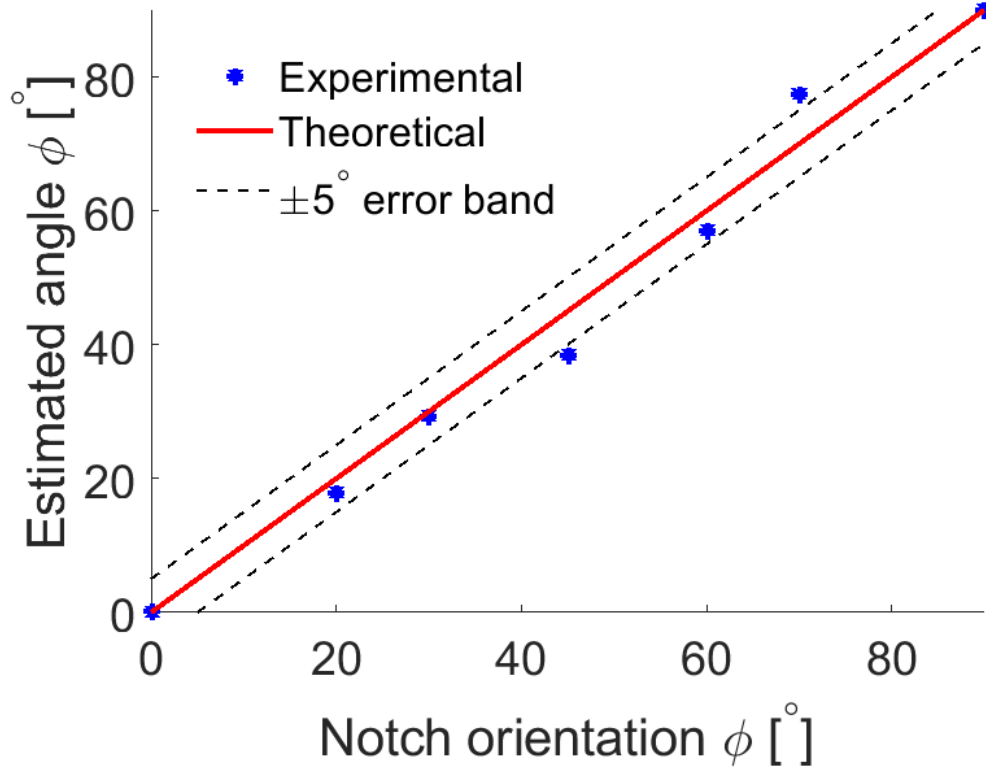


**Figure 4.14:** Experimental characterisation of the notch orientation. the notch estimated orientation was measured with respect to the first principal shear direction.

## 4.5 Discussion

The work presented in this chapter establishes a simple method of characterising the level of anisotropy and the principal shear directions of a material. The characterisation of the level of anisotropy and the orientation of the principal shear directions are achieved by measuring a shear wave splitting in the material. These serve the purpose of crack-like defect detection in this chapter, but they may have a broader application in the field of material characterisation (e.g. to inspect the homogeneity of larger samples, monitor the level of strains in a material, measuring residual stresses, etc).

In the presented work, the crack-like defect detection and the evaluation of its orientation in anisotropic media relies on the prior knowledge of the principal shear directions, which is obtained by characterising the material on a neighbouring region without defects. However, real applications may encounter situations more complicated than what we have

assumed here. For instance, the access to defect-free areas might be restricted, or whether an area has a defect or not could be unknown beforehand. In addition, the orientation of the PSDs may vary from one area to another due to factors such as grain micro-structural variations, localised inclusions in the material, or residual or thermally induced stresses, etc. I would aim to address these difficulties in future work by building up on the findings presented here. For example, I could explore the combination of two pairs of OCLC coils aligned with  $45^\circ$  equal gaps and study the differences between the signals from the pairs. I believe a system like this could be able to 1) characterise the PSDs of the shear waves, 2) determine whether a crack-like defect is present, 3) obtain the orientation of the crack if indeed present, all at the same time, which is an exciting and useful prospect to pursue. The compensation of the received signals proposed in section 4.3.5, used to estimate the orientation of the defect, assumes that the amplitude difference in the back-wall echoes is the result of the coils not being at the same lift-off with respect to the material. The compensation also assumes that the signals in equation 4.2 and 4.3 are equal. However, if the signals expressed in equation 4.2 and 4.3 are not equal due to the material anisotropy, the compensation method presented can be used to compensated this variation. In this case, the amplitude difference of the shear surface tractions needs to be eliminated before starting the inspection. In addition, in the theory and experiments presented, I have used bare metals without painting, so the reflection coefficients remain uniform; for real-world applications involving surface painting or other surface treatments that may affect the reflection amplitudes, more comprehensive investigations will be needed.

## 4.6 Conclusion

A methodology to detect and characterise the orientation of crack-like defects in anisotropic materials was presented. The proposed method utilises two orthogonal and co-located shear waves with linear polarisation to inspect the anisotropic material. With the use of two shear waves, it was possible to establish the level of anisotropy of a material, the orientation of the principal shear directions of the material, to detect the presence of a crack-like defect and to estimate the defect orientation with respect to the principal directions. The results obtained show the efficacy of the proposed method on an alu-

minium block. The orientation of the principal shear directions could experimentally be determined within  $\sim \pm 5^\circ$  error and the level of anisotropy of the material to  $\sim 0.5\%$ . Moreover, the notches orientation could be estimated experimentally within  $\sim \pm 5^\circ$ . To understand the interaction of the two orthogonal shear waves in the anisotropic material and with a crack-like defect, a study of the two waves propagating in the material was presented. The study was based on vector analysis of the strain components of the two shear waves travelling through the anisotropic material. The representation of the strain components of the shear waves as vector quantities allowed the estimation of the anisotropic material characteristics, as well as the estimation of the orientation of crack-like defects. Finally, the results obtained in this work showed agreement with the theory proposed. The detection methodology of crack-like defects with two orthogonal and co-located shear waves was extended to anisotropic materials. Additionally, the concept of estimating the defect orientation with respect to the principal axes of the material was added to the methodology.

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# Chapter 5

## Phased-Array EMAT: dipole source element

Most of the material in this chapter was taken with minor alterations from [P3] (with permission from NDT & E International).

### 5.1 Introduction

Phased-Array (PA) transducers are widely use in non-destructive evaluation (NDE) for defect detection [119], defect sizing [120, 121], tomography [122–124] and material characterisation [125]. They are popular in NDE because they allow the user to generate and steer an ultrasound wave at different angles into the component that is being inspected.

Conventionally, PA transducers are designed to generate and steer longitudinal waves by means of a group of piezoelectric transducers. Piezoelectric transducers are the preferred tool in ultrasound NDE of materials as they provide good ultrasound wave Signal-To-Noise-Ratio (SNR), do not require high power devices to be driven and can be used to excite ultrasound waves in any material. These piezoelectric transducers are placed one next to the other onto the surface of the inspected material. Each element is used to apply transient pressure pulses to excite longitudinal waves in the inspected material. Time delays between consecutive elements steer the emitted waves into different directions.

While a standard PA transducer steer longitudinal waves, it is possible to insert a Per-

spex wedge in between the PA transducer and the inspected material so that the excited longitudinal waves convert into shear waves [12]. In addition to wedges, other elements might be required for the correct implementation of inspections. For example, piezoelectric PA transducers require direct surface contact and coupling [126]. Hence, when a piezoelectric PA transducer is used to inspect a material, the surface of the material has to be prepared for the NDE inspection. Coating and surface roughness must be removed before the inspection. If the component is hot, the material must be cooled down, so that the array elements of the PA transducer that are in direct contact with the hot material surface are not damaged. That is if the coupling gel does not evaporate, or the Perspex wedge melts during the inspection. To minimise these complications, the NDE have used Electro-Magnetic Acoustic Transducers (EMATs) since EMATs are contactless, do not require a wedge to excite shear waves, can tolerate higher temperatures and are non-invasive in nature. However, EMATs are far from the ideal solution for any NDE inspection, EMATs have poor transduction, require high power amplification systems, can be used only on electrically conductive materials, and provide poor ultrasound wave SNR. Hence, selecting EMATs over piezoelectric transducers is only beneficial in scenarios where the coating and roughness of the inspected material cannot be removed, the inspected material is hot, direct contact is not possible, a Perspex wedge is required and couplant cannot be applied.

Prior works have shown that with EMATs an ultrasound wave can be excited at a fixed or variable angle. The first case has been achieved by using a meander-line coil [52] or by using a race-track coil and a periodically permanent magnet (PPM) arrangement in an EMAT. In this scenario, the fixed-angle depends on the wave speed and separation between coil tracks/magnets of the EMAT. For the second case, wave steering/focusing has been accomplished by varying the signal excitation frequency of a single race-track coil PPM EMAT or of a meander-line coil EMAT [127, 51, 57]; or by driving several coils of a PA EMAT independently [33, 56, 29, 34, 128].

Steering or focusing an ultrasound wave by varying the frequency of the excitation signal of an EMAT brings some disadvantages to the NDE inspection, it offers limited angle coverage and wavelength variation across its operational frequency range. These two constraints are due to the EMAT angle-to-frequency dependency. Steering or focusing an

ultrasound wave with a PA transducer is more attractive for a NDE inspection since it offers a wider-angle range of coverage at a constant wavelength. These features and the advantages that EMATs offer over piezoelectric transducers in scenarios where coating and surface roughness cannot be removed, the inspected material is hot, direct contact is not possible, a Perspex wedge is required and couplant cannot be applied, make PA EMATs desirable probes for shear wave NDE inspections of metallic materials.

Often, when PA EMATs are designed, it is assumed that only one of the three excitation mechanisms -Lorentz force (LF), magnetisation force (mF), or magnetostriction force (MF)- dominates the ultrasound wave generation. In addition to this, it is also assumed that a single-oriented force load is exerted due to this excitation mechanism [28]. While these two assumptions hold for simple EMAT designs on one particular material, these two assumptions might not remain true when the inspected material (especially its magnetic properties) is changed and therefore, compromising the use of the same PA EMAT design on different materials, since the emitted wavefield and coverage of the PA EMAT would vary from one material to another.

There have been prior efforts on describing the transduction mechanisms of EMATs and on PA EMAT design. Thompson [25] gave a detailed explanation of the wave generation in metallic materials using the LF and gave a summarised analysis of the three excitation mechanisms interacting in metallic materials. Hirao and Ogi [28] presented a comprehensive analysis of the three excitation mechanisms involved in the EMAT transduction, summarising the mathematical representations of the physical phenomena. Seher and Nagy [24] studied different mathematical approaches used to describe LF and mF in the literature. They concluded, despite the differences, that each method results in a good approximation of the transduction. Ribichini et al. [23] described how to model the MF induced in nickel. They evaluated the sensitivity of the excitation mechanism to the magnetic properties of the material and concluded that the excitation mechanism is not only affected by the magnetostrictive constants but also by the magnetic permeability. The validation results of their model had a discrepancy less than 20%. Clausse et al. [27] modelled and calculated the three excitation mechanisms involved in the transduction of a rectangular spiral coil EMAT. They concluded that for their EMAT design the LF and MF contributed alike on highly magnetostrictive materials. Sawaragi et al. [33] presented

a PA EMAT probe consisting of 8 segments that could steer a shear wave with a squint angle of  $20^\circ$ . Their results showed the feasibility to use PA EMATs to inspect welds. Le Bourdais and Marchand [56] utilised an 8 coils PA EMAT to induce and steer longitudinal waves in an aluminium block. Their design consisted of 8 race-track coils and a yoke magnetic circuit. The coils were placed with one of the tracks outside of the magnetic circuit, with the aim to reduce their participation in the wave generation. Their results showed that the outside tracks of the coils participated in the wave generation as well as the inner tracks of the coils, hence compromising the steerability of the PA EMAT. Pucci et al. [29] continued the work presented by Le Bourdais and Marchand [56] and proposed a 12 coils PA EMAT to steer longitudinal waves. Their PA EMAT consisted of 12 race-track coils and a Halbach magnetic circuit. Their design improved the steerability of the PA EMAT and their results showed an angle coverage of  $\pm 20^\circ$ . Isla and Cegla [34] presented a 8 race-track coils PA EMAT that exploited both tracks of each coil to exert surface loads onto a metallic material. Their design permitted the user to steer shear waves in the inspected material. The results confirmed the PA EMAT feasibility to detect crack-like defects in aluminium. And Zhai et al. [128] introduced two race-track coil PA EMAT designs for shear wave steering in a metallic material. The designs employed one or two tracks of the coils to induce a shear wave in the material, respectively. Their steerability and radiation pattern is presented. However, despite all those efforts, I am not aware of a study that investigates: the simultaneous interaction of the three excitation mechanisms present in a PA EMAT transduction, how the interaction of the PA EMAT with different materials affects the wave radiation pattern of the excited waves and finally, a demonstration of a PA EMAT design that withstands the differences in transduction that metallic materials display while maintaining the intended steering angle coverage of the PA EMAT. Therefore, this chapter focuses on addressing those issues:

Section 5.2 starts with a description of the race-track coils PA EMAT used throughout this study. Then, in section 5.3, the concept of the PA EMAT transduction and its material dependency is explained. The relationship of the three forces -LF, mF and MF- with different materials is studied in a 2D finite element analysis (FEA). In section 5.4, the effect that each excitation mechanism has on the radiation pattern of the PA EMAT is studied. First, the wave radiation pattern produced by one coil in diamagnetic, paramagnetic,

ferromagnetic and ferromagnetic and magnetostrictive materials is studied using a 2D FEA. Then, a 2D FEA steerability analysis of the shear waves that are generated by the PA EMAT is presented. In section 5.5, the experimental setup used to observe the wave radiation pattern of the PA EMAT is presented. In section 5.6, the experimental results are displayed and compared with the simulation results. Section 5.7 discusses the interaction of the three excitation mechanisms and their effect on the PA EMAT performance. The analysis includes a comparison of the capability of the PA EMAT to steer a shear wave in diamagnetic, paramagnetic, ferromagnetic and ferromagnetic and magnetostrictive metals. The conclusions of this work are presented in section 5.8.

## **5.2 1MHz Shear Vertical Wave Phased array EMAT: the dipole element**

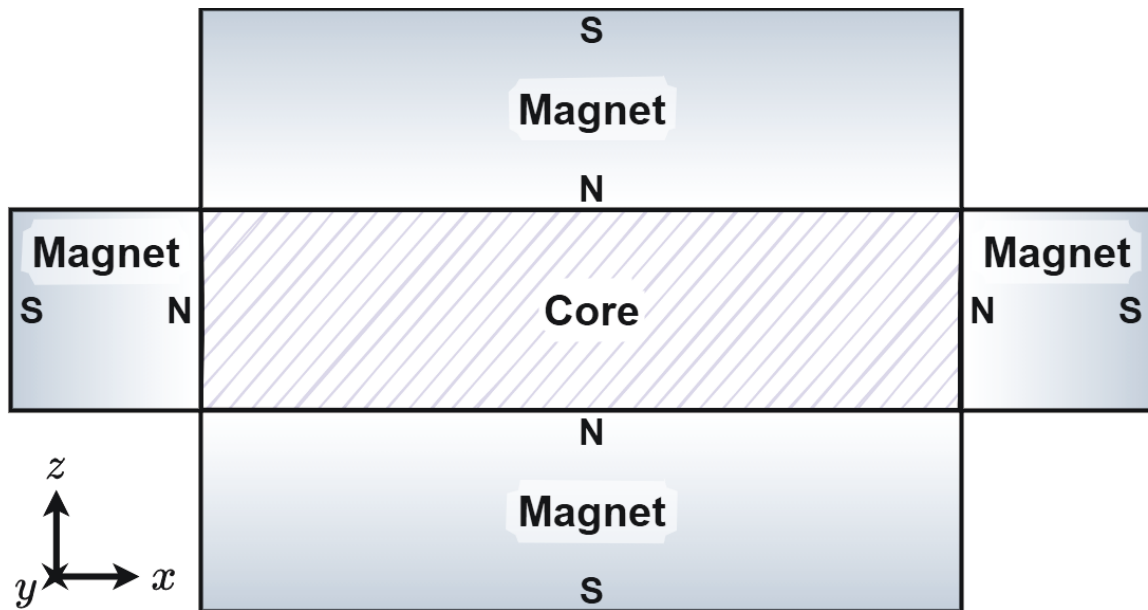
In this work, it is proposed the use of a 8 race-track coil PA EMAT to generate and steer 1 MHz shear waves into metallic materials in the same way regardless of whether the metallic material is diamagnetic, paramagnetic, ferromagnetic, or ferromagnetic and magnetostrictive (schematic of the PA EMAT is illustrated in figure 5.1).

The proposed PA EMAT induces shear waves into metallic materials by means of the three excitation mechanisms involved in the EMAT transduction. These mechanisms occur when a static magnetic field interacts with: a dynamic magnetic field, current; or when a static/dynamic magnetic field interacts with a magnetostrictive material. Therefore, to induce the static magnetic field, the PA EMAT has an internal magnetic circuit that generates a magnetic field normal to the surface of the inspected material. To guarantee the maximum magnetic field in the inspected material, the design of the magnetic circuit is based on the magnetic circuit concept presented by Isla and Cegla [32]. In which the magnitude of the magnetic field density was enhanced by placing 4 magnets around a metallic core, forming a cross. Therefore, the magnetic circuit of the PA EMAT is designed following the same architecture, it is composed of 4 permanent magnets and a mild-steel core. Where 2 permanent magnets have dimensions of  $10mm \times 10mm \times 20mm$ , 2 permanent magnets have dimensions of  $20mm \times 10mm \times 20mm$  and the core has dimen-

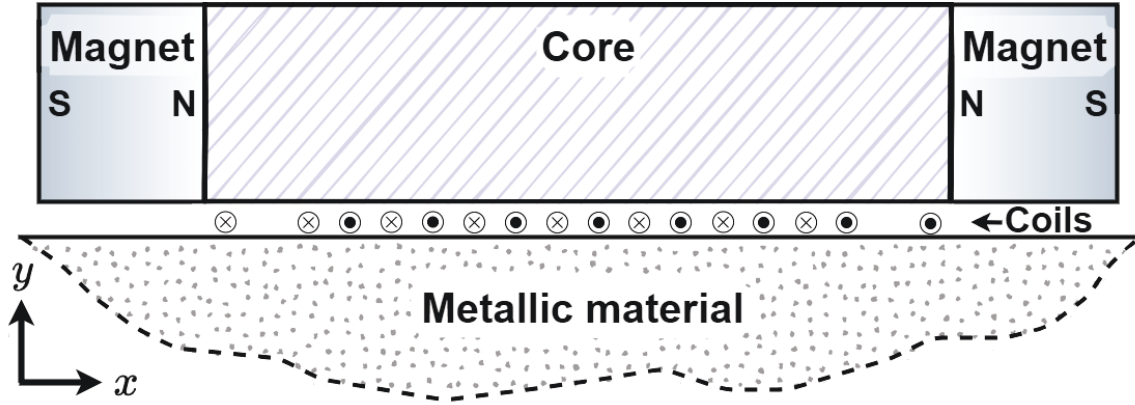
## 5. Phased-Array EMAT: dipole source element

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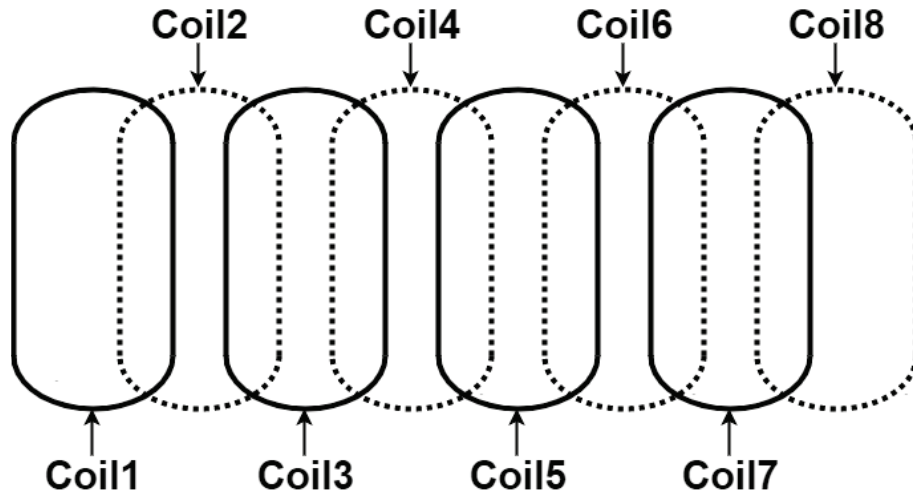
sions of  $20\text{mm} \times 10\text{mm} \times 20\text{mm}$ . The core is placed in the middle of the magnetic circuit and the magnets are positioned around the core, as shown in figure 5.1a. The permanent magnets are located with the same magnetic pole facing the core, so that the magnetic circuit induces a bias magnetic field normally oriented to the surface of the inspected material. Moreover, to induce the dynamic magnetic field and the current into the inspected material, the PA EMAT has 8 internal copper race-track coils. The 8 race-track coils are positioned in between the magnetic circuit and the inspected metallic material, as shown in figure 5.1b. The coils are located and aligned in the same plane, with  $1/3$  overlap, following the concept presented by Isla and Cegla [34]. This results in a line of equidistant coil-transducer elements as is common for ultrasound phased array transducers. The schematic of the coils alignment is shown in figure 5.1c. The coils of the PA EMAT were designed to steer  $1\text{MHz}$  shear waves in the inspected material, hence, the coils have a separation between tracks of  $3\text{mm}$  and a track width of  $0.4\text{mm}$ , so that the distance between each coil centre is  $\sim 1/3$  wavelength and the wave generation due to each coil track behaves similar to an ultrasound point source for the selected wavelength ( $\sim 3.1\text{mm}$ ).



(a)



(b)



(c)

**Figure 5.1:** Schematic of the 8 race-track coils PA EMAT a) Top view of the PA EMAT magnetic circuit. b) Cross section of the front view of the magnetic circuit and coil arrangement. c) Coils arrangement. Images not to scale.

In the next section, it is studied how the proposed PA EMAT induces the static magnetic field, dynamic magnetic field, and current density in the inspected materials and how the resultant surface loads are generated by the LF, mF and MF mechanisms in diamagnetic materials with and without magnetostriction, paramagnetic materials with and without magnetostriction and in ferromagnetic materials with and without magnetostriction.

### 5.3 Physical principles of phased array EMAT transduction

The electromechanical transduction of EMATs is described as the combination of three excitation mechanisms: Lorentz force, magnetisation force and magnetostriction force [28]. These three excitation mechanisms represent the resultant mechanical stresses that can be generated in metallic materials when electromagnetic fields are applied to them. Lorentz force is described as the mechanical stresses induced when a current density interacts with a magnetic field density in a metallic material [68]. Magnetisation force is the term used to name the mechanical stresses generated in a magnetised material when an external dynamic magnetic field is applied to the material [68]. And magnetostriction force is the phenomenon that describes the spontaneous strain that a material experiences when an external magnetic field is applied to it [69]. Eq. 5.1, eq. 5.2 and eq. 5.3 are the mathematical representation of the Lorentz force, magnetisation force and magnetostriction force, respectively. In this representation, the magnetostriction force is assumed to be nonlinear and isotropic [2, 31].

$$\mathbf{LF} = \tilde{\mathbf{J}} \times \bar{\mathbf{B}} \quad (5.1)$$

$$\mathbf{mF} = \mu_0 \cdot (\nabla \cdot \tilde{\mathbf{H}}) \cdot \bar{\mathbf{M}} \quad (5.2)$$

$$\begin{aligned} \mathbf{M}_{\text{an}} &= \tanh\left(\frac{\chi_0 \cdot \mathbf{H}}{M_s}\right) \\ \varepsilon_{\mathbf{m}} &= \frac{2\gamma_s}{3M_s^2} \text{dev}(\mathbf{M}_{\text{an}} \otimes \mathbf{M}_{\text{an}}) \\ \mathbf{MF} &= C_h \cdot \varepsilon_{\mathbf{m}} \end{aligned} \quad (5.3)$$

Where  $\tilde{\mathbf{J}}$  is the current density induced by the coil of the EMAT in the inspected material,  $\bar{\mathbf{B}}$  represents the magnetic field density in the inspected material caused by the magnetic circuit of the EMAT,  $\mu_0$  is the magnetic permeability in vacuum,  $\nabla \cdot$  is the divergence operator,  $\tilde{\mathbf{H}}$  is the dynamic magnetic field induced by the coil of the EMAT in the in-

spected material,  $\bar{\mathbf{M}}$  is the resultant magnetisation in the inspected material caused by the static magnetic field of the EMAT,  $\gamma_s$  represents the value at which the magnetostriction in the inspected material saturates,  $M_s$  is the value at which the magnetisation saturates in the inspected material,  $\chi_0$  is the initial susceptibility of the inspected material,  $dev()$  indicates the deviatoric elements of a tensor,  $\otimes$  is the tensor product operator,  $\mathbf{M}_{an}$  is a mathematical representation of the magnetisation experienced by an inspected material,  $\varepsilon_{\mathbf{m}}$  represents the strain induced by the magnetisation in the material and  $C_h$  is the strain-stress matrix of the material. Figure 5.2, in its right vertical axis, shows the magnetostrictive behaviour,  $\varepsilon_{\mathbf{m}}$ , of the different materials modelled.

The static and dynamic electromagnetic fields involved in the EMAT transduction are related. The constitutive physical relationships that govern the stationary electromagnetic fields are:

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} \quad (5.4)$$

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \quad (5.5)$$

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (5.6)$$

$$\mathbf{J} = \eta \mathbf{E} \quad (5.7)$$

$$\nabla \times \mathbf{A} = \mathbf{B} \quad (5.8)$$

Where  $\mu_r$  is the relative magnetic permeability of the material,  $\eta$  is the electrical conductivity of the material,  $\mathbf{B}$  is the magnetic field density,  $\mathbf{H}$  is the magnetic field intensity,  $\mathbf{M}$  represents the magnetisation of the material,  $\mathbf{J}$  is the current field density,  $\mathbf{E}$  represents the electric field,  $\nabla \times$  is the curl operator and  $\mathbf{A}$  represents the magnetic vector potential. Eq. 5.6, eq. 5.7 and eq. 5.8 represent the physical relationship between magnetic and

electric fields, whereas eq. 5.4 and eq. 5.5 are the constitutive material equations that relate the magnetic field density and material magnetisation to the magnetic field. Eq. 5.4 represents the change in magnetic field density in the material due to an applied magnetic field. While in eq. 5.5, the magnetic field density is separated into two components: the density of an applied magnetic field in the material and the material magnetisation. Where the second component represents the spontaneous magnetisation response of the material to an applied magnetic field or a remanent magnetisation in the material, or both. The use of eq. 5.4 and eq. 5.5 are utilised to estimate the magnetisation in the inspected material and in the EMAT.

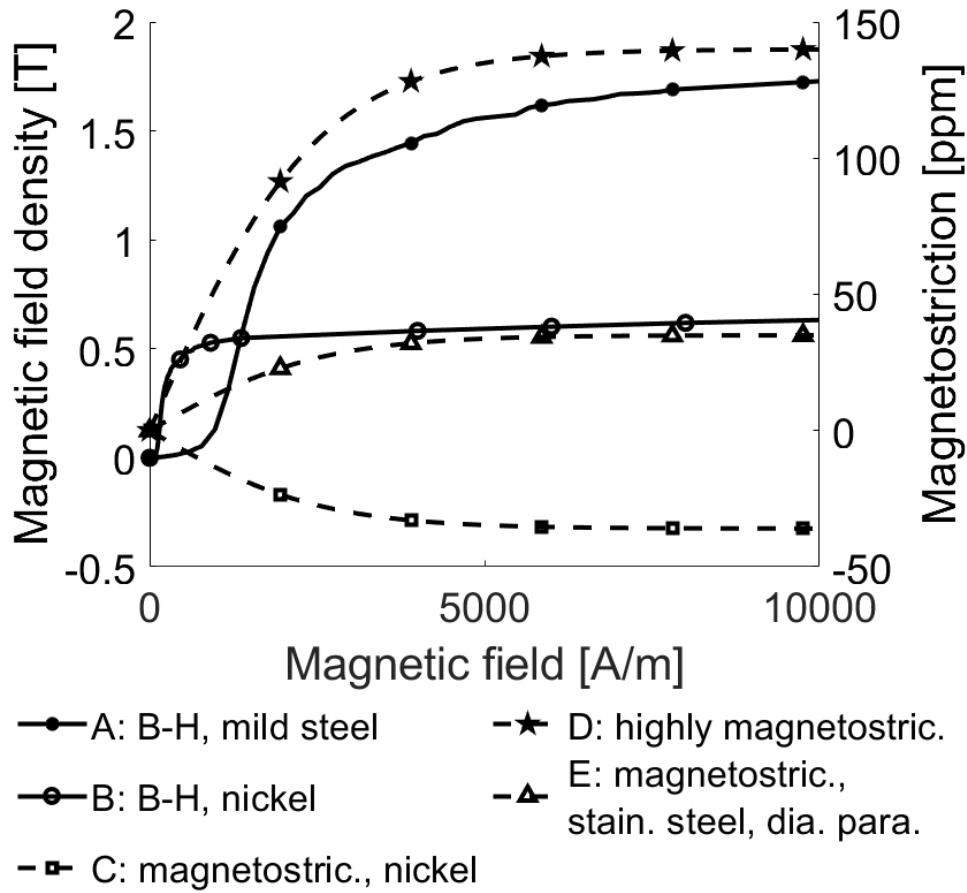


**Figure 5.2:** Electromagnetic and electromechanical property curves of the materials used in this study.

For ferromagnetic materials, the relationship expressed in eq. 5.4 is usually illustrated with the  $\mathbf{B} - \mathbf{H}$  curve of the material. On the vertical axis on the left of figure 5.2, the relationship of the magnetic field density versus an applied magnetic field in ferromagnetic

materials is shown. The  $\mathbf{B} - \mathbf{H}$  curves presented in figure 5.2 are the ones used in this study to represent the ferromagnetic materials investigated.

When the material is diamagnetic, the relative magnetic permeability of the material -  $\mu_r$ - is close to 1, meaning that the material experiences little magnetisation. The spontaneous magnetisation in the material is oriented in opposite direction to the applied magnetic field and therefore this phenomenon is represented with a negative magnetic susceptibility. For aluminium or copper, which are the diamagnetic materials used in this study, the magnetic susceptibility is  $-2.5 \cdot 10^{-5}$  [2]. In addition, like diamagnetic materials, paramagnetic materials experience little magnetisation and have relative magnetic permeability close to 1. However, the spontaneous magnetisation in the material is different, it is oriented in the same direction to the applied magnetic field and therefore, the magnetic susceptibility is positive. To model the paramagnetic behaviour that some stainless steels have, the magnetic susceptibility of the material is modelled as  $2.5 \cdot 10^{-5}$  [2].

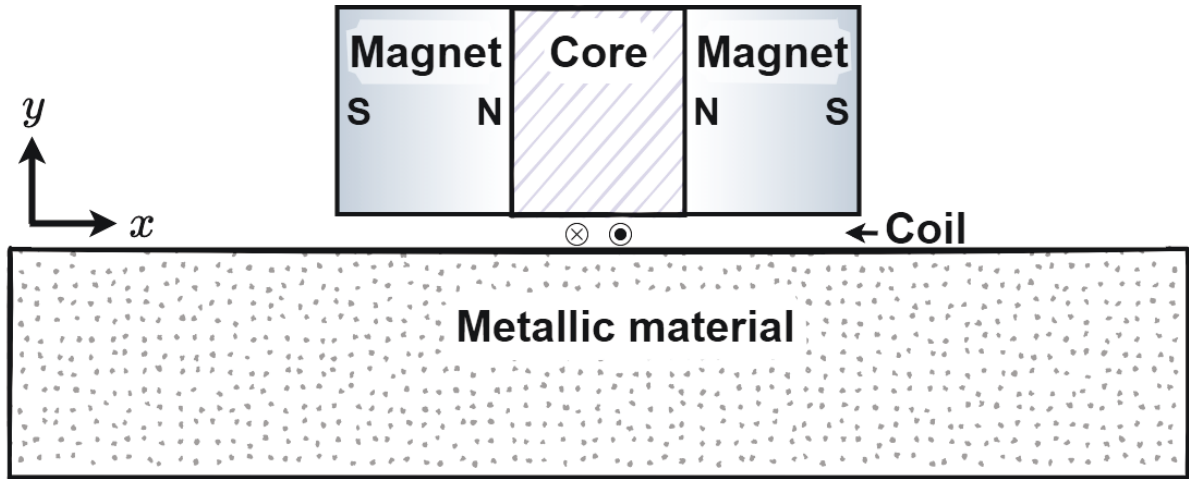
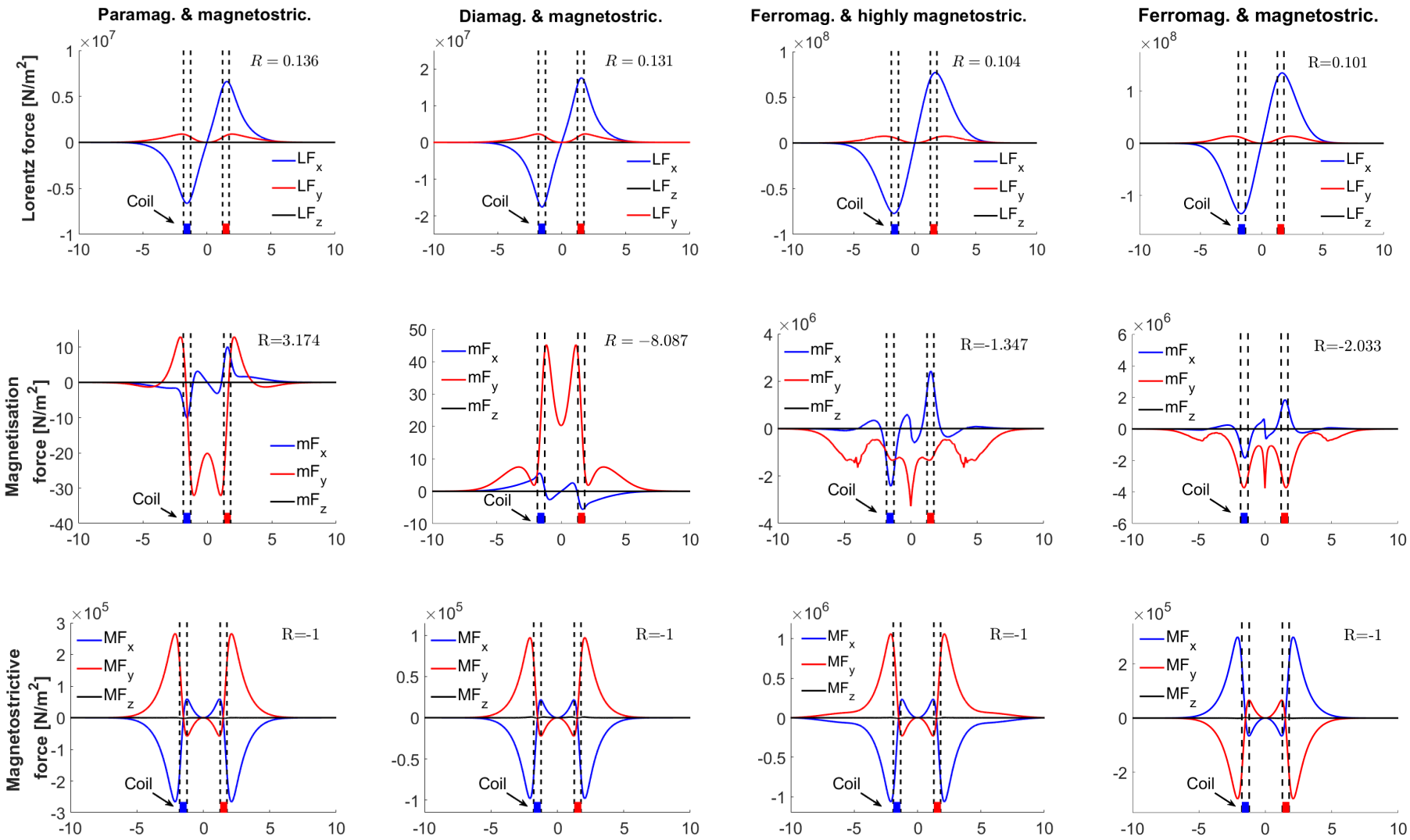


**Figure 5.3:** Schematic of the one race-track coil PA EMAT.

To estimate the surface tractions that one element of the PA EMAT exerts in different materials, a 2D finite elements (FE) model was implemented using the commercial software Comsol [129]. FEA is a versatile numerical tool that allows the user to estimate physical phenomena that otherwise would be difficult to determine.

The 2D FE model consisted of an air box of  $1m \times 0.6m$  with the EMAT and inspected specimen placed in the centre of it. The EMAT was composed of two permanent magnets of  $10mm \times 20mm$ , one metallic core with measures of  $10mm \times 20mm$  and a race-track



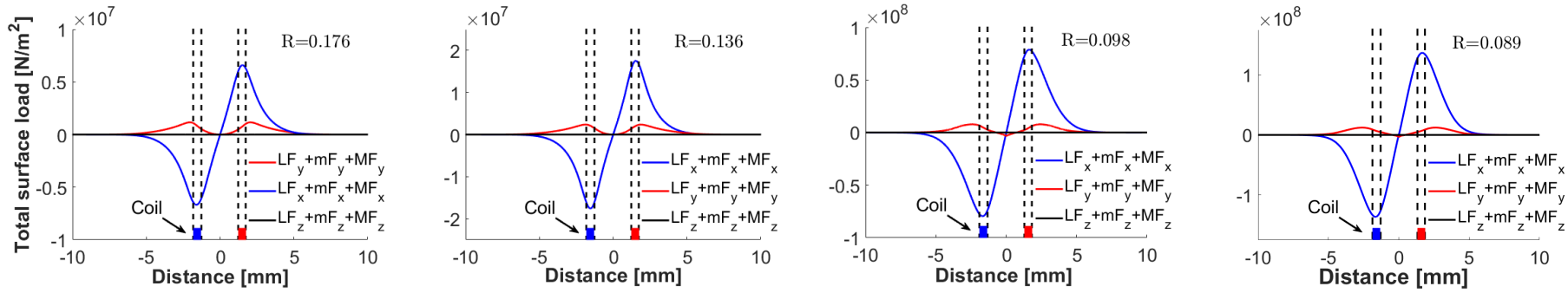


**Figure 5.4:** Surface loads exerted by one race-track coil of the PA EMAT on different metallic materials. The first column shows the surface loads exerted by one coil of the PA EMAT in paramagnetic materials with magnetostrictive behaviour (curve E, figure 5.2). The second column illustrates the surface loads exerted by one coil of the PA EMAT in diamagnetic materials with magnetostrictive behaviour (curve E, figure 5.2). The third column illustrates the surface loads exerted by one coil of the PA EMAT in a ferromagnetic material (curve A, figure 5.2) with highly magnetostrictive behaviour (curve D, figure 5.2). The fourth column shows the surface loads exerted by one coil of the PA-EMAT in a ferromagnetic material (curve B, figure 5.2) with negative magnetostriction behaviour (curve C, figure 5.2). The plots in the row are the calculated Lorentz forces, magnetisation forces, magnetostrictive forces and total forces -respectively- in the surfaces of the inspected materials. The horizontal distance in each plot is measured from the centre of the coil.  $R$  is the peak amplitude ratio between excited surface loads and it is calculated by dividing the peak amplitude of the surface load in the  $y$ -direction by the peak amplitude of the surface load in the  $x$ -direction.

coil with track measures of  $0.4mm \times 1mm$ . The coil is placed  $0.5mm$  away from the magnetic circuit. The metallic specimen used for the FE simulation had dimensions of  $300mm \times 30mm$ . The EMAT race-track coil has  $0.5mm$  lift-off from the top surface of the metallic specimen. The schematic of the EMAT placed on top of the specimen is shown in figure 5.3.

The magnetic properties of the inspected material were varied between diamagnetic, paramagnetic and ferromagnetic with and without magnetostriction in the FE analysis. The magnetic response of the inspected material was modelled using eq. 5.4. When the material was modelled as ferromagnetic, one of the  $\mathbf{B} - \mathbf{H}$  curves (curve A or B) shown in figure 5.2 was selected. While when the material was modelled as diamagnetic or paramagnetic, the  $\mu_r$  was modelled as  $1 - 2.5 \cdot 10^{-5}$  or  $1 + 2.5 \cdot 10^{-5}$ , respectively. To evaluate the magnetostriction force in the inspected material, the relevant magnetostriction curve (curves C, D or E) shown in the right vertical axis of figure 5.2 was selected. The magnetic response of the ferromagnetic core was modelled with the  $\mathbf{B} - \mathbf{H}$  curve A shown in figure 5.2. The coil of the EMAT was model as diamagnetic copper with  $\mu_r$  of  $1 - 2.5 \cdot 10^{-5}$ . The permanent magnets were modelled as a material with  $1.45T$  of remanent magnetic field density and with a  $\mu_r$  of 1.05.

To ensure the accuracy and stability of the estimation, the FE geometry was discretised in  $\sim 2.4$  million quadrilateral elements of the 3rd order. One FE simulation took approximately 48 hours to solve on a data Cruncher with an Intel Xeon(R) Silver 4110 with 32 CPUs at  $2.1GHz$  and consumed about  $700Gb$  of RAM.

In figure 5.4, the surface loads exerted by the EMAT in different inspected materials are shown. The surface load were calculated in the FE analysis using eq. 5.1, eq. 5.2 and eq. 5.3. In figure 5.4 the surface load plots are organised in columns and rows. Each column collects the plots of the surface loads induced by the EMAT in a specific inspected material and in each row are the surface loads induced by one of the excitation mechanisms of the EMAT in the inspected material. The last row in figure 5.4 shows the total surface load exerted by the EMAT. The surface loads were obtained by adding each possible excitation mechanism exerted by the EMAT in the inspected material. This calculation assumed that the materials could be magnetostrictive.

## 5.4 Wave propagation and directivity

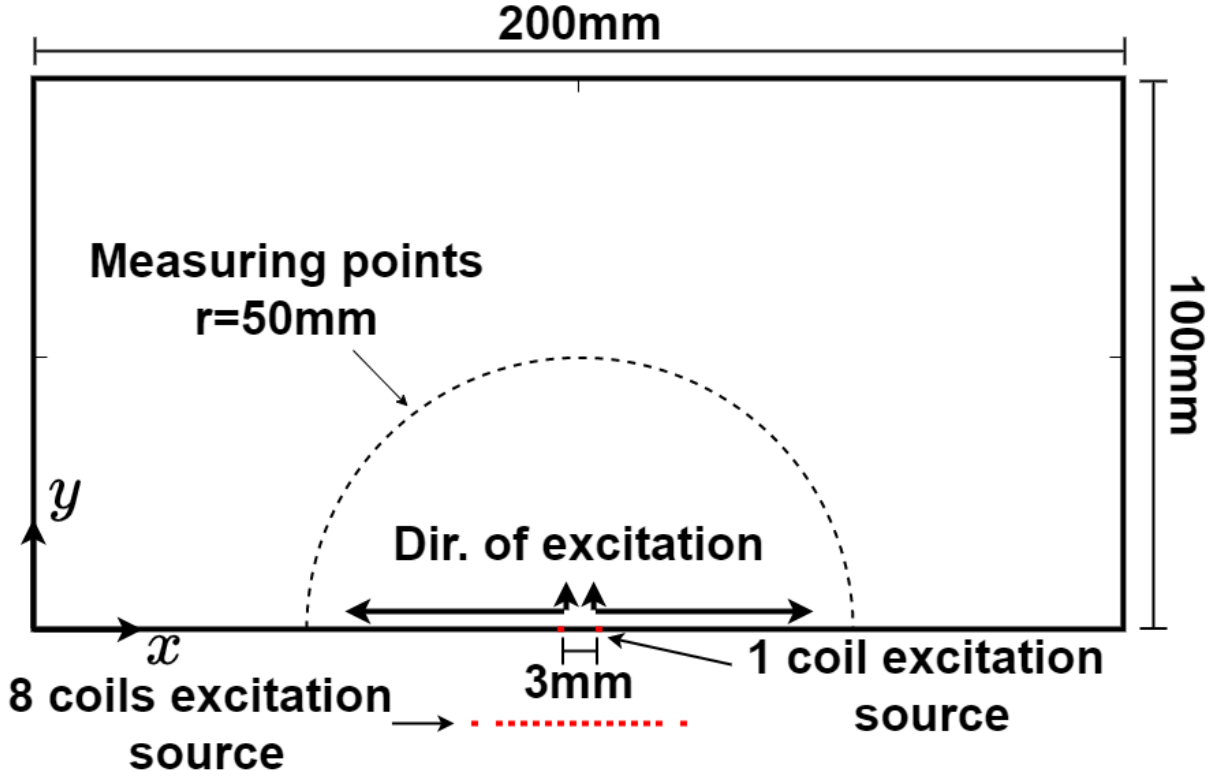
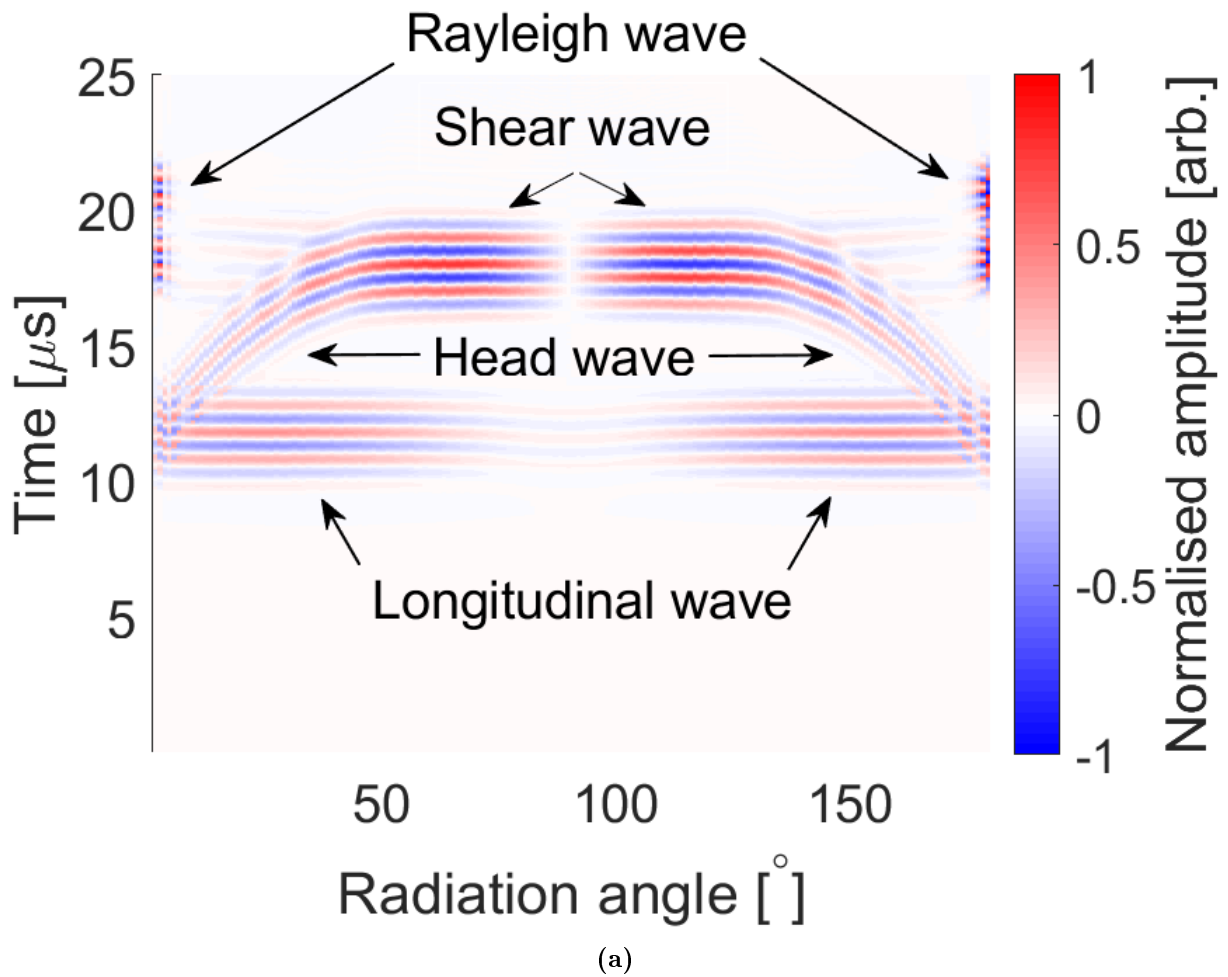
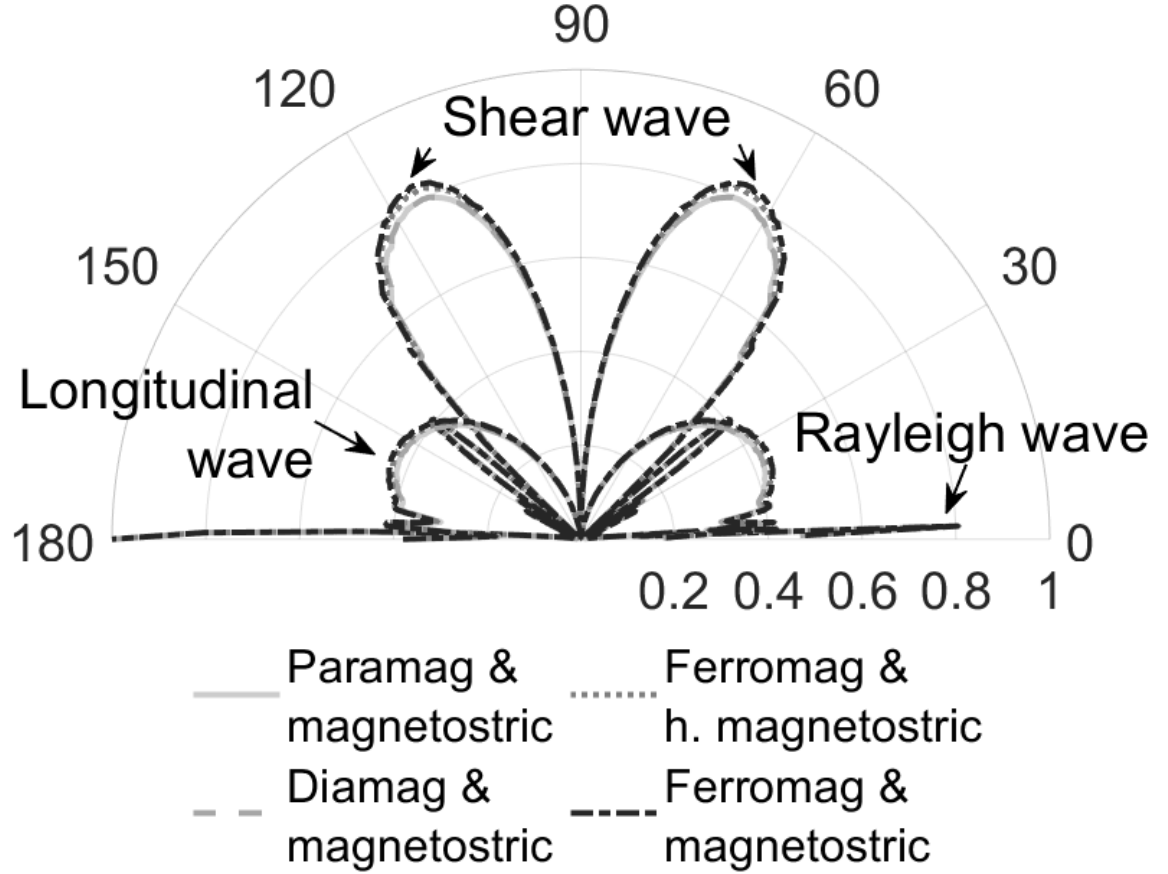


**Figure 5.5:** Schematic of the FE setup. The red lines represent the line excitation sources used in the 2D FEA. The excitation sources used throughout the 2D FEA were the 1 coil excitation source and 8 coils excitation source shown in the figure. The directions of excitation arrows were drawn to represent the difference in surface load amplitude between the horizontal and vertical loads.

In order to estimate the wave radiation pattern of the PA EMAT in metals, a 2D FEA was employed. In the analysis, the wave radiation pattern of one coil was studied first, and then the steerability capability of the 8 coils PA EMAT was analysed. The simulations were performed on a  $200\text{mm} \times 100\text{mm}$  block with free boundaries, here the mechanical properties of the block were modelled as aluminium ( $\rho = 2700\text{kg/m}^3$ ,  $E = 70.76\text{GPa}$ ,  $\nu = 0.3375$ ) or steel ( $\rho = 7932\text{kg/m}^3$ ,  $E = 216.9\text{GPa}$ ,  $\nu = 0.2865$ ), depending on whether the material was diamagnetic or paramagnetic/ferromagnetic, respectively. The simulated tests were performed in a pitch-catch mode, in which the wave excitation sources, either 1 coil or 8 coils, were located at the centre bottom of the block and the receiving semi-circle points at a radius of  $50\text{mm}$  away from the excitation sources, as shown in figure 5.5. The receiving semi-circle points were placed from  $0^\circ$  to  $180^\circ$  with an an-

gular step of  $1^\circ$ . The excitation sources were modelled as a  $0.4mm$  line sources, where the surface load ratio, normal load amplitude to tangential load amplitude, were selected based on the material investigated. The magnetic materials tested were diamagnetic and magnetostrictive, paramagnetic and magnetostrictive, ferromagnetic and magnetostrictive and ferromagnetic and highly magnetostrictive. For each material, the surface load ratio,  $R$ , was selected from the total surface loads shown figure 5.4. The amplitude of the tangential surface load is  $100N$ . The excitation signal used was a 5-cycle Hanning-windowed toneburst, with centre frequency of  $1MHz$ , giving a wavelength of  $\sim 3.1mm$  in aluminium or steel.





(b)

**Figure 5.6:** Induced ultrasound waves with one coil of the PA EMAT. Ultrasound waves recorded at the measuring points. The ultrasound waves were exerted with the surface loads shown in figure 5.4. a) B-scan recorded at the measured points when the inspected material is modelled as ferromagnetic and highly magnetostrictive metal. b) Ultrasound wave directivity pattern recorded at the measuring points for different metals.

The FE simulations were performed with the Simula Abaqus/Explicit FEA package [81]. To ensure the stability and accuracy of the simulations, square elements with edge length of  $0.1mm$  and a time step of  $10ns$  were used. The FE model contained 2 million elements and took approximately  $35min$  to solve on a data Cruncher with Intel Xeon(R) 32 CPU ES-2667 at  $3.4GHz$  and consumed  $40Gb$  of RAM approximately.

To understand how shear waves can be steered with the proposed PA EMAT, the wave radiation pattern and directivity of a single coil of the PA EMAT was studied. The direction of propagation and amplitude distribution of the shear waves excited by a single coil of the PA EMAT dictate the angular directions at which the excited shear waves can

be steered. To investigate how the wave radiation pattern and directivity of the shear wave induced by a single coil of the PA EMAT is affected by the inspected metals, the wave propagation induced with the 4 different total surface loads obtained in section 5.3 were simulated.

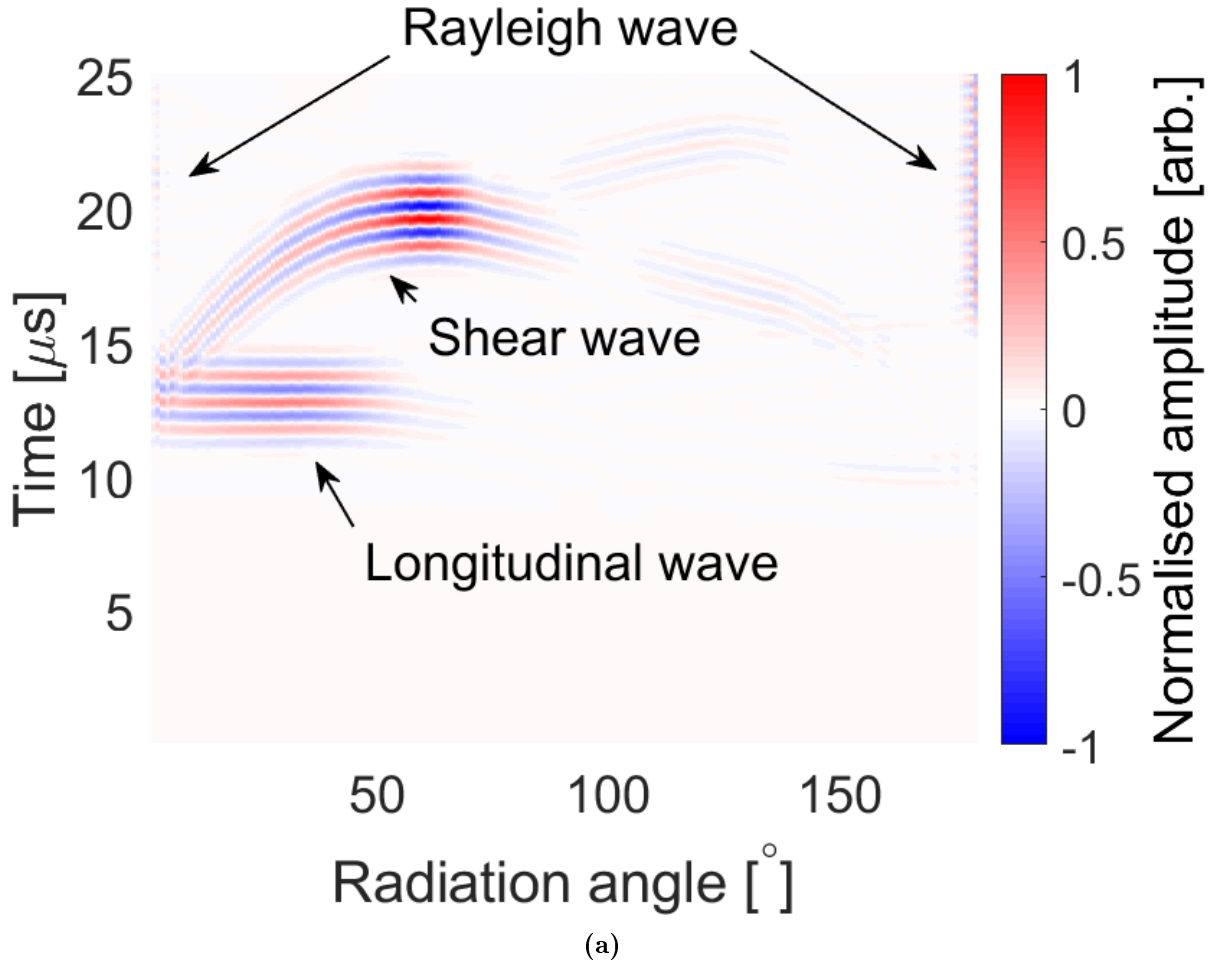
Figure 5.6 shows the wave radiation pattern and wave directivity obtained when a single coil of the PA EMAT is used to excite ultrasound waves in metals. The result shown in figure 5.6a is the wave propagation pattern obtained on the ferromagnetic and highly magnetostrictive material. The excited wavefield of the longitudinal wave, shear wave, Rayleigh wave and the head wave are shown; where the head wave is generated by the interaction of the longitudinal wave with the free edges of the block [70, 73]. In figure 5.6b, the directivity of the waves excited by a single coil of the PA EMAT in different metals is presented. To estimate the directivity of the waves induced, the time at which the maximum amplitude of the longitudinal and shear waves passed by the measuring points were recorded and then the wave amplitude at those times were represented as a single line. The FE result shown in figure 5.6 were normalised to its maximum wave amplitude recorded in each FE simulation.

To evaluate the angles at which a shear wave can be steered using the proposed 8 coils PA EMAT, the 8 coils excitation source shown in figure 5.5 was used in the 2D FEA. To steer the excited shear waves induced by the PA EMAT, the 8 coils of the PA EMAT were excited simultaneously, however, a time delay in the input signal of each coil was implemented. The time delay was calculated based on the plane wave steered method, which depends on the angle desired, the shear wave speed and the distance between the centre of each coil as follow:

$$t_d = \frac{N_{coil} \cdot c_d \cdot \cos(\theta)}{vel_{shear}} \quad (5.9)$$

Where  $t_d$  is the time delay applied to coil  $N_{coil}$ ,  $N_{coil}$  is the number of the coil,  $c_d$  represents the distance between centre of each coil,  $\theta$  is the desired steered angle measured from the surface of the inspected material and  $vel_{shear}$  is the wave speed of the shear wave in the inspected material.

In figure 5.7, the FE results obtained when the proposed 8 coils PA EMAT is used to excited and steer shear waves at  $60^\circ$  with respect to the surface of the inspected material is presented. Figure 5.7a shows the wave radiation pattern of the waves recorded at the measuring points and figure 5.7b shows the shear wave directivity obtained when the 8 coils PA EMAT is used to excited shear waves that are steered to  $60^\circ$ . The excitation surface load pattern that was used results that are presented in figure 5.7 was the total surface load obtained for the ferromagnetic and highly magnetostrictive material. To estimate the directivity of the shear waves, the time at which the maximum amplitude of the shear waves passed the measuring points was recorded and then the wave amplitude at that time was plotted as a line. The ultrasound wave amplitude in figure 5.7a and in figure 5.7b where normalised with respect to the maximum amplitude recorded for each plot.



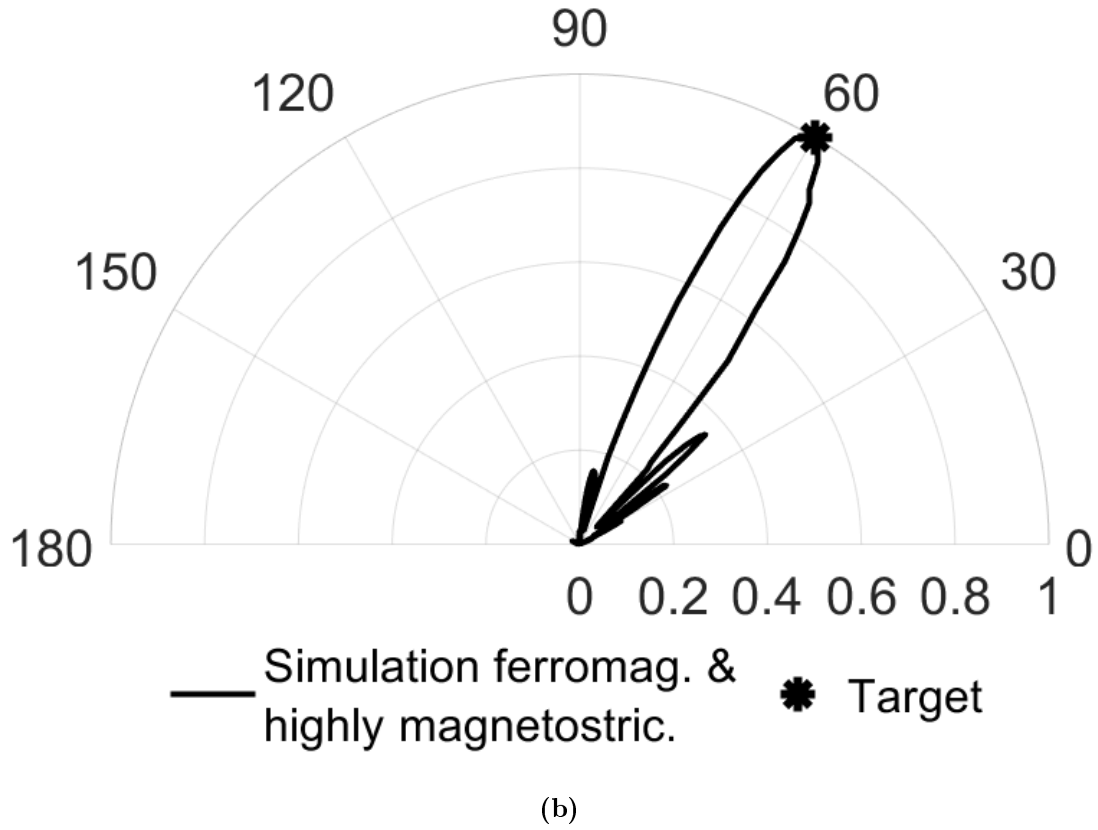


**Figure 5.7:** Induced ultrasound waves with the 8 coils PA EMAT when it is used to steer shear waves at  $60^\circ$ . Ultrasound waves recorded at the measuring points. The ultrasound waves were exerted with the surface loads shown in figure 5.4 for ferromagnetic and highly magnetostrictive a) B-scan recorded at the measured points. b) Shear wave directivity recorded at the measuring points.

Figure 5.8 summarises the shear wave directivity results obtained when the 8 coils PA EMAT is used on the ferromagnetic and highly magnetostrictive material. The induced shear waves were steered from  $35^\circ$  to  $145^\circ$  with a  $1^\circ$  increment. The assembly of each shear wave directivity result into one image facilitates the visualisation of the steerability and angle coverage of the proposed PA EMAT. The amplitude shown in figure 5.8 was normalised with respect to its maximum amplitude.

## 5.5 Experimental setup

Once the wave excitation sources and the steering capability of the 8 coils PA EMAT were obtained, see section 5.3 and section 5.4, respectively; an experimental setup was designed to validate the steering capabilities of the 8 coils PA EMAT on different metallic

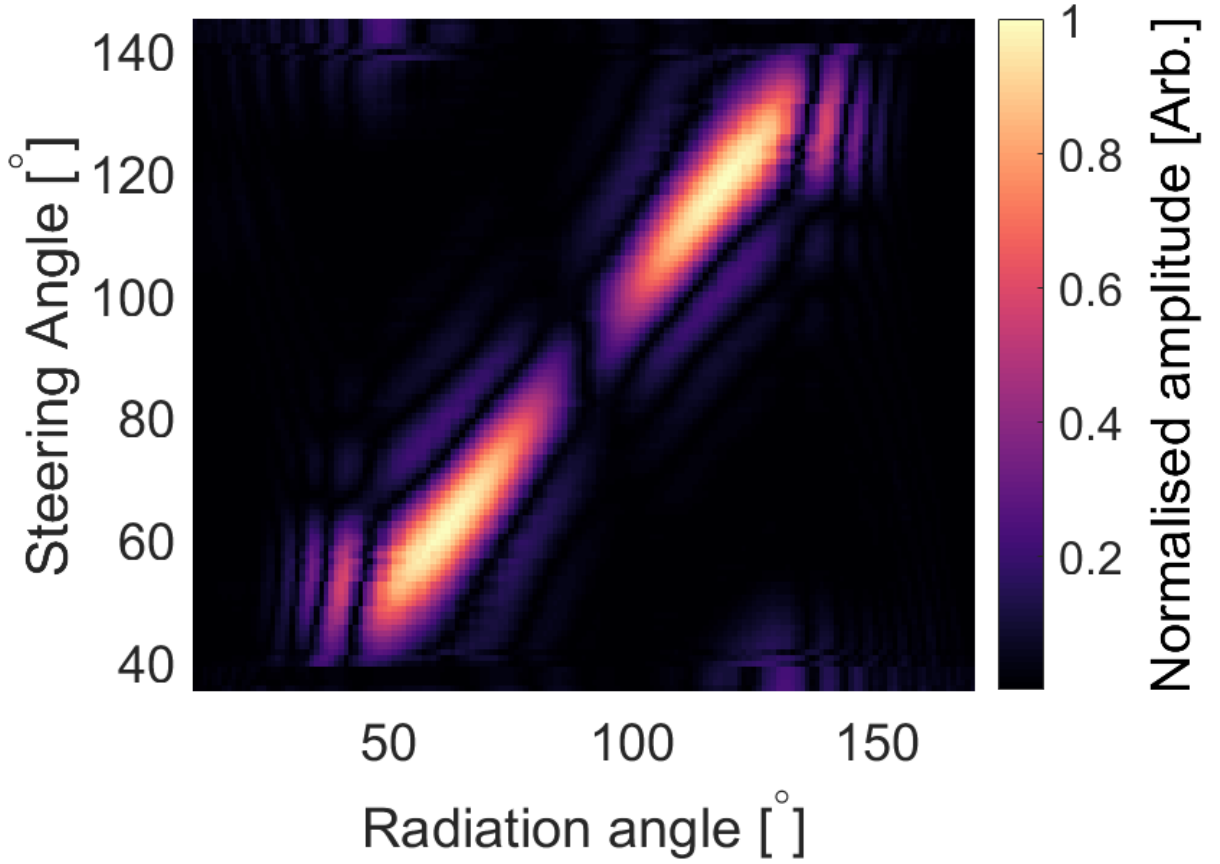


**Figure 5.8:** Shear wave steerability of the 8 coils PA EMAT. The 1 MHz shear waves were excited with the surface loads shown in figure 5.4 for ferromagnetic and highly magnetostrictive. The induced shear waves were steered from  $35^\circ$  to  $145^\circ$  with a  $1^\circ$  increment.

materials. The experimental setup was composed of a computer (PC), a data acquisition (DAQ) system, an arbitrary wave generator (AWG), a transmitter amplifier (Tx Amp), a receiver amplifier (Rx Amp), a shear wave piezoelectric transducer (UT-PZT), the 8 coils PA EMAT and a half-cylinder specimen. The schematic of the setup used to validate the FE results is shown in figure 5.9a.

The materials selected for the experiments were materials that are commonly used in industry and that represent the magnetic properties investigated. The materials were: aluminium 6082 (paramagnetic), mild steel EN1A (ferromagnetic), stainless steel 304 (paramagnetic), stainless steel 316 (paramagnetic) and Nickel 201 (ferromagnetic and magnetostrictive). Each of them was machined to form a half-cylinder of dimensions:  $100\text{mm}$  long and  $50\text{mm}$  radius. The different half-cylinders used throughout the experiments are shown in figure 5.9b.

## 5. Phased-Array EMAT: dipole source element

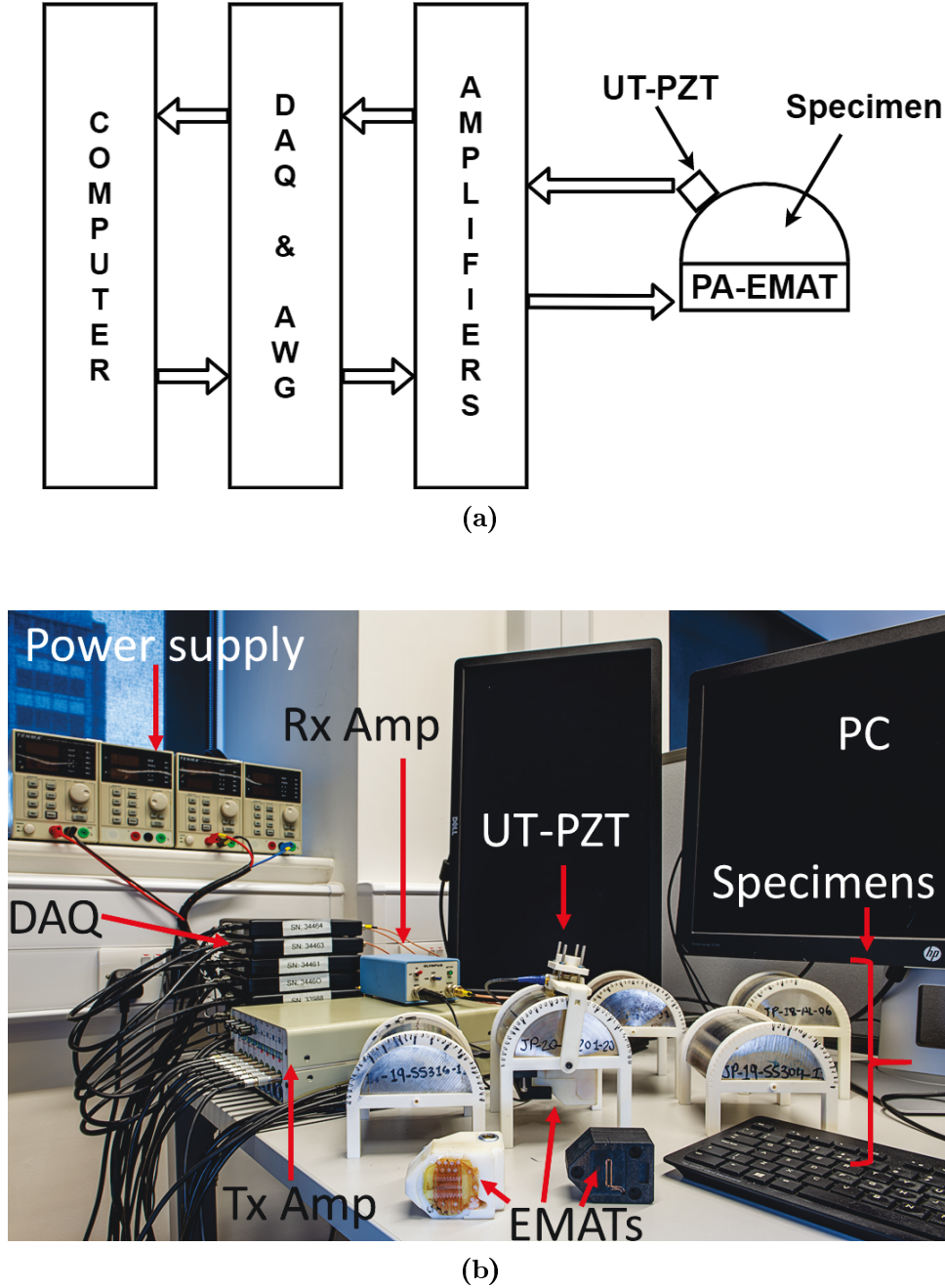


**Figure 5.9:** Experimental setup. a) Schematic. b) Actual experimental setup.

Each component of the experimental setup had a specific function. The computer was used to calculate and transmit the 8 coils excitation signals to the AWGs, to initiate the pitch-catch test and to store the measured signals; all these was carried out by means of a code implemented in the commercial software Matlab [99]. The AWG convert the excitation signals into electric signals and then send them to the transmitter amplifier. The transmitter amplifier is an in-house designed and manufactured amplifier that allows

the user to induce enhanced electric signals in the coils of the PA EMAT. The 8 coils of the PA EMAT were excited simultaneously to maximise the energy sent to the inspected material. the excitation signals were constructed to mimic the ones used during the FE analysis. Once ultrasound waves were induced in the inspected metallic material, the shear wave piezoelectric transducer was used to record the shear waves coming from the PA EMAT. A spring was used to exert pressure on the piezoelectric transducer, to ensure the direct surface contact of the transducer with the surface of the inspected material. The signal recorded with the piezoelectric transducer were sent to a  $60dB$  Olympus receiver amplifier, which improved the signal-to-noise-ratio of the measured signal. The signal amplified by the receiver transducer were digitised with the DAQ system and transmitted to the computer for later post-processing. The DAQ system and AWGs were parts of 8 Handyscope (HS5). The HS 5 were synchronised, so they generated the electric excitation signals and recorded the measured signals simultaneously. Figure 5.9b shows the actual setup used.

To measure the wave radiation pattern generated by 1 coil of the PA EMAT and the steerability of the 8 coils PA EMAT, several pitch-catch tests were performed. To perform one pitch-catch test, the EMAT was placed at the centre of the cut surface of the half-cylinder metallic specimen; Then, the PA EMAT was used to induce ultrasound waves in the inspected material and, the induced waves were recorded with the piezoelectric transducer. Each pitch-catch test was averaged 500 times to minimise random noise. To obtain the wave radiation pattern induced by a single coil of the PA EMAT in a metallic material, 37 pitch-catch tests were performed. In each pitch-catch, the PA EMAT was used to excite ultrasound waves while the piezoelectric transducer was used to record the induced ultrasound waves at a specific angle. The piezoelectric transducer was placed from  $0^\circ$  to  $180^\circ$  with a step of  $5^\circ$ . While for estimating the steerability of the 8 coils PA EMAT in one material, 851 pitch-catch tests were performed; 37 pitch-catch tests for each steering angle; the steering angle was varied from  $35^\circ$  to  $145^\circ$  with a step increment of  $5^\circ$ . Hence, to evaluate the wave radiation pattern of a single coil of the PA EMAT and the steerability of the 8 coils PA EMAT in the 5 different metallic materials proposed, a total of 4440 pitch-catch tests were performed.

## 5.6 Experimental results

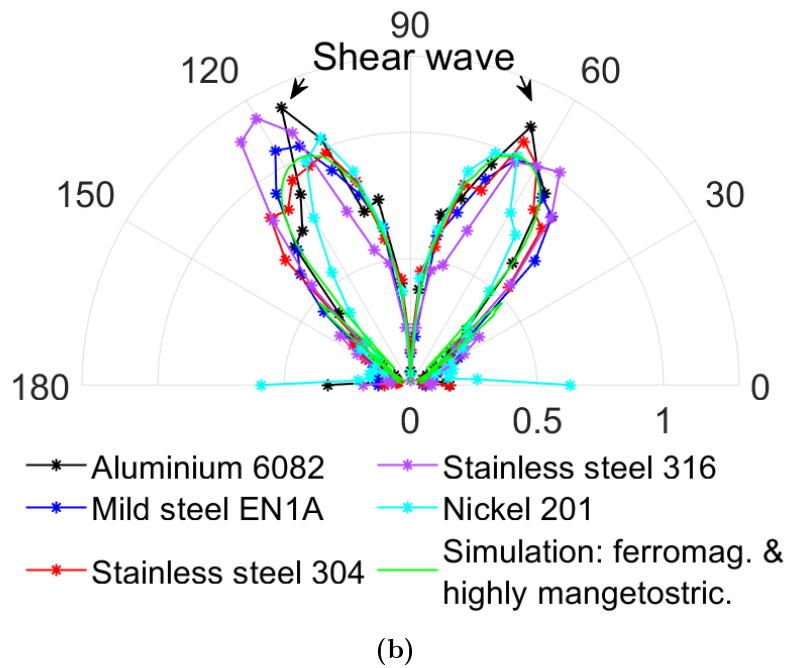
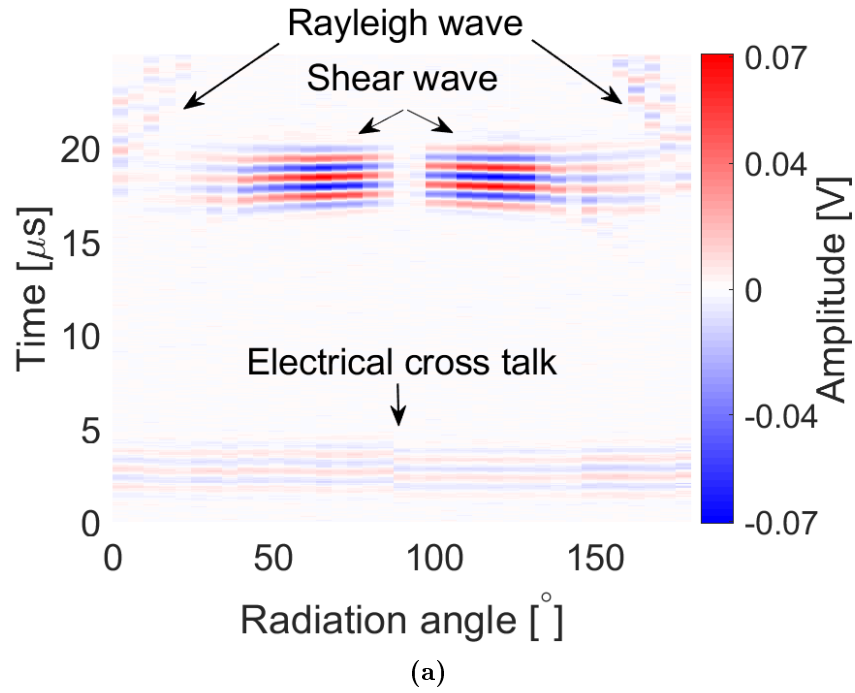
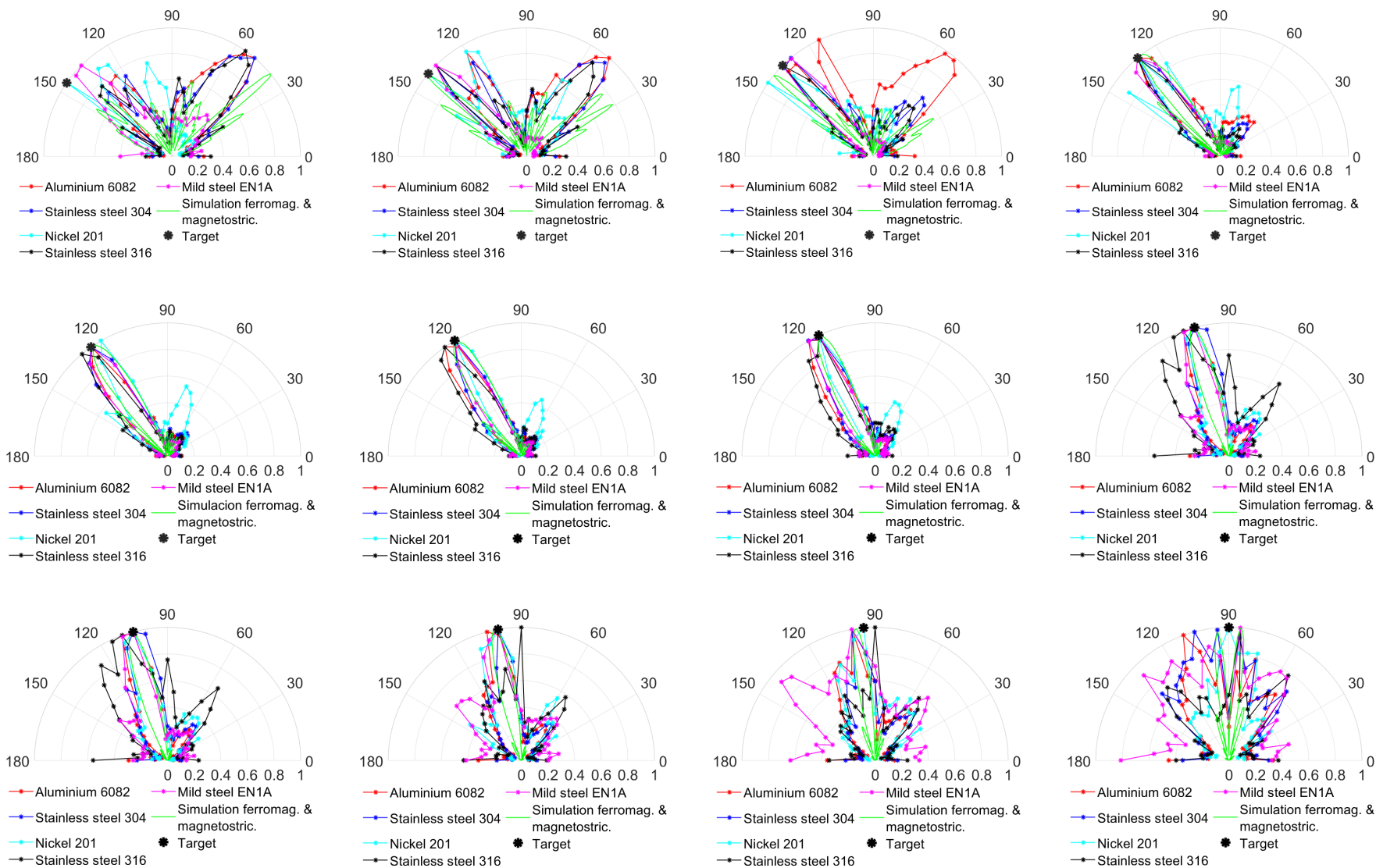


**Figure 5.10:** Measured wave radiation pattern and shear wave directivity of a single coil of the PA EMAT on different metals. a) Wave radiation pattern recorded on mild steel EN1A. b) Shear wave directivity measured on different metals.



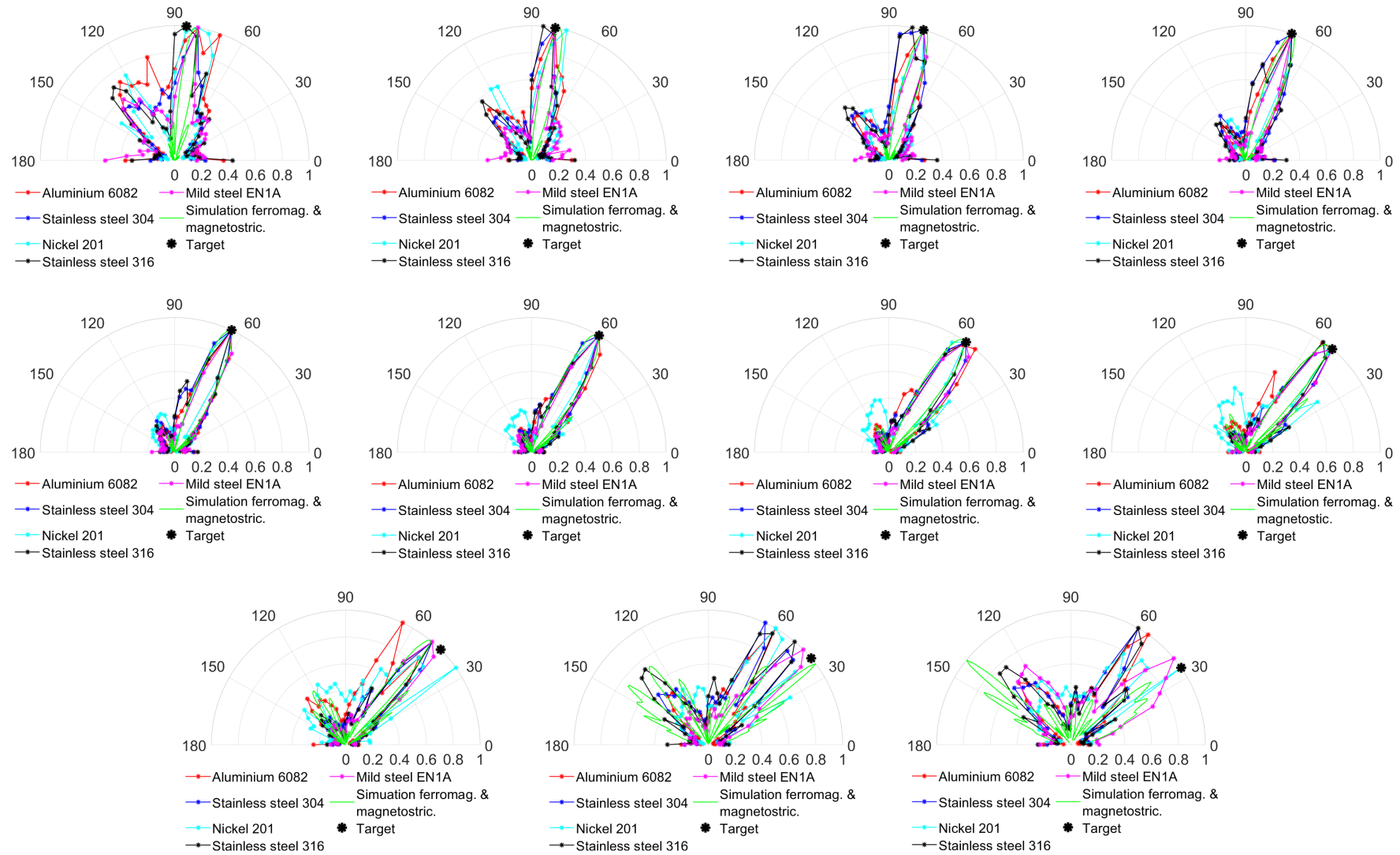


**Figure 5.11:** Experimental steerability results measured on different metals and compared with FE simulation result. The excited 1 MHz shear waves were steered from  $35^\circ$  to  $145^\circ$  with a degree step of  $5^\circ$  and measured from  $0^\circ$  to  $180^\circ$  with a degree step of  $5^\circ$ . Each steerability result presented in this figure was normalised to its own maximum value.

The wave radiation pattern and shear wave directivity of a single coil of the PA EMAT measured experimentally are shown in figure 5.10. The wave radiation pattern shown in figure 5.10a was obtained by stacking the time-traces recorded from  $0^\circ$  to  $180^\circ$  with an angle step of  $5^\circ$  in 37 different pitch-catch tests. The pitch-catch were recorded on the specimen made of mild steel EN1A. In figure 5.10b the shear wave directivity of a single coil of the PA EMAT obtained on aluminium 6082, mild steel EN1A, stainless steel 304, stainless steel 316, nickel 201 are presented and compared with the FE simulation results obtained when the material was simulated as ferromagnetic and highly magnetostrictive. Figure 5.10b was obtained from the wave radiation pattern of the waves excited on each inspected material by mimicking the procedure done to extract the wave directivity from the FE simulations. Each of the shear wave directivity shown in figure 5.10b were normalised to its value measured at  $60^\circ$ , so the obtained directivities could be compared. The experimental results shown in figure 5.11 are the shear wave steering results obtained when the 8 coils PA EMAT is used to plane wave steer shear waves in different metals. The shear waves were plane wave steered by implementing a time delay in each coil excitation signal. The time delay was calculated using equation 5.9. The experimental results obtained on aluminium 6082, mild steel EN1A, stainless steel 304, stainless steel 316, nickel 201 were compared to the FE results obtained when the material was simulated as ferromagnetic and highly magnetostrictive. The shear wave directivity at each steering angle was extracted from the time where the maximum amplitude of the measured shear waves occurred and then the wave amplitudes measured at each receiving angle at that time were plotted as a line. The results were grouped into polar plots based on the steering angle at which they were steered. To make the results comparable at each steering angle, the shear wave directivity lines were normalised to their own maximum value.

## 5.7 Discussion

The PA EMAT described in this chapter excites and steers  $1MHz$  shear vertical waves in metallic materials. the centre frequency of  $1MHz$  was selected due to the possibility of fast prototyping and hand-wiring the coils used in the PA EMAT. However, shear wave PA EMATs with centre frequency above  $1MHz$  are more appealing for NDE inspection

of defects placed in welds, thick plates, or metals in general. Shear waves with centre frequency above  $1MHz$  are preferred as they are more sensitive to small defects. Manufacturing shear wave PA EMATs with centre frequency above  $1MHz$  requires machine precision fabrication. This, to obtain the element width and element pitch necessary to steer the excited shear waves. I believe that with the current printed circuit board manufacturing technologies, and the power electronics available in the NDE industry, the fabrication of a shear wave PA EMAT with centre frequency of  $2MHz$  is possible. Going beyond  $2MHz$  could bring further challenges for the implementation of PA EMAT for defect characterisation, i.e., poor SNR due to the combination of a small ultrasound source, weak EMAT transduction and coherent noise induced by the grain size of the inspected material [130], or the design of an electrical amplification system capable of delivering the amplification gain needed to obtain good SNR and fast NDE inspection deployment.

Similar to shear vertical wave PA EMATs, shear horizontal wave PA EMATs are an attractive solution for the inspection of defects present in metallic material. Shear horizontal waves are an interesting option as they do not mode convert to other bulk wave modes when interacting with out-of-plane defects present in an inspected material [P2]. However, I am not aware of the existence of a shear horizontal wave PA EMAT offered in industry. I believe that the lack of shear horizontal wave PA EMAT offers for NDE inspections is due to the difficulty of designing an array of coils that can excite and steer  $1MHz$  or higher shear horizontal waves when combined with a permanent magnetic circuit. Studying possible PA EMAT designs to excite and steer  $1MHz$  or higher shear horizontal waves could be the next step forward in the research of PA EMATs.

Despite considering the paramagnetic and diamagnetic materials to be magnetostrictive in the FE simulations; in practice, it is hard to find a material that is paramagnetic and magnetostrictive or diamagnetic and magnetostrictive, hence in the experiments these materials were represented by the paramagnetic metals. The theoretical exercises of simulating paramagnetic and magnetostrictive or diamagnetic and magnetostrictive materials were done to explore unfavourable scenarios for the PA EMAT.

The results obtained depend on the conductivity of the inspected material and on the magnetic properties of the material. However, the results showed that unless the material is a poor electrical conductor, the Lorentz force will dominate the wave excitation in the

material.

In the 2D FE simulations, a specimen of rectangular shape was used rather than a specimen of semi-circular shape, the reason for this is that it facilitates the implementation of a structured mesh. However, in the experimental setup the specimens were shaped as a half-cylinder, the reason for this is that it allows to attach a receiving transducer and used to record the excited wave at an angular position. The difference in specimen shapes between experimental setup and FE simulations explains why the Rayleigh waves in the 2D FE simulations are received only at  $0^\circ$ ,  $5^\circ$ ,  $175^\circ$  and  $180^\circ$ , while in the experiments, the Rayleigh waves were recorded at the measuring angle. In the FE simulations, the Rayleigh waves passes across the measuring points along the edges ( $0^\circ$ ,  $5^\circ$ ,  $175^\circ$  and  $180^\circ$ ) only, whereas in the experiments, the Rayleigh waves travel beyond the specimen edge and around the cylindrical surface passing where the receiving transducer is and therefore, they get getting recorded at the angular position where the receiving transducer is.

Due to the lack of an ultrasound piezoelectric transducer capable of measuring longitudinal and shear waves simultaneously, the experimental results only show the shear waves recorded.

The shear waves steering simulation and experimental results were obtained by steering the induced shear waves with the plane wave steering method. Nonetheless, due to the independence of each ultrasound element of the presented PA EMAT, the PA EMAT can be used to focus shear waves to a focal point. This can be achieved by using the focusing wave method to calculate the time delay needed for each coil.

For comparison, the experimental results were normalised, the reason for this is that the receiving transducer was loaded with pressure coming from a spring placed at its back. Neither the compression of the spring nor the pressure exerted by it on the transducer was measured, complicating the comparison between signals recorded from different specimens. Hence, to facilitate the comparison, the wave directivity results obtained from different metallic specimens were normalised and placed in the same figure.

### 5.8 Conclusion

A study of the shear wave steering capacity of the race-track coil PA EMAT was presented. In this study, the steering capacity of the PA EMAT was analysed as a function of the inspected material. The steering performance of the PA EMAT was evaluated on four different types of magnetic materials: diamagnetic, paramagnetic, ferromagnetic and ferromagnetic with magnetostriction. The materials tested were aluminium 6082, stainless steel 316 and 304, mild steel EN1A and nickel 201. The results obtained show that the angle coverage of the PA EMAT studied is almost insensitive by inspected material. The measured angle coverage of the PA EMAT was from  $50^\circ$  to  $80^\circ$  and from  $100^\circ$  to  $140^\circ$  with a difference between materials of  $\sim \pm 5^\circ$ . Additionally, the results obtained showed that the steered shear wave amplitude varies across the two steering ranges and with a maximum amplitude at  $\sim 65^\circ$  and  $\sim 125^\circ$ . To understand the effect that different materials induce in the PA EMAT transduction, the three excitation mechanisms involved in the PA EMAT transduction were studied. The three excitation mechanisms -Lorentz force, magnetisation force and magnetostriction force- were estimated on the materials investigated. The results showed that each of the mechanisms exerts a surface load normal and tangential to the surface of the inspected material. Each of these surface loads have a distinctive pattern. However, the resultant surface loads are similar across the materials analysed. The reason of this similarity is that the PA EMAT design presented favours the Lorentz force, which exerts mainly a surface load tangential to the surface of the inspected material. Therefore, the material magnetostrictive effect has little success in affecting the transduction of the PA EMAT. Finally, the results conclusively show that the presented PA EMAT design can be reliably used to steer waves regardless of the magnetic properties of the metal that it is placed on.

# Chapter 6

## Conclusions

### 6.1 Thesis review

The work presented in this thesis focused on two main topics:

- designing an methodology that allows the user to measure the thickness of a material and, simultaneously, detect and characterise surface-breaking defects, and
- design of a shear wave phased array EMAT whose steerability is independent of the material that it inspects.

Chapter 2 gives a detailed overview of the physical principles of wave generation, wave propagation and wave directivity of bulk ultrasound waves in elastic media. The summary was focused on giving the reader the theoretical framework needed to understand the other chapters. I explain what an EMAT is, how an EMAT can be designed and how EMATs generate ultrasound waves. A detailed explanation of the EMAT transduction and its dependency on the electromagnetic properties of materials is presented. The three excitation mechanisms that are involved in the transduction of EMATs are explained for a magnet and a butterfly coil EMAT. Finally, a detailed study of the wave radiation pattern as a function of mechanical source orientation is given. The study compared a single element source, a dipole element source 8 single element sources and 8 dipole element sources. The results presented were the wave radiation pattern of a single element source and a dipole element source, the wave radiation pattern of the dipole element source as a

function of the distance between its mechanical loads, the steerability of 8 single element sources and the steerability of a 8 dipole element sources.

Chapter 3 shows how two co-located shear waves with orthogonal polarisation can be used to simultaneously measure the thickness of a material and to detect the presence of a surface-breaking defect. It was demonstrated how two orthogonal shear waves can be excited by means of an EMAT. The proposed EMAT had two orthogonal and co-located coils that in combination with a magnetic circuit exert mechanical loads into metals by means of the Lorentz force. It was also demonstrated that orthogonal shear wave with linear polarisation interacts differently with surface-breaking defects and that the resultant amplitude difference is an indicator of the presence of the defect. The results showed that with the proposed EMAT surface-breaking defects of depth exceeding  $0.3\text{mm}$  ( $0.2\text{wavelengths}$ ) or higher can be detected. However, for defects that are deeper than  $3.1\text{mm}$  ( $2\text{wavelengths}$ ) the amplitude drop of the measured signal plateaus, meaning that amplitude drop cannot be used to size defects greater than  $3.1\text{mm}$  but only detects them. In addition, the results also showed that the amplitude drop depended on the relative orientation of the two shear waves with the surface-breaking defect.

In chapter 4, the methodology of chapter 3 -the use of orthogonal and co-located shear waves for thickness gauging of metals and surface-breaking defect detection in an inspected material- was generalised to anisotropic materials. It was established that the level of anisotropy of a material, the orientation of the principal shear directions of a material, the presence of a surface-breaking defect in an inspected material, and the orientation of a surface-breaking defect can be estimated using the properties of the two shear waves. The proposed methodology was tested on an aluminium block. The results showed good agreement with the expected values. The estimation of the orientation of the principal shear direction and the surface-breaking defects had an error of  $\sim \pm 5^\circ$ . Level of anisotropy of the material was estimated to  $\sim 0.5\%$ .

Chapter 5 presented a study of the steering capability of a shear wave phased array EMAT. The phased array EMAT studied is composed of a permanent magnet magnetic circuit and 8 race-track coils. The study focused on the steerability of the shear wave phased array EMAT as a function of the inspected material. The steerability was assessed on different metals: paramagnetic, diamagnetic, ferromagnetic and magnetostrictive. The materials

investigated were aluminium 6082, stainless steel 304 and 316, mild steel EN1A and nickel 201. The results showed that the proposed shear wave phased array EMAT design maintained its steerability regardless of the type of inspected material. The proposed shear wave phased array can steer shear waves from  $50^\circ$  to  $80^\circ$  and from  $100^\circ$  to  $140^\circ$  with a difference between materials of  $\sim \pm 5^\circ$ . In addition, the study showed that the amplitude of the steered shear wave varied across the steering range with a maximum amplitude at  $\sim 65^\circ$  and  $\sim 125^\circ$ .

## 6.2 Main findings

The main findings of this thesis are:

- A new methodology for the simultaneous thickness gauging and detection of surface-breaking defects. The methodology used two orthogonal and co-located shear waves propagating at a right angle to inspect metals. The methodology used the time of flight of the shear waves to estimate the thickness of the material and the amplitude of the measured shear waves to estimate the presence and size of the surface-breaking defect.
- A novel EMAT design that allows the user to excite simultaneously two orthogonal shear waves with linear polarisation in metallic materials. The EMAT is composed of a magnetic circuit and two orthogonal and co-located butterfly coils.
- A new methodology for the characterisation of anisotropic materials. The methodology used two shear waves to estimate the level of anisotropy of a material, the orientation of the principal shear directions, the detection of surface-breaking defects and the orientation of a surface-breaking defect present in the inspected material.
- A wave radiation and steerability study of a dipole ultrasound wave source element. In the study, the wave radiation pattern of two normal loads and two tangential loads (both directions given with respect to the surface of the inspected material) was investigated. The effect that the distance between the elements of the dipole source had on the wave radiation pattern was also studied.

- A novel shear wave phased array EMAT design that maintains its steerability insensitive to the inspected material. This is the first EMAT reported (known to the author) to be insensitive to the changes that the electromagnetic material properties may bring to the transduction of the EMAT.

### 6.3 Further work

The work presented in this thesis can be expanded in two main areas: in the design of EMATs and in the area of defect detection and characterisation. Here are some of the ideas I have:

- The design of the OCLC EMAT can be combined with another magnetic circuit to generate 3 co-located ultrasound waves: two shear waves and one longitudinal wave. The information gathered with the three ultrasound waves can be used to simultaneously compensate the temperature effects in the measurement, to thickness gauging and defect detection.
- Use two orthogonal and co-located shear waves for monitoring internal stresses in a material. It is known that the principal shear directions of a material are the result of the internal structure of the material. The internal structure of a material can suffer changes when an internal stress in the material appears. This changes in the internal structure of the material could be detected by monitoring the orientation of the principal shear direction of the material.
- Design of a shear wave phased array EMAT that has continuous steering angle coverage, i.e. from  $50^\circ$  to  $140^\circ$  and has a steerability insensitive to the inspected material. This can be achieved by changing the design of the coil used in the shear wave phased array EMAT presented in this thesis so that only on track of the coil generates mechanical loads in an inspected material.
- Determine the probability of detection of common defects. i.e., pitting holes, surface-breaking defects, general corrosion, etc, with the shear wave phased array EMAT presented in this thesis. The obtained probability of detection can be compared with

the equivalent longitudinal phased array, and by this, determine the best usage of each type of phased array.

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# Appendix: calculating the orientation angle of a crack-like defect

In Chapter 3, the orientation angle of a crack-like defect was defined as the angle formed between the crack-like defect and one of principal shear directions of the anisotropic material. It is illustrated as  $\phi$  in figure 4.9 and in figure 4.10. The mathematical formula used in chapter 3 to estimate the orientation angle is equation 4.13. In this appendix, it is summarised the mathematical steps used to obtain the equation mentioned before. Equation 4.13 was obtained by following the next steps:

$$\frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB} = \frac{[A_1 * \cos^2(\phi) + A_2 * \sin^2(\phi)]}{[A_1 * \sin^2(\phi) + A_2 * \cos^2(\phi)]} = \frac{\cos^2(\phi) + A_2/A_1 * \sin^2(\phi)}{\sin^2(\phi) + A_2/A_1 * \cos^2(\phi)}$$

$$\frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB} = \frac{[1 + A_2/A_1 * \tan^2(\phi)]}{[\tan^2(\phi) + A_2/A_1]}$$

$$[\tan^2(\phi) + A_2/A_1] * \frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB} = 1 + A_2/A_1 * \tan^2(\phi)$$

$$\tan^2(\phi) = \frac{1 - A_2/A_1 * \frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB}}{\frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB} - A_2/A_1}$$

$$\phi = \tan^{-1} \sqrt{\frac{1 - A_2/A_1 * \frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB}}{\frac{CoilA \rightarrow CoilA}{CoilB \rightarrow CoilB} - A_2/A_1}}$$

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# List of Publications

## Written publications

- [P1] Jaime Parra-Raad, Pouyan Khalili, and Frederic Cegla. "Shear waves with orthogonal polarisations for thickness measurement and crack detection using emats". *NDT E International*, 111:102212, 2020.
- [P2] Jaime Parra-Raad, Bo Lan, and Frederic Cegla. " Orthogonally polarised shear waves for evaluating anisotropy and cracks in metals". *NDT E International*, 121:102440, 2021.
- [P3] Jaime Parra-Raad, Frederic Cegla. "On the steerability of phased array EMATs: The dipole element". *NDT E International*, 125:102563, 2022.

## Separate posters & oral presentations

- [P4] Jaime Parra-Raad, and Frederic Cegla. "Steerability Study of a Phased Array Emat on Paramagnetic, Ferromagnetic and Magnetostrictive Materials". *48th Annual Review of Progress in Quantitative Nondestructive Evaluation*, Online conference, 28-30 Jul 2021.