FPGA Based Digital Electromagnetic Sensing Technique for Detection of Pit Corrosion

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the faculty of Science and Engineering

2017

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List of Symbols

\( A \) Magnetic potential \((V \cdot s \cdot m^{-1})\)
\( B \) Magnetic flux density \((T)\)
\( D \) Electric displacement field \((C \cdot m^{-2})\)
\( E \) Electric field \((V \cdot m^{-1})\)
\( H \) Magnetic field strength \((A \cdot m^{-1})\)
\( V \) Electric potential
\( \delta \) Skin depth \((mm)\)
\( \varepsilon \) Electrical permittivity \((F \cdot m^{-1})\)
\( \mu \) Magnetic permeability \((H \cdot m^{-1})\)
\( \mu_0 \) Magnetic permeability of free space \((H \cdot m^{-1})\)
\( \mu_n \) Magnetic permeability in nth layer material \((H \cdot m^{-1})\)
\( \sigma \) Electrical conductivity \((S \cdot m^{-1})\)
\( \omega \) Angular frequency \((rad/s)\)
\( L \) Self-inductance
\( \phi \) Magnetic flux linkage
\( j \) Complex number
\( Z \) Impedance
\( X_L \) Reactance
\( r \) axis in spherical coordinate \((mm)\)
\( z \) axis in cylindrical coordinates \((mm)\)
\( \ell_1 \) Distance of the coil to the surface of the inspection \((mm)\)
\( \ell_2 \) High of the coil to the surface of the inspection \((mm)\)
\( \alpha \) Integration variable
\( r_n \) Radii of the coil \((mm)\)
\( J_1(x) \) First order Bessel function
\( K_1(x) \) Second order Bessel function
Nomenclature

A/D: Analogue to Digital converter
AC: Alternating Current
ACFM: Alternating Current Field Measurement
AET: Acoustic Emission Testing
ASNT: American Society for Non-destructive Testing
BEM: Boundary Element Method
CUI: Corrosion Under Insulation
D/A: Digital to Analogue converter
DDR: Double Data Rate
DDS: Direct Digital Synthesizer
EC: Eddy Current
EFG: Element Free Galerkin
EM: Electromagnetic
EMAT: Electromagnetic Acoustic Transducer
ET: Electromagnetic Testing
FDM: Finite Difference Method
FEA: Finite Element Method
FEM: Finite Element Method
FFT: Fast Fourier Transform
FPGA: Field Programmable Gate Array
GMR: Giant-Magneto Resistance
IR: Thermal/Infrared Testing
LPT: Liquid Penetrant Testing
LT: Leak Testing Method
LTM: Laser Testing Method
MAC: Multipler and Accumulative process
MFL: Magnetic Flux Leakage
MPT: Magnetic Particle Testing
<table>
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<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
</tr>
<tr>
<td>NRT</td>
<td>Neutron Radiographic Testing</td>
</tr>
<tr>
<td>PDE</td>
<td>Partial Differential Equation</td>
</tr>
<tr>
<td>PEC</td>
<td>Pulsed Eddy Current</td>
</tr>
<tr>
<td>RT</td>
<td>Radiographic Testing</td>
</tr>
<tr>
<td>SECM</td>
<td>Scanning Electrochemical Microscopy</td>
</tr>
<tr>
<td>UT</td>
<td>Ultrasonic Testing</td>
</tr>
<tr>
<td>VA</td>
<td>Vibration Analysis</td>
</tr>
<tr>
<td>VT</td>
<td>Visual Testing</td>
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Abstract

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Doctor of Philosophy
December 2016

This thesis describes the development of an eddy current instrument and its application in detecting early-stage pitting corrosion. Eddy current testing has previously been used in Non-Destructive Testing (NDT) applications detecting large defects, like cracks. However, the challenge of detecting corrosion pits of less than 1 mm³ remains unaddressed. This research involved the design of a Field Programmable Gate Array (FPGA)-based eddy current instrument, and the design and modelling of a novel differential electromagnetic sensor. The FPGA provided accurate synchronisation among the major electronic components. The firmware developed as part of this research allowed for exact interfacing to A/D and D/A converters, performed a real-time demodulation and signal generation, the instrument also supported a multi-frequency eddy current application. The firmware showed promising end-results in terms of sensitivity and stability in relation to pitting corrosion detection. In summary, this instrument offered significant improvement in sensitivity; the size of corrosion detected is improved more than 10 per cent compared to the previously reported, which enabled the detection of pits smaller than 1 mm³. For the sensor probe, a novel differential sensor was proposed to minimise the background signal for plate scanning and improve the sensitivity. The designed probe has an advantageous feature: the sensor response can be analysed using a closed form analytical solution.
Declaration

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Publications


Acknowledgments

I would like to express my sincere gratitude to my supervisor Dr Wuliang Yin for his time, guidance, advice and support during my studies. Without his influence, experience and discussions, this PhD would not have been possible.

I appreciate the time and support I received during the experimentation stage, particularly from Yuxi Wang and Dr. Rafael Leiva.

To my beautiful wife Natalia, for being by my side. For all the support, time, effort, love, for all encouragement words and understanding during the writing of the thesis. Thanks Natalia. To Julian, my lovely son, whose smile gave me the courage to continue and complete this thesis. To my parents, for all the support, guidance and advice during all these years.

Finally, I would like to thank the National Council of Science and Technology (CONACyT) for the scholarship provided for this PhD study at the University of Manchester.
Chapter 1 Introduction

Metallic structures are ubiquitous in a range of industries such as transportation, construction, plants, infrastructures, etc. [1], [2]. Corrosion of metal and alloys can lead to equipment failures, human injuries and can be potentially costly in terms of the environment and asset repairs [2]. Prevention and control of corrosion are the primary methods used to reduce damages as a result of corrosion [3].

Within different types of corrosion, pitting is considered to be more dangerous than uniform corrosion as it is harder to detect and predict [3], [4]. Pitting is deemed to be autocatalytic in nature. Once a pit starts to grow, the developed pit chemistry conditions are such that further pit growth is promoted [5]. This type of corrosion is also associated with other forms of corrosion, such as intergranular corrosion and environment-assisted cracking. During the early stages of corrosion, the pit is a small being of a few micrometres in depth and diameter. It is difficult to detect visually, particularly when corrosion happens under a coating. As a result, alternative methods must be applied for inspection. A feasible detection method must be capable of probing the surface of the material in which the pitting corrosion is present.

For this purpose, several Non-Destructive Test (NDT) methods are currently employed to interrogate the material under investigation, by using the interaction of an energy source and the material under inspection, the detection can be carried out. The main difference between individual NDT methods is the nature of the energy source used, which can be in the form of sound, vibration, and electromagnetism [3].

Several Non-Destructive Test (NDT) techniques such as acoustic emission [6], [7], microwaves [8] and radiograph, have been applied to detect the possible hidden corrosion [9]. These techniques present some advantages and disadvantages. Radiography is well known as a very powerful method, which can detect flaws with high accuracy. However, without strict control during the testing it can be potentially be harmful.
The Eddy Current (EC) method is the most popular of all the NDT methods, due to its testing speed, reliability, low cost and so on. Besides its popularity, EC is a feasible option when a conductive material is under investigation. The electromagnetic nature of EC makes it very responsive to the electromagnetic properties (conductivity and permeability) of the material. This is due to the fact that the electromagnetic field generated by the probe interacts with the material such that several characteristics can be extracted. These include hardness, thickness, crack and corrosion, which is the main focus of this research. Pipes can be made of different material, such as concrete, plastic, and metal (carbon steel, stainless steel, copper, aluminium and others); as an example, oil and gas distribution pipes are usually constructed using carbon steel with a treatment for the corrosion. However, despite the coating, the pipes inevitably still suffer corrosion, and EC is a candidate to detect the pitting corrosion in those pipes. This research focuses on the detection of early-stage pitting corrosion. Pitting corrosion is a challenge due to its small size, which usually tends to be a few hundredths of a micrometre during the early stages. The detection during this early-stage is crucial to ensure that effective actions can be taken to mitigate the problem within time. As mentioned, the Eddy Current Method is a feasible option when the investigated material is conductive or permeable.

This thesis will explore Eddy Current application for pitting corrosion detection by building a Field Programmable Gate Array (FPGA) based digital system. Digital systems have the potential of offering higher accuracy and flexibility than traditional analogue systems. The FPGA allows for the exact synchronisation of peripheral devices such as converters (D/A, A/D) and Direct Digital Synthesizer (DDS) and the high speed processing, such as digital signal demodulation, which improves the sensitivity and accuracy of the eddy current system.

1.1 Aims and objectives

The reliability of metal structures is a major concern not only in the industry but also in daily life. Monitoring these elements is complex and difficult. Electromagnetic methods, especially eddy current testing (EC) techniques, have remarkable advantages based on their contactless nature.
The thesis aims were to detect localised pit corrosion using eddy current techniques. The major challenge was to increase instrument sensitivity and, therefore, detect smaller pits than previously possible, in the range of a few hundred micrometres to millimetres. The detection of small variations in the magnetic field due to a pit in a metallic object is essentially required. This thesis entailed the design of an FPGA-based Eddy Current Instrument and a novel differential probe. In combination, the instrument and the probe offered increased sensitivity to detect pits in the range of few hundredths of a micrometre. The sensor was also designed according to an analytical solution. Thus, accurate models could be established to evaluate and predict its performances without resorting to time-consuming and less accurate numerical techniques.

1.2 Contributions of the thesis

To realise the overall aim, a series of contributions had been achieved and are summarised as follows:

- Analysis and optimisation of a novel probe. The probe was constructed using three coils, which formed a gradiometer configuration.
- The analysis of the novel probe was based on purely analytical solutions in classical closed form, which avoided time-consuming and less accurate numerical techniques in practice at high frequencies.
- Validation of analytical solutions using commercial modelling software (COMSOL®) for two typical probes, i.e. a) planar, and b) cylindrical.
- Generation of pitting corrosion in samples of carbon steel and characterisation of these samples with coherent optical methods.
- Development of firmware for the Eddy Current Instrument using VHDL programming that provided the exact synchronisation of the peripheral and allowed flexible switching within a range of frequencies for the experiments on carbon steel samples.
- Experimentation with the sensor design, assessing the capability of the instrument and validation through a comparison with theoretical analysis.

The contributions listed above can be found mainly in the chapters 4 and 5. In Chapter 4 Simulation Techniques describes the contributions listed in the first three
bullets, and the other contributions are detailed within the Chapter 5, Experimental evaluation.

1.3 Thesis outline

The thesis is divided into several chapters as follows:

Chapter 2 Literature Review. Corrosion & NDT techniques. This chapter explores the corrosion problem and the theory that is involved. The first part aims to put the challenges of detecting corrosion in context and in particular, pitting corrosion. The second part of this chapter explores different NDT techniques applied to detect corrosion and specifically pitting corrosion. Each NDT technique presents differences in its approach to solve the same problem. The advantages and disadvantages will be explored.

Chapter 3 Eddy Current Testing Method. The goal of this chapter is to present the background and theory of the eddy current method and its application on pitting corrosion. The chapter will elaborate on the eddy current problem, its analytical solutions (closed forms) different sensor probes and the characteristics of a corrosion flaw. Furthermore, the research methodology will be presented in terms of the modelling and experimental methodologies, which will be demonstrated in the succeeding chapters.

Chapter 4 Simulation Techniques. This chapter focuses on the classical analytical expression applied to fundamental eddy current problems. The problems are divided in two categories, i.e. when a rectangular cross-sectional air-coil is placed near to a conductive plate and when the rectangular cross-sectional air-coil surrounds a cylindrical material. In both cases, an analytical expression is presented and solved using MATLAB® software to calculate the magnetic vector potential and the real physical quantities that are involved in Eddy Current testing.

The chapter also presents a numerical simulation with COMSOL Multiphysics® 4.4. The simulation uses the same parameters as in the analytical simulation. A comparison of both analytical and numerical techniques is carried out. The last part of the chapter presents the analysis of a novel differential probe. The analytical simulation
is used to solve a complex probe geometry, which is composed of a double-coil excitation and a receiver coil.

Chapter 5 Experimental evaluation. The simulation in Chapter 4 required verification. The goal of this final chapter is to present the process of sample preparation, the pitting corrosion characteristics and the methodology used to carry out the verification experiments. The instrumentation development is also described. The details of experiments and the collected data are presented. The analysis of the results is also shown. The prediction from the analytical expression is compared with the measurement results and correlation between the experimental results and the pitting corrosion is also presented.

Finally, Chapter 6 Conclusions and future work. The scope and achievements are concluded and possible future work is recommended.
Chapter 2 Literature Review. Corrosion & NDT techniques

Corrosion is an important problem in a wide range of industries. The problem of corrosion comes in several forms i.e. homogeneous, pitting, intergranular, and others. It is critical to detect the problem during the earlier stages. The pit size at the earlier stages can be considered to be 0.5 mm² in size and have a depth of 0.4 mm². Detection of pit corrosion is a major concern in the industry due to the fact that a single pit can lead to a failure [9]. NDT is a solution for the identification of cracks, corrosion and other types of flaws. This chapter presents the literature review of different NDT methods used within the industry for corrosion detection. The chapter is divided into two sections. The first section presents the corrosion problem including the corrosion process, the influence of the others types of corrosion in industry, and the corrosion controlled size generation. Once corrosion starts, it is likely to continue and may evolve to a different type of corrosion i.e. pitting corrosion is likely to induce homogeneous corrosion. Structural integrity is assessed through regular inspections, this action allows for the gathering of qualitative and quantitative information if any damage exists; if so, action needs to be taken to stop or minimise the impacts due to the corrosion.

The second section discusses the different NDT methods applied for corrosion detection. The traditional techniques relating to corrosion evaluation are presented. The advantages and limitations of each technique is presented. The state-of-the-art of eddy current (EC) techniques, in particular the modelling and analysis of the EC problem are discussed in the following chapter.

2.1 Introduction

Rust is a synonym for corrosion. However, corrosion is a degradation process that occurs in any materials [10], and rust is the corrosive process that occurs in iron [11]. This corrosion process ends up with a degradation of the materials, which causes a reduction in its reliability. In practice, we can find different types of corrosion [3], [11].
Some of the corrosion types end in loss of material, degradation, and change the properties of the material itself [3]. From a chemical viewpoint, corrosion is a process wherein metal is oxidized by a chemical reaction; the atom leaves the metal, and an exchange of energy occurs [11]. In mechanics, corrosion can be explained as the loss of metal and a consequent modification of the resistance of the material [12], [13]. In both points of view, the properties of the material such as grain, strength, resistance, etc. are changed.

Nowadays, due to the extensive use of metals, corrosion represents as a common problem. The corrosion on chairs, tables, traffic signs and many others objects are daily life examples of this problem [3], [14], [15]. The metals used in different kinds of work are exposed to a corrosive condition. So, corrosion can be seen as an inevitable problem [16]. Once metal is produced, oxidation of this metal starts due to its interaction with environmental conditions.

“The driving force that causes metals to corrode is a natural consequence of their temporary existence in metallic form.” [3]

As corrosion is inevitable [3], [17], the only solution is the minimization of its impact on materials [15]. The material protection e.g. active corrosion protection, passive corrosion protection, permanent corrosion protection and temporary corrosion protection, are the first actions used to mitigate corrosion. The second action is through regular inspections and assessments of the conditions, and then implementing corrective actions that can minimize the problem [10], [15].

The cost of corrosion to the industry is a significant concern [15]. Corrosion usually results in monetary or environmental losses, an interruption in operation and even humans losses [15].

Table 2.1 shows the economic impact of corrosion from which it is clear that corrosion is a serious problem to be tackled [1], [2]. Mitigation and protection are the only possible solutions. The insight and knowledge of the structural condition or level of corrosion is vital in the selection of the appropriate mitigation action for the corrosion. For that purpose, NDT plays a critical role to quantitatively and qualitatively evaluate the condition of the materials under investigation.
Table 2.1 Historical annual cost of corrosion problem in industrial nations

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>TOTAL ANNUAL CORROSION COST</th>
<th>PERCENT OF GDP</th>
<th>YEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.A</td>
<td>$5.5 billion</td>
<td>2.1</td>
<td>1949</td>
</tr>
<tr>
<td>India</td>
<td>$320 million</td>
<td>—</td>
<td>1960</td>
</tr>
<tr>
<td>Finland</td>
<td>$54 million</td>
<td>—</td>
<td>1965</td>
</tr>
<tr>
<td>Germany</td>
<td>$6 billion</td>
<td>3.0</td>
<td>1967</td>
</tr>
<tr>
<td>UK</td>
<td>$1.365 billion</td>
<td>3.5</td>
<td>1970</td>
</tr>
<tr>
<td>Japan</td>
<td>$9.2 billion</td>
<td>1.8</td>
<td>1974</td>
</tr>
<tr>
<td>U.S.A</td>
<td>$70 billion</td>
<td>4.2</td>
<td>1975</td>
</tr>
<tr>
<td>Australia</td>
<td>$2 billion</td>
<td>1.5</td>
<td>1982</td>
</tr>
<tr>
<td>Kuwait</td>
<td>$1 billion</td>
<td>5.2</td>
<td>1987</td>
</tr>
<tr>
<td>U.S.A</td>
<td>$276 billion</td>
<td>3.1</td>
<td>2002</td>
</tr>
</tbody>
</table>

* Cost in US dollar  
** Source: [2]

NDT researchers have put enormous efforts into developing a set of techniques to assess the structural condition of an object during the corrosion process. These techniques vary with the application and most importantly, the sources of energy used to interrogate the material [9]. The next section explores the official definition and classification of corrosion, the sources that promote corrosion and the variables concerned in a corrosion process. Corrosion can be categorized according to the type of the damage and its growing process [5], [11], [18]. The aim of this work was the detection of pitting corrosion. Therefore, the techniques for the controlled generation of pitting corrosion are also summarised.

### 2.2 Definition of the corrosion

#### 2.2.1 Corrosion definition

The process in which a metal suffers from chemical or electrochemical attack by its environment is defined as *corrosion* [3]. Corrosion is a very significant problem nowadays, because it not only represents an enormous economic inconvenience (shown in Table 2.1), but also has safety implications [3], [15], [1], [2]. Researchers have put their attentions on studying and understanding the corrosion, even though it is almost impossible to avoid [3], [11]. The common solution is to mitigate the possible incidents and implications as a result of corrosion.
The exchange of energy between metals and their environment leads to the corrosion process [10]. The theory of electrochemical reaction can be used to explain the process [11]. Corrosion starts with the formation of ions and the liberation of the electrons. When this process happens, a deterioration begins on the surface of a metal [3]. A mass loss occurs when a reaction starts consuming the free electrons. Two chemical processes cause the corrosion. i.e. the anodic reaction and the cathodic reaction. The corrosion process usually occurs in the anodic reaction.

\[ \text{Zn} + 2\text{H}^+ \rightarrow \text{Zn}^{2+} + \text{H}_2(g) \]  

(2.1)

The corrosion process can be generalized as in (2.1) [3]. The full process of corrosion can be divided into two stages a) oxidation and b) reduction or mass loss [17]. The corrosion can be categorized as uniform corrosion, localized corrosion and granular corrosion [3].

2.2.2 Anodic corrosion process

Anodic reaction takes place when the atoms of the metals are ionized typically by a solution. The atoms are transferred to the solution from the metal by virtue of this reaction [11]. Anodic corrosion can be generalized as

\[ M(s) \rightarrow M^{n+} + n\text{e}^- \]  

(2.2)

The \( M \) from (2.2) can be considered as the metal or metal alloy in the oxidation process and \( n\text{e}^- \) is typically described as Hydrogen. So the generalization of the anodic chemical reaction tries to explain the oxidation of a metal (\( M \)) when a liberation of electrons “\( n \)” occurs.

2.2.3 Cathodic corrosion process

Corrosion by a cathodic reaction emerges when the free electrons within the metal are captured by a chemical reaction in contact with it, which means that the electrons react to the electrolyte and leave the metal, causing a loss of material. The cathodic process relates to metal loss, which can be described by a cathodic reaction of the hydrogen shown in (2.3).

\[ 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2(g) \]  

(2.3)
2.2.1 Types of corrosion

For a proper solution, an appropriate identification of the corrosion must be conducted. In the literature, identifiable features are used for corrosion classification [3]. Figure 2.1 presents a classification of corrosion in three groups [11]. In the following subsection, the most common corrosion types will be briefly treated.

![Diagram of corrosion types]

Figure 2.1 Different types of corrosion problems divided into groups of incident. Source: [11]

2.2.1.1 Uniform corrosion

According to NACE International, uniform corrosion is a general corrosion attack in which the metal suffers the greatest metal lost [11], which is relatively easy to visually inspect. Some examples of this type of corrosion are depicted in Figure 2.2.
2.2.1.2 Pitting corrosion

Pitting corrosion is a localized corrosion, which is the most common type of corrosion in the industry [11], [19]. This type of corrosion results in a small volume of metal loss, i.e. pits. Figure 2.3 shows different examples of pitting corrosion.

Size, growth prediction and location, such as subsurface or hidden by a coating material, lead to pitting corrosion being considered as a difficult type of corrosion. Also, pitting corrosion is more dangerous than the other types of corrosion due to the fact that pitting corrosion can promote other corrosion types.

Studies on the evolution of pitting corrosion were conducted by Turnbull, et al. [21]; involving simulating pitting growth and studying the transition of pitting corrosion to a crack, which are two of the main concerns to both researchers and industry. The evolution of the pit-to-crack definitely depends of the particular conditions of objects or metals, such as humidity, environmental conditions and the application of the material subject to corrosion [10], [21]. The growth of pitting corrosion is harder to estimate, the method to predict the evolution is to get the density over an area and calculate the rate of growth [11], [22]. In order to estimate this evolution, it is important to detect the pitting corrosion at an earlier stage; this is considered to be when the corrosion is in a
range of 0.5 to 2 mm² in size at the mouth of the pit, and having a depth of 0.4 to 0.8 mm².

Another motivation for pitting corrosion detection at an earlier stage is the reduction in cost in terms of money and safety. An example of a disaster caused by a single pit took place in 1997, in Guadalajara, Mexico; an explosion caused by a single pit resulted in the death of 215 people and also had a huge economic impact [11]. Besides safety, corrosion requires a huge amount of money to implement prevention and corrective actions (Table 2.1). A specific amount of money required for the corrosion detection is difficult to estimate as stated in the following study [1]. In the oil industry, the total cost of corrosion in oil transportation pipes can be between $32,500 to $55,500 per km, which represents 4.4% to 7.6% of the total cost of the pipe construction [23], [24]. It is clear that the cost of corrosion is large, but the problem can be mitigated, inspection typically gives an idea of the structural condition of the object under corrosion attack. Replacement of the corroded objects is one of the last actions to be taken, this is due to the economic cost involved. Replacing the corroded area usually takes place when there is a 20% loss in thickness. In some cases like oil and gas transport [25], the metal loss condition can be attributed more to the pressure used in the transportation task (600 to 1000 psi).

Detecting pitting corrosion at an early stage can reduce or mitigate the cost of the corrosion. By detecting pitting corrosion in small volumes there is the possibility to monitor the evolution in the object and therefore decide when is the best time to mitigate the corrosion. The growth of the pitting corrosion usually take hundreds or thousands of hours, depending on the environment of the object under investigation [21]. Detection of pit corrosion is also used to study the corrosion, mainly in controlled localized corrosion, which is discussed later in the chapter, and can be used to monitor the pit growth.

**2.2.1.3 Stress corrosion**

Stress corrosion is induced by microstructural cracks, which are produced by the stress on the material in a corrosive environment [11]. When microstructural corrosion occurs, the stress in the material can lead to the failures. But in some cases, the failure may happen after several years [3].
2.3 Stages of pitting corrosion

Pitting corrosion is initiated under some conditions, according to the evolution of pitting corrosion propagation [5]. The initiation of pitting corrosion requires a passive film breakdown. Metastable pitting happens in the following step and finally, the growth of pitting corrosion starts. In general, the stages can be classified as the initiation of the pits and the propagation. In the following subsections, a brief description of the stages will be presented.

2.3.1 Passive film breakdown

When a metal is fabricated, a thin film covers the surface. In simple words, this film is imperceptible [3] and the purpose of the film is to isolate the metal from the environment. In a real world scenario, the passive film is very complex [26]. But in general terms, the weakness and breakdown of the passive film relates to the initiation of pitting corrosion. The three categories are classified by the theory of passive film breakdown: a) passive film penetration, b) film breakdown, and c) corrosion initiation.

2.3.2 Metastable pitting

Following the passive film breakdown, the pitting corrosion initiates. This stage is named differently within different theories [19]. According to Frankel [5], this stage
is called metastable. At this stage, the dimensions of the pit are typically in the order of microns.

### 2.3.3 Pit growth

Pit growth depends on the material and electrolyte concentration in the metastable pits. A chemical reaction takes place in the pit growth where the metal loss occurs [5]. From this point, some actions must be taken to mitigate the multiplication of pitting corrosion. The pitting corrosion is transformed to other forms of more severe corrosion [20]. The work presented in this thesis was the detection of pit corrosion during this stage using electromagnetic methods (EM) methods.

### 2.4 Controlled pitting generation

To facilitate the study of corrosion in a controllable manner, the corrosion needs to be induced in the laboratory. For pitting corrosion, the important variable to control is the size of the pits. For this purpose, several methods can be used to initiate pitting corrosion and to control its size.

#### 2.4.1 Coating electrode

One of the methods developed by Zhou et al. [27] works for smooth specimens. The smooth working surface is coated with lacquer and paraffin wax with an opening. Then the sample is immersed in an acidic FeCl₃ solution with applied currents. Anodic dissolution occurs on the exposed region in the specimen. The location of the pit becomes the opening of the coating.

#### 2.4.2 Potentiostatic method

A potentiostatic method can be applied for controlling corrosion generation over stainless steel. The technique uses a counter electrode and a working electrode. Polarisation of the sample (stainless steel) induces pitting corrosion. Once the pits grow, polarisation is performed below the pitting corrosion potential. This is the method used to control the size of the corrosion [28]. The metal behaviour between these potential ranges can be defined as imperfect passivation, where no new pit can be initiated and the existing pits can only grow to more than a certain depth [26], [28].
2.4.3 **Galvanostatic method**

The galvanostatic method employs an electric current to induce corrosion. The amount of implemented current can be used to control the growth of the pits. The current induces anodic corrosion over the metal plate. Controlling of the current flowing in the electrode decides the generation rate [29].

2.4.4 **Scanning electrochemical microscopy with probe**

The controlled pitting generation method used in this work differed from the electrochemical methods mentioned before. Scanning electrochemical microscopy (SECM) is a method that involves a potentiostat and a potential programmer, a current amplifier, a piezoelectric positioner and controller, and a computer [30]. A variation is found in Fregonese et al. [20]. This method is based on the local generation of aggressive ions by the reduction of the medium. The set-up consists of a working electrode, an auxiliary electrode, a reference electrode (usually SCE), a micro-capillary, a syringe pump, a potentiostat and a PC. The solution in the micro-capillary can be held because of the capillary phenomenon. A glass micro-capillary is placed next to an electrode with the syringe pump, which controls the injection of the chloride ions and maintains a nearly constant chloride concentration, in order to study the pit propagation process [13]. With the help of a potentiostat, the sample is first polarised to positive to be passivated and then the chloride ions are injected for pit initiation. A motor positioning system moves the XYZ platform in three directions.

2.5 **Non-Destructive Test**

For most industries, an increase in productivity is of utmost importance and any optimisation in equipment replacement represents a possibility to increase productivity. For instance, in industrial companies such as oil and gas, aerospace, nuclear and so forth [3], [4], the priority is to maintain the equipment in good structural condition. Good structural condition will decrease the potential for damage to the environment and workers, and as a result, a possible increase in earnings [1], [2]. A periodic inspection plays a significant role with regards to the lifetime of any component in the industry. For this inspection, most industries have two potential approaches: destructive and non-destructive tests.
Destructive tests are rarely a viable choice for the industry unless complete characterisation is required. This type of inspection is a destructive procedure, e.g. changing the physical parameters of the tested piece and, almost all of the time ending in the destruction of the piece. Since this method is highly intrusive, it is almost the last option for the industry. In contrast, non-destructive tests come into sight, for almost every type of industry. The American Society for Nondestructive Testing (ASNT) defines:

“Nondestructive testing (NDT) is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system” [31].

For example, the components of the tested piece can still be in operation during or after the inspection. NDT offers several methods to inspect the physical properties of the materials, assess the quality of the materials and find possible discontinuities. The main difference between these methods lies in the injected energy sources and the interactions between the material and the energy [9].

NDT researchers have developed a number of methods in past decades. NDT methods are classified based on the interactions of the energy source and the object being the tested. The main methods are: Acoustic Emission Testing (AET), Electromagnetic Testing (ET), Laser Testing Methods (LTM), Leak Testing (LT), Magnetic Flux Leakage (MFL), Liquid Penetrant Testing (LPT), Magnetic Particle Testing (MPT), Neutron Radiographic Testing (NRT), Radiographic Testing (RT), Thermal/Infrared Testing (IR), Ultrasonic Testing (UT), Vibration Analysis (VA) and Visual Testing (VT) [9].

The following sections provide a brief description of the most common NDT techniques used in the industry for corrosion detection, e.g. Radiography Technique (RT), Ultrasonic Technique (UT), Magnetic Flux Leakage (MFL) and Thermography.

2.5.1 Acoustic Emission Testing

Acoustic Emission (AE) is a versatile NDT method. It can be used in structural inspection, e.g. bridges, concrete structures in loading testing, corrosion detection and
others applications [32]–[35]. The materials that can be tested using AET are extensive, these include, ceramics, concrete, metals, wood and compound materials [9].

AE testing is based on the detection of sound produced by an alteration in the testing material [36]. The acoustic phenomenon occurs when a source, the material under investigation, creates a rapid release of energy, usually due to a defect in the testing material. The acoustic system monitors and detects these acoustic waves. Defects generate waves of different types, identifying and categorizing these waves provides insight into, and knowledge of, the possible flaw [9]. The most common waves found in the AE testing are longitudinal waves, transverse waves and reflected waves [37]. In addition, a load can be applied to the tested material to produce the acoustic phenomenon by stressing the material. By triangulation of the AE, the source can be located.

Piezoelectric sensors are the basic elements used to receive the AET, these sensors convert the vibrations to voltages [9], [36]. In some applications e.g. bridge [33] monitoring, the testing can be carried out whilst of the object, machinery or, in this case, the bridge is in operation. A brief description of the technique is depicted in Figure 2.5.

![Figure 2.5 Schematic for acoustic emission testing](Source: [36], [38])

Fregonose et al. [20] reported a study of pitting corrosion steps using austenitic stainless steel. The initiation and propagation were studied. The dimensions of the square samples used in the experiment were 2.8 cm² and they were 2 mm thick. The instrumentation used composed of a piezoelectric transducer (R15D), a preamplification and acquisition device and a PC, which controlled the experiment. For this study, the pitting corrosion morphological parameters were 200 μm to 450 μm deep. The report concluded that the early stage pitting corrosion produced an AE signal that was too weak to discern at the initiation of pitting corrosion. Conversely, the signal became large when the pitting corrosion began to propagate. A study carried out by Darowicki, K. et al. [39], used the AE method to evaluate pitting corrosion in austenitic
steel. The report concluded that AE was not suitable for detecting pitting corrosion, as no correlation between the potentials of pitting corrosion and AE were identified.

A paper within the aviation industry is presented in [7]. This study used the digital system, a Field Programmable Gate Arrays (FPGA) chip. The AE instrument combined the advances in the digital system and the possibility of recording at high speed to analyse the signal parameters to get corrosion rates. A study to detect pitting corrosion in steel 316L was carried out by Lee et al. [40]. The corrosions were accelerated using salt water and the potentiostatic technique. The specimen dimension in the study was 200×375×2 mm. The acoustic signal was detected when a stress was applied to the sample under investigation. The pitting corrosion was estimated by calculating the amplitudes the of noise and signal.

Detection of pitting corrosion in austenitic steel SS304 using AET technique was explored by Jirarungsatian and Prateepasen [6]. The study focused on the duration and frequency of AET signals to identify and classify the corrosion type, e.g. pitting and uniform corrosion. The use of electrochemical analysis was compared with experimental measurements. Frequencies in the order of kHz were used to implement the AET. The duration of the AET signal was used to classify the source of damage. Some correlations of the AET signal were presented and used to identify and classify the damage. Further investigation on steel plates (stainless steel 304) was carried out by [16]. The study consisted of a stainless steel plate of 12mm × 35mm × 5mm (width, height, thickness) and a pit corrosion of approximately 7 mm. A corrosive solution generated the pitting corrosion. The corrosion was identified by analysing the relationship between the signal amplitude and the AE source. AET signal classification was the purpose of the study carried out by Yu and Zhou [41]. The investigation applied a machine vector to classify the AE signal generated by several AET sources. The results showed the application of genetic algorithm to classify the type of signal and distinguish the noise.

2.5.2 Ultrasonic Technique (UT)

The Ultrasonic Technique (UT) is another popular method in NDT. The injected energy is a high-frequency sound energy; an ultrasonic transducer/sensor usually comes from a piezoelectric material. Once the energy is injected, the sound pulses are fed into the material. If the sound pulses are interfered with due to cracks, voids or any other
discontinuities, an echo can be detected from the reflection of these discontinuities. The delay between a transmitted and reflected pulse can be used to calculate the position, size and other characteristics of the flaw. A simple pulse/echo configuration is presented in Figure 2.6.

![Figure 2.6 Simplified Ultrasonic Testing method (UT)](image)

**Source:** Modified from Shull, P. J. [9]

In recent years, researchers have combined eddy current with the ultrasonic, resulting in the emerge of the Electromagnetic Acoustic Transducer (EMAT) [42]. Simulations play a significant role in this technique, and a Finite Element Method (FEM) is used to predict the behaviour of the ultrasonic waves in the object. To couple the sensor/transducer, the technique requires a medium, usually gel, water, oil or another liquid [9]. The coupling medium could represent a disadvantage for this type of technique, since the type of medium could introduce some changes at the surface of the material being investigated, or even the corrosion. Ultrasonic techniques present difficulties when the crack is in the same direction of the testing waves [9]. Metallurgical structures can be evaluated by the UT technique [43].

The development of non-contact UT for corrosion detection was the purpose of the work proposed by Hernandez-Valle et al. [44]. Detection and localisation of stress corrosion using EMAT was presented on performing time-frequency analysis to inspect the object. Models were studied and the prediction of the signal shape was vital to getting a quantitative data when applying EMAT systems [45].
2.5.3 Magnetic Flux Leakage (MFL)

When pipeline inspection must be conducted, a popular inspection method is the Magnetic Flux Leakage [46], [47]. The theory behind this method is relatively straightforward [47],[48]. The material under test is magnetized or preferably saturated by a magnetic flux [47]. The magnetic flux is generated by either magnets or electromagnets [9]. When the electromagnet is selected, the magnetic field can be adjusted. Therefore, more control over the magnetic flux can be acquired. Reciprocally, the magnets, e.g. rare earth magnets are more powerful without using an extra current source.

When a magnetic flux is inside a flawless material, the magnetic flux will proceed without interference in its path from the magnetic field source [49]. Conversely, if a flaw is encountered within the path of the magnetic flux, the magnetic flux around the flaw bends or leaks from the material [9]. To detect the perturbation of the magnetic flux, two types of sensors are usually used, i.e. induction coils and a Hall-effect sensor.

When a magnetic field is placed near to an induction coil, a voltage is induced in the coil. The induced voltage will depend on the characteristics of the coil, e.g. the number of turns and the area of the coils [49]. On the other hand, the voltage in Hall effect sensors varies with regard to the absolute values of the flux density [49].

![Figure 2.7 Magnetic Flux Leakage testing](image)
Source: Modified from Wang et al., [48]

Some advances in MFL have been done. An open crack was studied by Koziel et al. [50]. The notches were simulated using FEM to predict the response. Canny edge detection was used to extract the crack edge. The notches in the surface of carbon steel plates (about 20 mm long and 1.6 mm depth) were investigated in the experiments.
In pipelines, the traditional method is MFL using smart PIGs (some cases claimed as “Pipeline Inspection Gauge”) [51], as shown in Figure 2.8. Industry uses this application when pipelines called piggable pipelines need to be inspected. Piggable means that the pipeline is big enough to introduce the inspection instrument.

![Image of PIG implementation](image.png)

Figure 2.8 Model of PIG implementation

Lijian, et al. [49] studied differential coil sensors which suppressed the background noise. Background noise cannot be completely cancelled, but it can be reduced to an acceptable level. The study also compared the responses from a Hall effect sensor and a coil sensor by analysing the signals recorded during the experiments. Yang et al. [52] reported a Pulsed Magnetic Flux Leakage sensor for corrosion detection in pipelines. The study explored the different model sensors, evaluated their responses over the thickness of a wall and retrieved quantitative corrosion data. Analytical analyses using a dipole model were employed to investigate flaws caused by corrosion in [53]. The metal in the experiment had about 10 mm × 10 mm internal defects and 1 mm × 1 mm external flaws. Tri-axial measurements were applied in the study.

### 2.5.4 Alternating Current Field Measurement

Alternating Current Field Measurement (ACFM) is another electromagnetic method. Similar to the other electromagnetic methods, this method has the advantage of being contactless [54],[55]. ACFM is based on the local injection of uniform electric current [56]. If the object is free of flaws at the moment of inspection, the injected electric current remains undisturbed. When there is a flaw in the test piece, the normal current flow is disturbed and the magnetic field will undergo an alteration, which can be
related to the crack since it is proportional to the crack density [56]. Usually, the magnetic fields in the “x” and “z” directions, i.e. Bx and Bz, are monitored.

A defect can be found almost everywhere. Structures like offshore platforms are susceptible to corrosion and other kinds of cracks. Alternating current field measurement was applied to detect underwater defects in [57]. The study involved a current-carrying coil, which generated the uniform magnetic field. The study simulated the underwater conditions using ANSYS with a working frequency of 6kHz. The simulated flaw was a semi-elliptical crack with a length and depth of 10 mm and 4 mm respectively. A seawater environment simulation was repeated to apply statistic quantification. The study concluded with relatively high accuracy detection. Larger coils were used by M. Smith and C. Laenen in magnetic induction [58]. Detection of pipe crack was the aim of the study [59]. A Finite Element Method (FEM) model with a coaxial excitation coil and rectangular cracks was simulated in ANSYS at 6kHz. The size of the crack was around 0.004 m crack. Wei et al. [60] tested a U-shape probe design using the ACFM system, a 6kHz frequency was simulated and selected as the working frequency. The set up included a carbon steel plate with a crack using a U-shaped inducing probe and a rectangular alternating current driven by a coil with a ferrite magnetic core. A semi-elliptical crack with a dimension of around 8 mm was investigated. The result showed a correlation between the dimension and the crack shape with an order of 10% error.

![Figure 2.9 a) Simulation of signal produced in ACFM, b) a proposed instrument of ACFM. Source: [60]](image)
2.5.5 Radiography Technique (RT)

Radiology testing is based on the interaction of the radiation beam with the object under investigation. The attenuation of the radiation is proportional to both the material density and thickness. The radiation source could be X-rays or gamma rays. A gamma ray is produced by radioactive atoms, e.g. Iridium (Ir-192), Cesium (Se-75) or Cobalt (Co-50). An X-ray is generated by electrical means (generator tubes), which provides the opportunity of varying the intensity of the beam as well as the resolution of detection. By putting the object between the source of energy and the recording medium, the projection of the beam can be recorded using a film or by digital means. A schematic for the RT method is depicted in Figure 2.10.

A cross-sectional image of the object under testing can be reconstructed, by interposing the object between the radiation and the recorded media. This type of testing is used to inspect the internal structural variation in welding, flaws, corrosion and any other discontinuity in a material. Computed tomography can be used to reconstruct a 3D image by recording the interaction of the radiation at different angles. The major drawback of this technique is that it presents a hazard with regards to handling the radioactive waste. Highly qualified technicians are required to handle the process with strictly regulated equipment.

![Radiographic testing representation](image)

**Figure 2.10 Radiographic testing representation**
Source: [9]

The inspection of stainless steel containers used for nuclear waste was the purpose of the research by Ghahari et al. [26]. The implementation of the radiography
technique in situ was the methodology to assess the object. The synchrotron X-ray imaging method was compared with a 2D finite element modelling. Detection of 25 μm pits was monitored during the initialisation and growth. The technique performed the monitoring and identification with high resolution and provided complete and accurate information on the material under investigation. The major drawback using this method was the high cost.

2.5.6 Thermography

Thermography is a technique that measures the distribution of heat in the object [61]. Thermography systems are widely used for different applications within different areas, e.g. military, NDT, medicine and others. The first reported uses were for military purposes. The systems were used to detect the human body. Recent advances in infrared cameras facilitate increasing the uses of this methodology. The thermal images are presented on a screen indicating the distribution of temperatures in a grey scale or a colour scale.

The classification of thermal techniques depends on the heating source. For example, the classification type for inspection of an object at ambient temperature is applied to detect flaws or a human body. In NDT, the inspection gives qualitative results. The second classification of the technique occurs when the object under investigation is heated using an artificial source. In the second category, the thermal technique receives greater attention with the combination of other techniques, e.g. thermography combined eddy current, ultrasound, or any other heating source. This technique combination allows for the extraction of quantitative information about flaws. A schematic of the testing process is depicted in Figure 2.11.
Hidden corrosion detection using Infrared (IR) thermography was the purpose of the study conducted by S. Marinetti and V. Vavilov [64]. 2D and 3D thermal simulations were presented. The Fourier transformation in time domain was the methodology applied and 40 mm diameter corrosion flaws were identified. The analysis using flash and a square-pulse heating procedure was implemented. Insulation paint hid the corrosion. A combination of thermography and eddy current was a variation of the technique presented in [65], [66]. The research demonstrated angular defect inspection and quantification using thermography and finite element analysis (FEA) simulation. The pulsed eddy current was used for heating the object under investigation using magnetic induction [67]. A combination of ultrasound as the inductive thermal source was presented by Plum and Ummenhofer [68]. A steel plate was the object under investigation. The ultrasonic transducer was used to inject waves. The generation of heat was recorded by an infrared camera. The inclusion of microwave methods is also available with the thermography technique, which was carried out by Pieper et al. [69].

2.5.7 Terahertz (THz) techniques

These techniques involve the generation of electromagnetic waves from 0.1THz to 10 THz [70], [71], [72]. The first use of these techniques was in the detection of hidden objects [70]. The THz wave penetrates the object and allows for analysis of the changes in the waves to generate a reconstruction of the object. The imaging system consists of an emitter as the source of the waves, detection devices usually an antenna, pre-process steps and communication with a computer [73]. Two variations of these types of systems can be found, i.e. a THz pulsed system and a continuous THz system.
The inspection has better results on a dry material. This opens the gate for the inspection of a metallic object, searching for discontinuities or any flaws on the surface [73].

Despite the application of THz in NDT, other areas have used the technique for explosives detection, chemical object detection and even in biology. The THz technique was used by Anastasi and Madaras [74] to detect hidden corrosion. By using a system from Picomatrix, Inc, the signals were generated and detected by optical excitation. Aluminium samples were painted with different layers so that different thicknesses were analysed. The Picometrix systems was also used to investigate the detection of hidden defects in the work of Duling and Zimdars [72].

### 2.6 Conclusions

The chapter presented the corrosion problem, focusing on pitting corrosion. This type of corrosion is considered to be one of the most dangerous types of corrosion. The dimensions of pitting corrosion represent a challenge in detection because the corrosion can appear under coating material or under paint protection in pipes, tanks or other metal. An example of a disaster induced by a pit was presented in this chapter; the reason behind pitting corrosion being considered dangerous is because it can promote other types of corrosion or if the corrosion is hidden, it can grow and result in severe metal loss, leading a failure of the structure. The importance of detecting pitting corrosion does not end in the prevention, it can also be applied to monitor the pit growth and can be used in studies on the evolution of the corrosion, which is usually a variable studied in localised pit generation presented in the section of controlled pitting generation.

NDT techniques present a range of methods with differences, advantages and disadvantages. Due to increasing demand from the industries such as aerospace, nuclear, medical and oil/gas, researchers continue to develop techniques for new applications and tackle existing problems within these industries. This chapter reviewed a number of popular NDT methods and a newly developed technique, i.e. the Terahertz technique for corrosion detection. Each of the presented methods have their advantages and disadvantages. As an example, the radiographic method possesses high fidelity in characterizing the test piece under investigation; but at the same time, it presents a
major disadvantage associated with its ionising hazardous nature. Most of the methods show different sensitivity to corrosion detection, but are mainly oriented to uniform corrosion. Pitting corrosion presents a challenge due to its small size at the initiation stage and the growth stage. Pitting corrosion has been studied in the laboratory. The detectable size in AE is in the order of a few millimetres. However, pitting corrosion smaller than this detectable size presents difficulties due to noise from AE emission. Other methods presented in this chapter show similar range of detection, i.e. they are all in the order of a few millimetres. Table 2.2 presents a comparison of the techniques mentioned through this chapter. The aim of this thesis was to design an EM instrument that could detect pits below mm dimensions in real time.
Table 2.2 NDT Advantages and limitations of the NDT techniques presented through the chapter.

<table>
<thead>
<tr>
<th>NDT METHOD</th>
<th>APPLICATION</th>
<th>ADVANTAGES</th>
<th>LIMITATIONS</th>
<th>INSPECTION MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Emission (AE)</td>
<td>AE is applied to a variety of applications like: weld monitoring, bridge connections and aerospace. The test detects cracks due to fatigue, metal corrosion.</td>
<td>The testing can be done during the operation of the material under investigation, which means a usual load is applied. A few sensors are needed for the test, and are not required at both sides (surface and bottom). The sensor can be fixed during the test.</td>
<td>The complexity of reproducible signal source. The need to compare the results with others method. The magnitude of the signal generated by a defect is usually much smaller than a ultrasonic signal, which means that sensor and systems require more sensitivity.</td>
<td>Metals, Ceramics, Polymers, Composites (including those with metal, ceramic, and polymer matrices and a wide variety of reinforcement materials), Wood, Concrete, rocks and geologic materials.</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>If the condition of sound transmission and surface finish are good and the object shape is not complex, it can be used for most materials.</td>
<td>Sensitive to both surface and sub-surface defects, good penetration depth.</td>
<td>Requires a coupling fluid, surface must be accessible, rough and irregular shaped materials are difficult.</td>
<td>Metals in general &amp; composite.</td>
</tr>
<tr>
<td>NDT METHOD</td>
<td>APPLICATION</td>
<td>ADVANTAGES</td>
<td>LIMITATIONS</td>
<td>INSPECTION MATERIAL</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Magnetic Flux Leakage (MFL)</td>
<td>Pipelines and many others.</td>
<td>Versatile and robust for examining the geometry of metal loss. General wall loss, pitting.</td>
<td>Unable to detect flaws parallel to the magnetic field e.g. axial slots.</td>
<td>Ferromagnetic.</td>
</tr>
<tr>
<td>Radiography</td>
<td>Can be used for almost any material, shapes and structure manufactured or in-service.</td>
<td>Capable of detecting both surface and subsurface defects, provides a permanent record of inspection. Greater penetration power, less scatter, no electrical or water supplies needed.</td>
<td>Delamination and planar cracks are difficult to detect; the material must have two-side accessibility. Higher energy level requirement, poorer quality radiographs, longer exposure time</td>
<td>Virtually for all materials.</td>
</tr>
<tr>
<td>Thermography</td>
<td>Delamination, disbond, voids and inclusions. Emissivity, thermal conductivity, electrical conductivity and magnetic permeability.</td>
<td>Fast and cost effective technique for thermal analysis over relatively large area.</td>
<td>Sensitive to material emissivity, affected by probe-sample proximity.</td>
<td>Metals in general &amp; composites.</td>
</tr>
<tr>
<td>NDT METHOD</td>
<td>APPLICATION</td>
<td>ADVANTAGES</td>
<td>LIMITATIONS</td>
<td>INSPECTION MATERIAL</td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>------------</td>
<td>-------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Alternating Current Field Measurement (ACFM)</td>
<td>Coil dimension and geometry, frequency of operation.</td>
<td>Defect sizing without calibration, less affected by probe lift-off effect.</td>
<td>Lower sensitivity to shallow defects at normal operating frequencies (5 KHz), tight geometries, edges and branched defects are difficult to inspect</td>
<td>Ferromagnetic and non-ferromagnetic.</td>
</tr>
</tbody>
</table>
Chapter 3 Eddy Current Testing Method

3.1 Introduction

This chapter presents an overview of the eddy current testing technique. It deals with the brief history of the method, the principles and some variables in eddy current testing. The eddy current method has been established as a popular and effective approach for the inspection of conductive materials [75]. The applications of EC inspection appeared around the 1920’s in the metal industry [9], [66]. The modern era of EC testing began approximately in the 1950’s and introduced some new developments, an example being the complex impedance plane, i.e. the graphic representation of the inductive component reactance (representing energy storage) against resistance (representing energy loss) [76].

An Alternating Current (AC) in a coil generates a magnetic field. The interaction between the conductive material (object under investigation) and the magnetic field represents the basic eddy current inspection process. Detection and characterisation of a flaw are achieved by monitoring the change in the probe impedance. The impedance can be calculated from the induced voltage by the pickup coil [77]. The basic instrumentation used for this method includes an AC signal generator, the coil probes, and a device to measure the impedance changes of the coil probes. This chapter presents the theory behind the Eddy Current Method.

3.2 Brief history

The study of eddy currents can be traced back to the start 19th century (1830) to the work of J. B Foucault [9]. Eddy currents as one of the NDT methods was first used in 1879, by D. E. Hughes for sorting metals [10], [51]. Later in the early fifties, Förster published work on the theoretical and practical aspects of the eddy current technique, which was similar to the eddy current technique we know nowadays, though it had some limitations with regards to the instrumentation. Another important advance in the
study of eddy currents as a non-destructive testing method was carried out by Libby; his work treated the coil as a transformer [50].

From the early 1960’s further progress was reported by Dodd and Deeds et al. [51] on the analytical solutions of several eddy current problems. The derivation of the eddy current diffusion equation based on the magnetic vector potential from Maxwell’s equations was presented. A number of assumptions such as sinusoidal currents excitation, linear, isotropic media with axisymmetric geometry were made.

### 3.3 Inspection principles

Eddy current inspection is one of several NDT methods that uses the principle of “electromagnetism” for examination. Several other methods, such as Remote Field Testing (RFT), Flux Leakage and Barkhausen Noise, also use this principle.

Eddy currents are created by electromagnetic induction. When alternating current is applied to a conductor, such as copper wire, a magnetic field develops in and around the conductor. If another electrical conductor is brought into proximity to this changing magnetic field, current will be induced in this second conductor. Eddy currents are induced electrical currents that flow in a circular path. They get their name from “eddies” that are formed when a liquid or gas flows in a circular path around obstacles when conditions are right.

![Figure 3.1 Eddy current technique schematic](image)

Source: modified from [9]

#### 3.3.1 Maxwell’s equations for time harmonics

There are four equations that relate the electric and magnetic fields, and their interaction with the medium around them [9]. The Maxwell’s equations are extremely
important in engineering. The four equations are a combination of Ampere’s law, Faraday’s law and Gauss’ law [81], [82]. When eddy currents must be studied, Maxwell’s equations are applied. From Faraday’s law, if a time harmonic magnetic field is applied, it generates a voltage potential $E$. If a conductor is then approached, $j_{eddy} = \sigma E$ [82] can be used to calculate the current density. For a time harmonic study, Maxwell’s equations are defined as:

$$\nabla \times \mathbf{H} = (\sigma + j\omega\varepsilon)\mathbf{E}$$  \hspace{1cm} (3.1)

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}$$  \hspace{1cm} (3.2)

$$\nabla \cdot \mathbf{D} = \rho$$  \hspace{1cm} (3.3)

$$\nabla \cdot \mathbf{B} = 0$$  \hspace{1cm} (3.4)

With constitutive relations:

$$\mathbf{D} = \varepsilon\mathbf{E}$$  \hspace{1cm} (3.5)

$$\mathbf{B} = \mu\mathbf{H}$$  \hspace{1cm} (3.6)

$$\mathbf{J} = \sigma\mathbf{E}$$  \hspace{1cm} (3.7)

By using the constitutive relations and a quasi-static electromagnetic field, the eddy current and the interactions of the mediums can be analysed [9]. Using a conductive material, with some assumptions such as linearity, and being isotropic, the eddy current is generally studied at frequencies below 10 MHz, where the displacement current is negligible [78].

### 3.3.1.1 Self inductance

If there is current flowing in a conductor, a magnetic field will be produced [9], [81]. The magnetic flux lines will have a concentric path in a straight conductor. In a coil, the magnetic flux lines will interact with the magnetic flux in each turn in the coil, and the final strength of the magnetic field will be a function of the number of turns in the coil [76]. The interaction with each turn can be considered as an induction in the coil, so self-inductance is a specific property of a coil in which a voltage is induced through itself. Self-inductance can be considered as a special case of mutual inductance [83]. A definition of self-inductance can be represented as:
Where \( L \) is self-inductance, \( N \) is the number of turns of a coil, \( I \) is the current flowing in the coil and \( \phi \) is the magnetic flux linkage. Another definition is given by Cheng [83],

\[
L = N \frac{\phi}{I}
\]  

\[ (3.8) \] [76]

\[ (3.9) \]

The latest formulation is useful when the coil is used as the excitation and also as the detector or receiver coil in eddy current testing.

3.3.1.2 Mutual inductance

When more than one coil is used in a eddy current testing probes, the interaction between the coils can be explained using mutual induction [9], [83]. In eddy current testing, we can find different arrangements of the probe, and the mutual inductance can be used to analyse the field and reflected field [76]. The mutual inductance is usually defined as \( L_M \).

3.3.1.3 Coil impedance

In circuit theory, the impedance is in opposition to the current due to an applied voltage [81]. The eddy current testing probe can be modelled using a transformer [76]. The transformer model can be characterized using the impedance. The impedance is defined as:

\[
Z = \frac{V}{I} = R + j\omega L
\]  

\[ (3.9) \]

Where \( R \) is the resistance, \( L \) is inductance and \( j = \sqrt{-1} \). In eddy current testing, the voltage and current in the coil are measured to calculate the impedance of the coil [9], [76].

Generally, the impedance can be used to represent the results of the scanning object under investigation by phasor notation, which has the following relation for the impedance.

\[
Z = \sqrt{R^2 + X_L^2}
\]  

\[ (3.10) \]

The phase angle can be calculated using
3.4 Variables and effects in eddy current testing

3.4.1 Lift-off effect

Eddy current testing could be considered a contactless test [66]. But in some cases, the probe being in contact with the test piece is desirable during the test. During the test, some variations could exist between the surface of the probe and the surface of the test piece. This happens due to different factors such as the coating and the irregular shapes in the test piece [84], [85]. This distance between the coil and the surface object under investigation is called lift-off [9] and is a major drawback during tests. The lift-off in some cases hides the possible defects in the test piece. For that reason, lift-off is considered as noise, and causes difficulties for flaw identification and quantisation [84], [85].

Some studies to compensate and mitigate the lift-off effect have been carried out in [31]. A Finite Element (FE) simulation was performed, the simulation studied the effects of the lift-off and tilt measurements in a sensor. An investigation to reduce or compensate the lift-off effect was presented in [27] which proposed using two signals to reduce the lift-off. One signal was used as a reference in free space, and the other signal was the scanning object signal, and the differential signal between them was then computed. This test was performed in aluminium.

Analytical analysis of the lift-off by describing the inductance change and the improvements in a double air coil were studied in [87]. The analysis was compared with a sensor coil with the same characteristics in a computational simulation. To compensate for this lift-off effect, Yin et al. [88] published a research finding on an analytical model based on multi-frequency excitation and coil design aimed at the reduction of this effect. Theodoulidis et al. [89] presented an analytical model of wobble in a heat exchanger tube inspection.

3.4.2 Edge effect

Eddy currents flow in a circular pattern [9]. During the test, if the probe is near to an edge of the test piece, a phenomenon called “edge effect” emerges [76], [85]. This
effect happens when the drive coil is near the end of the test piece. The magnetic field and the current flow become distorted. This distortion occurs because the eddy current can no longer flow in circular pattern. To avoid this effect, two approaches can be adopted: 1) the inspection area must be decreased in order to avoid the edges. In this approach, the edges must be at least three times the diameter of the drive coil [76], [90]. 2) The drive coil diameter can be reduced; but this will impact the response and the induction in the test piece. The effect can be represented as in Figure 3.2. Theodoulidis et al. [91] proposed a model to calculate the quasi-static EM field of a coil probe in the edge of a conductive metal block.

![Diagram](Image)

Figure 3.2 Current flow distorted by edge effect. a) Shows the coil probe generating the magnetic as B. b) The distortion of the magnetic flux $J_x$. Source: Modified from [9]

### 3.4.3 Skin effect

In eddy current testing, when the probe approaches the test piece eddy currents are induced. The distribution of the eddy current is [9] on the surface of and inside the material. To determine how deep the eddy current could be, the skin depth is studied. Skin depth explains how the eddy current density decays as the current penetrates the
test piece [92], [93]. To extract the information from the eddy current testing, the eddy current needs to have some density. The eddy current density decreases with the increment of penetration depth. The standard skin depth is called the penetration of eddy current when some information can still be extracted, and is defined as $3\delta$ [9], [76].

Working frequency becomes a very important parameter in eddy current testing, in combination with skin depth. The frequency testing can be adjusted to generate eddy current, which penetrates as much as possible in order to detect subsurface flaws. Skin depth characterises the deduction of eddy current penetration due to the electromagnetic properties of the test piece. Thus, the combination of electrical conductivity, magnetic permeability and working frequency can be used to deduce the standard depth penetration, which is defined as $\delta$.

$$\delta = \frac{1}{\sqrt{\pi \mu \sigma f}}$$  \hspace{1cm} (3.12)

Figure 3.3 depicts the electromagnetic field penetration in pure aluminium using the skin depth theory. An example of different materials at different frequencies is presented in Table 3.1. From the table, it is easy to see that the lower the frequency, the deeper the penetration of eddy current, conversely for higher frequencies. Deep penetration is desirable when a subsurface inspection is carried out and when a characterisation of the flaws needs to be done as in [93].

![Skin depth penetration, as a factor of working frequencies of 200 Hz (red) and 10 kHz (blue)](source: [76])
Table 3.1 Standard depth penetration in different materials
*IACS: The International Annealed Copper Standard
Source: [94]

<table>
<thead>
<tr>
<th>METAL</th>
<th>CONDUC. ( \sigma ) %IACS</th>
<th>RESIS. ( \rho ) (( \Omega \cdot \text{m} ))</th>
<th>PER. ( \mu ) (H/m)</th>
<th>1kHz</th>
<th>4kHz</th>
<th>16kHz</th>
<th>65kHz</th>
<th>256kHz</th>
<th>1MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>100</td>
<td>1.7</td>
<td>1</td>
<td>0.082</td>
<td>0.041</td>
<td>0.021</td>
<td>0.01</td>
<td>0.005</td>
<td>0.0026</td>
</tr>
<tr>
<td>1061 T-6</td>
<td>42</td>
<td>4.1</td>
<td>1</td>
<td>0.126</td>
<td>0.063</td>
<td>0.032</td>
<td>0.016</td>
<td>0.008</td>
<td>0.004</td>
</tr>
<tr>
<td>7075 T-6</td>
<td>33</td>
<td>5.3</td>
<td>1</td>
<td>0.144</td>
<td>0.072</td>
<td>0.036</td>
<td>0.018</td>
<td>0.009</td>
<td>0.0046</td>
</tr>
<tr>
<td>Magnesium</td>
<td>37</td>
<td>4.6</td>
<td>1</td>
<td>0.134</td>
<td>0.067</td>
<td>0.034</td>
<td>0.017</td>
<td>0.008</td>
<td>0.0042</td>
</tr>
<tr>
<td>Lead</td>
<td>7.8</td>
<td>22</td>
<td>1</td>
<td>0.292</td>
<td>0.146</td>
<td>0.073</td>
<td>0.37</td>
<td>0.018</td>
<td>0.0092</td>
</tr>
<tr>
<td>Uranium</td>
<td>6</td>
<td>29</td>
<td>1</td>
<td>0.334</td>
<td>0.167</td>
<td>0.084</td>
<td>0.042</td>
<td>0.021</td>
<td>0.0106</td>
</tr>
<tr>
<td>Zirconium</td>
<td>3.4</td>
<td>70</td>
<td>1.02</td>
<td>0.516</td>
<td>0.258</td>
<td>0.129</td>
<td>0.065</td>
<td>0.032</td>
<td>0.0164</td>
</tr>
<tr>
<td>Steel</td>
<td>2.9</td>
<td>60</td>
<td>750</td>
<td>0.019</td>
<td>0.0095</td>
<td>0.0048</td>
<td>0.0024</td>
<td>0.0012</td>
<td>0.006</td>
</tr>
<tr>
<td>Cast steel</td>
<td>10.7</td>
<td>16</td>
<td>175</td>
<td>0.018</td>
<td>0.0089</td>
<td>0.0044</td>
<td>0.0022</td>
<td>0.0011</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

3.5 Modelling approaches

Models in engineering and physics are frequently used to acquire insight into a specific object. The eddy current technique is not excluded from this modelling approach to understand the complex interactions and phenomena during the test. The purpose of the modelling done in relation to eddy current testing is to understand the interaction of the eddy current with regards to a particular problem. By modelling the eddy current, a researcher can solve the inverse problem and simulate very particular situations. The simulation allows predicting the interaction of eddy currents with flaws that can be encountered in real life problems. The simulation also includes probe design, and most importantly, an optimisation in order to get the best response when a defect is encountered.

The modelling approaches are divided in two branches: a) analytical approaches and b) numerical approaches. In both branches, the solution is based on Maxwell’s equations. Once a model is created and solved, a comparison with the real experimental tests can be carried out to determine whether the modelling approximation is comparable and within an appropriate margin to real experiments. The analytical and numerical approaches are respectively presented in the following subsections.

3.5.1 Analytical models

Analytical models used in NDT are based on Maxwell’s equations. The resulting analytical approach uses the magnetic vector potential \( (A) \) [95], [96] which was solved by Dodd and Deeds and is a classical solution of the eddy current analytical solution for
NDT. As in other analytical solutions, some assumptions have been made. For example, the problem remains axisymmetric, isotropic and the medium remains homogeneous [78], [83].

The differential equation for vector $A$ is the tool used to calculate the magnetic quantities along with other phenomena during the test. The geometry of the coil is assumed to have a rectangular section and it be driven by sinusoidal currents; boundary conditions are included. Therefore, the problem is divided into several regions, and in each region vector $A$ is calculated. The general differential equation for vector potential $A$ is defined as

$$\frac{\partial^2 A}{\partial r^2} + r^{-1} \frac{\partial A}{\partial r} + \frac{\partial^2 A}{\partial z^2} - \frac{A}{r^2} - j \omega \mu \sigma A = 0 \quad (3.13)$$

Dodd and Deeds presented solutions based on different setups. The solution depends on the arrangement of the coil in relation to the test piece. For the scope of this work two setups were explored, a) a planar configuration which consisted of a coil over a planar conductive surface and b) a cylindrical conductor encircled by a rectangular cross-section coil.

### 3.5.1.1 Planar configuration

The eddy current problem for the planar configuration is depicted in Figure 3.4. The boundary problem was taken into account. The problem was divided into four different regions. The region II was the region between the drive coil and the conductor (lift-off). The regions III and IV were the layered conductors.

![Figure 3.4 Planar eddy-current problem](modified from [80])
The “closed form” is a vector potential based formulation proposed by Dodd and Deeds [80], [97]. The planar problem was divided into four regions. The vector potential for each region is presented in (3.14)-(3.17):

\[
A^{(1)}(r, z) = \frac{\mu i_0}{2} \int_0^\infty \frac{1}{\alpha^3} I(r_2, r_1) J_1(\alpha r) e^{-\alpha z} \left\{ e^{(\alpha t_2)} - e^{(\alpha t_1)} - e^{-\alpha t_1} \right\} d\alpha
\]

(3.14)

\[
A^{(11)}(r, z) = \frac{\mu i_0}{2} \int_0^\infty \frac{1}{\alpha^3} I(r_2, r_1) J_1(\alpha r)(e^{-\alpha t_1} - e^{-\alpha t_2}) \times \left\{ \frac{[(\alpha + \alpha_1)(\alpha_1 - \alpha_2) + (\alpha - \alpha_1)(\alpha_2 + \alpha_1)e^{2\alpha_1 c}]}{[(\alpha - \alpha_1)(\alpha_1 - \alpha_2) + (\alpha + \alpha_1)(\alpha_2 + \alpha_1)e^{2\alpha_1 c}]} e^{-\alpha z} \right\} d\alpha
\]

(3.15)

\[
A^{(12)}(r, z) = \frac{\mu i_0}{2} \int_0^\infty \frac{1}{\alpha^3} I(r_2, r_1) J_1(\alpha r)(e^{-\alpha t_1} - e^{-\alpha t_2}) \times \left\{ \frac{\alpha (\alpha_2 + \alpha_1)e^{2\alpha_1 c} e^{\alpha_1 z} + \alpha(\alpha_2 - \alpha_1)e^{-\alpha_1 z}}{[(\alpha - \alpha_1)(\alpha_1 - \alpha_2) + (\alpha + \alpha_1)(\alpha_2 + \alpha_1)e^{2\alpha_1 c}]} \right\} d\alpha
\]

(3.16)

\[
A^{(14)}(r, z) = \frac{\mu i_0}{2} \int_0^\infty \frac{1}{\alpha^3} I(r_2, r_1) J_1(\alpha r)(e^{-\alpha t_1} - e^{-\alpha t_2}) \times \left\{ \frac{2\alpha \alpha_1 e^{(\alpha_2 + \alpha_1) e^{\alpha_1 z}}}{[(\alpha - \alpha_1)(\alpha_1 - \alpha_2) + (\alpha + \alpha_1)(\alpha_2 + \alpha_1)e^{2\alpha_1 c}]} \right\} d\alpha
\]

(3.17)

The expression for the electric field is calculated using cylindrical coordinates, and using the magnetic vector \( A \) is defined as:

\[
E_\phi(r, z) = -j\omega A^{(r)}
\]

(3.18)

where:

\( \alpha \rightarrow \) integration variable;

\( \alpha_n \rightarrow \sqrt{\alpha^2 + j\omega \sigma_n \mu_n} \)

\( \omega \rightarrow \) angular frequency of excitation current;

\( \mu_n \rightarrow \) the permeability of the conducting plate;

\( \mu_0 \rightarrow \) the permeability of free space;
\[ \sigma \rightarrow \text{the conductivity of the conducting plate;} \]
\[ r_1 \text{ and } r_2 \rightarrow \text{inner and outer radius of the probe respectively;} \]
\[ \ell_1 \text{ and } \ell_2 \rightarrow \text{height of the bottom and top of the probe;} \]
\[ c \rightarrow \text{the thickness of the plate;} \]
\[ J_1(x) \rightarrow \text{a first-order Bessel function of the first kind.} \]
\[ A^{(*)} \rightarrow \text{vector potential in a desired region} \]

3.5.1.2 Cylindrical configuration

The eddy current problem is depicted in the Figure 3.5. Dodd and Deeds [80] divided the problem into several regions and considered the interaction amongst the different regions for the solution of the problem. The “closed form” is a vector potential based formulation, as shown in the equation (3.19) – (3.22) from the work of Dodd and Deeds [80], [97]. The formulation of the vector potential in each region of the problem is depicted in Figure 3.5.

![Figure 3.5 Cylindrical eddy-current problem](image)

Source: modified from [80]

\[
A^{(1)}(r, z - z_0) = \frac{\mu l}{\pi} \int_0^\infty \frac{r_0 K_1(\alpha r_0)}{ab} \frac{\alpha \ell_1(\alpha z_0 \cos(z - z_0))}{D} d\alpha
\] (3.19)
\[ A^{(i)}(r, z - z_0) = \frac{\mu I}{\pi} \int_0^\infty r_0 K_1(\alpha r_0) \left\{ [\alpha_2 I_1(\alpha_1 a) I_0(\alpha_2 a) - \alpha_1 I_1(\alpha_2 a) I_0(\alpha_1 a)] K_1(\alpha_2 r) + [\alpha_2 K_0(\alpha_2 a) I_1(\alpha_1 a) + \alpha_1 K_1(\alpha_2 a) I_0(\alpha_1 a)] I_1(\alpha_2 r) \right\} \cos \alpha(z - z_0) \, d\alpha \]

\[ A^{(ii)}(r, z - z_0) = \frac{\mu I}{\pi} \int_0^\infty r_0 K_1(\alpha r_0) \left\{ I_1(\alpha r) \right. \]

\[ \left. - \left[ \frac{K_1(\alpha_2 b)}{bDK_1(ab)} [\alpha_2 I_1(\alpha_1 a) I_0(\alpha_2 a) - \alpha_1 I_1(\alpha_2 a) I_0(\alpha_1 a)] K_1(\alpha_2 b) + \frac{I_1(\alpha b)}{K_1(ab)} K_1(\alpha r_0) \right] \cos \alpha(z - z_0) \, d\alpha \right\} \]

\[ A^{(iii)}(r, z - z_0) = \frac{\mu I}{\pi} \int_0^\infty r_0 K_1(\alpha r_0) K_1(\alpha r) \left\{ \frac{K_1(\alpha_2 b) [\alpha_2 I_1(\alpha_1 a) I_0(\alpha_2 a) - \alpha_1 I_1(\alpha_2 a) I_0(\alpha_1 a)]}{K_1(ab) bD} \right. \]

\[ \left. + \frac{I_1(\alpha b)}{K_1(ab) bD} [\alpha_2 I_1(\alpha_1 a) K_0(\alpha_2 a) + \alpha_1 K_1(\alpha_2 a) I_0(\alpha_1 a)] - \frac{I_1(\alpha b)}{K_1(ab)} \right\} \cos \alpha(z - z_0) \, d\alpha \]

where \( D \) is defined as:

\[ D = [\alpha_2 K_0(\alpha_2 \cdot \alpha) K_1(ab) - \alpha K_0(ab) K_1(\alpha_2 \cdot b)] [\alpha_1 I_1(\alpha_2 a) I_0(\alpha_1 a) - \alpha_2 I_1(\alpha_1 a) I_0(\alpha_2 a)] \]

\[ + [\alpha_2 K_0(\alpha_2 a) I_1(\alpha_1 a) - \alpha_1 K_1(\alpha_2 a) I_0(\alpha_1 a)] [\alpha I_1(\alpha_2 b) K_0(ab) + \alpha_2 I_0(\alpha_2 b) K_1(ab)] \]

where:

\( \alpha \rightarrow \) integration variable;
\[ r_o \rightarrow \text{mean coil radius}; \]
\[ \alpha_n \rightarrow \sqrt{\alpha^2 + j\omega\sigma_n\mu_n} \]
\[ \omega \rightarrow \text{angular frequency of excitation current}; \]
\[ \mu \rightarrow \text{the permeability of the conducting plate}; \]
\[ \mu_0 \rightarrow \text{the permeability of free space}; \]
\[ \sigma \rightarrow \text{the conductivity of the conducting plate}; \]
\[ r_1 \text{ and } r_2 \rightarrow \text{inner and outer radius of the probe respectively}; \]
\[ z_0 \text{ and } z \rightarrow \text{height of the bottom and top of the probe}; \]
\[ a \text{ and } b \rightarrow \text{inner and outer material radii}; \]
\[ I \rightarrow \text{current density.} \]
\[ K_n(x) \rightarrow \text{a second-order Bessel function of the kind defined in the subscript.} \]
\[ I_n(x) \rightarrow \text{a first-order Bessel function of the kind defined in the subscript.} \]
\[ A^{(+)} \rightarrow \text{vector potential in a desired region.} \]

### 3.5.2 Numerical modelling methods

In contrast to the analytical approach, the numerical methods can be less rigid when solving a particular problem. Some nice features are demonstrated by analytical solutions include the simulation of higher complexity shape models and, in particular to eddy currents, the interaction of eddy currents with complex geometries.

The numerical modelling methods are divided into meshless and meshed methods [98]. In both categories, the solution of an electromagnetic problem is based on Partial Differential Equations [96]. The most common numerical method based on mesh methods is the Finite Difference Method (FDM). This method generally approximates the differential operator by replacing derivatives. FDM is now rarely used because of its simplicity and its limitations; but it was the basis for the succeeding numerical method, the Finite Element Method (FEM). This method is popular for solving magnetic and electrostatic problems [99]. FEM dominates the commercial numerical solver market. Other available numerical methods include the Volume Element Method (VEM) based on the Green’s function [96] and the Boundary Element Method (BEM). In meshless methods, the Element Free Galerkin (EFG) method is the most frequently used in EC NDE [99].

As mentioned before, FEM is the dominant method and commercially available FEM software such as COMSOL Multiphysics, ANSYS and MagNet can be easily attained. All the software mentioned above has the flexibility to simulate eddy current
problems in both 2D and 3D. Compared to the analytical approach, the numerical method can simulate the environment without axis-symmetry. A major drawback of this approach is that it is more time consuming when solving a reasonably complex problem as compared to the closed form solution presented in the previous section. In some cases, when the geometry is relatively simple, the analytical solution is more efficient and accurate than the numerical solution. Research conducted on the analytical and numerical solutions to eddy current problems is represented in section 3.8.

### 3.6 Measurements equipment

This section presents a brief description of the components in Eddy Current equipment. Several companies offer commercial Eddy Current equipment, such as Olympus Corporation, Rohman USA, and Zetec inc. Each company offers instrumentation with specific features, such as multi-frequency capability, specific probes with a specific frequency range and the possibility of the display being integrated into the apparatus or having interconnection with a host computer. The essential devices and electronics in an instrument used for the Eddy Current method are depicted in Figure 3.6.

![Figure 3.6 Diagram of eddy current instrument](Source: Modified from [9], [76])

The system can be balanced using a bridge circuit [76]. Any variations can be measured between ports A and B as depicted in Figure 3.6. Impedance $Z_1$ and $Z_2$ in the bridge are fixed impedances. One impedance allows for balancing of the circuit and the
other one is connected to the Eddy Current probe [9]. Differential coils are usually connected to this type of circuit [78].

Lopes Ribeiro et al. [100] reported the construction and experimental results of eddy current instrumentation used to measure the thickness of metallic plates. The instrument consisted of a pancake coil with a sinusoidal driven current and it detected variations with a Giant Magneto-Resistor (GMR) sensor, which was connected to a bridge circuit. Betta et al. [101] used an Eddy Current instrument based on GMR. The study reports crack detection on a surface of a conductive material. A commercial sensor was used and was connected to a Wheatstone bridge. An instrument using coils was reported by Martens et al. [102]. This instrument also used a bridge circuit which was connected to the coil. The other devices in the instrumentation were a National Instrument data acquisition board with D/A and A/D converters and a PC with USB connections. A study on several EC sensors was reported by Mook et al. [103]. The instrument had a demodulator card with an amplifier as an input. Adjustable resistance was used to allow for a coil, Hall effect sensor and GMR to be used. The instrument performed a 2D scan and reconstructed an image of the conductive material. The scan was carried out using a X-Y system.

A digital system used for the Eddy Current Method was the reported by Yin et al. [104]. This instrument was highly integrated and exploited the advantages of a digital system. The main device in the instrument was a Field Programmable Gate Array (FPGA), which is interfaced with A/D and D/A converters. The FPGA implemented demodulation using a Multiplier Accumulator (MAC) module, data acquisition, signal generation and the communication interface.

### 3.7 Sensors

This section presents popular sensors used for the Eddy Current Method. Coil sensors are some of the most popular sensor devices used in the Eddy Current Method. In literature, the coil sensor is also known as a search coil or a pickup coil [105]. This coil can be constructed as an air-core coil and a ferromagnetic core coil.

Induction sensors are also popular and several types can be found, such as Hall-effect sensors, SQUID, Fluxgates and so on [106]. Their main difference, despite the structure of the sensor, is the range of the magnetic field that can be detected. Table 3.2
depicts this range. In the next sections, the most common magnetic sensors used in the eddy current technique are presented.

Table 3.2 Magnetic sensor field range
Source: modified from [105], [107]

<table>
<thead>
<tr>
<th>Magnetic Sensor</th>
<th>Detectable Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1nT</td>
</tr>
<tr>
<td>Search-Coil Magnetometer</td>
<td></td>
</tr>
<tr>
<td>Flux Gate Magnetometer</td>
<td></td>
</tr>
<tr>
<td>Hall-effect</td>
<td></td>
</tr>
<tr>
<td>Magneto resistor</td>
<td></td>
</tr>
</tbody>
</table>

### 3.7.1 Inductive coils

An induction coil is known as a search coil or a pick up coil [105]. A multi-turn solenoid can be seen as a simple and basic induction coil magnetometer [107]. Faraday’s law governs the induction coil sensor [105], [108].

\[
V = -N \frac{d\Phi}{dt} = -N\mu_0\mu_rA \frac{dH}{dt}
\]  

(3.23)

Where \(N\) is the number of turns in the coil, \(\Phi\) is magnetic flux and \(A\) is the area of the coil. The law states that the induced voltage is proportional to the magnetic field. The main difference between the air-core and the ferromagnetic core is the material of the core [76]. The major drawback of a ferromagnetic coil is the loss of linearity. The ferromagnetic core ends with the incorporation nonlinearity, are the noise and a drop in the resolution of the sensor [76], [105]. However, at the same time, the ferromagnetic core increases the concentration of the magnetic flux which is useful for the detection of surface cracks and relatively low conductivity materials [109]. Both air and ferromagnetic coils depend on the area of the coil, the number of coil turns and the frequency, which is also limited by the core material [106]. This sensor is frequently used not only because it detects large field ranges, as depicted in Table 3.2 as low as 20 fT, but also because of its low cost of fabrication and due to the fact that Eddy Current method works in intermediate frequencies (1 kHz to 1 MHz), the inductive coils’ response presents effective performance [106].

Gradiometer sensors are commonly used to suppress the ambient noise [105]. This type of sensor is composed of two or more coils, which are connected in differential form. The typical connections for the gradiometer are vertical, planar or asymmetric [105].
3.7.1.1 Wired EC Probes

These types of probes generate the magnetic field through the wound wire and the AC current flowing. EC probes can be constructed by hand, and this is a major reason why this type of EC probe is popular amongst researchers; another reason is its range of detectable field, presented in Table 3.2. The construction of an EC probe usually entails a fine wire being wound around a ferrous material or non-conductive material. This section discusses the categories, and geometries reported, and a comparison of the commercial counterpart. Two major categories of EC probes based on coils can be found: absolute and differential.

3.7.2 Hall Effect Sensor

The Hall effect was discovered in 1879 [108], and is named after the discoverer Edwin H. Hall [110].

“Edwin Hall found that a voltage difference appears across a thin rectangle of gold placed in a strong magnetic field perpendicular to the plane of the rectangle when electric is sent along its length” [107].

Lorentz force is the name given to the force an electron experiences while moving in a magnetic field [110]. This force is perpendicular to the direction of the magnetic field and the direction of movement; as depicted in Figure 3.7.

![Figure 3.7 Hall effect sketch](source)

This type of sensor is most widely used in the detection of linear position, velocity, rotation and current [110]. This technology is integrated onto a silicon, and has a sensitivity range of 10G to 1000G and a limited frequency of around 1MHz [107]. One advantage is that this type of sensor can be integrated into a tiny encapsulation. The
Hall effect sensor has great importance in microelectronics technology due to its the
dimension and compatibility with a variety of applications [108].

### 3.7.3 Fluxgate magnetometers

A common fluxgate magnetometer is depicted in Figure 3.8. The sensor is composed of a core magnetic material around which two search coils are wound [106], [108], [111].

![Figure 3.8. Search coil magnetometer](Source: [106])

The fluxgate magnetometer uses the induction and saturation in the ferromagnetic core [106]. When the core is saturated the resistance of the magnetic field increases (reluctance), and these changes are detected by the coil [107]. Thus, the sensor sensitivity depends on the hysteresis, and the shape of the core. The sensitivity of the magnetometer is around $10^{-2}$ to $10^7$ nT. In literature, different types of magnetometers can be found with different core shapes; for example, single-rod, double rod or ring core [108].

### 3.8 The state of art in Eddy Current Inspection

Researchers have explored the ability of this method to detect defects in both surfaces and sub-surfaces. The Eddy Current method is used in an extensive range of industries, which require both qualitative and quantitative characterisation of defects. In this section, the progress made in relation to the Eddy Current method is presented. The outline of the section is as follows: the progress in crack detection, the progress in corrosion detection and finally, other applications.
3.8.1 Cracks

Defects such as notches and slots of different shapes have been the subject of many studies. This section summarises the modelling and experimentation progress in this area. Due to computational advancements, numerical simulations have received considerable attention. The study of the interaction with an ideal crack was the purpose of a paper by J. R. Bowler [112]; an ideal crack was simulated using a dipole density. A multi-layered eddy current problem had been investigated by Dodd and Deeds [95] using an analytical method.

The objective of EC researchers is to acquire quantitative information on defects, such as size, position, and geometry [96]. In order to accomplish this, they proposed a several methods and variations of the EC technique [52], [66], [67], e.g., pulsed eddy current (PEC), a combination of PEC and thermography and probe optimisation.

As was previously mentioned the distance between the probes and the test sample is defined as the lift-off. This parameter greatly impacts the test result and can mark the possible flaws. Therefore, some investigations were carried out like, the reduction of the lift off effect is proposed by Tian and Sophian [84] using a subtraction with a reference signal. Experimental verification was presented by simulating metal loss in an aluminium plate. Other approaches used an array of probes [113].

The design of a multi-coil probe was investigated by Huang et al. [114]. The purpose of the investigation was the identification of crack direction and the detection of outer defects in steam tubes. The design consisted of an excitation coil and a receiver coil. Numerical simulations investigated the parameters of the coil.

The corrosion detection is an area wherein some researchers focus their attention [66]. The sizing of stress corrosion has attracted the attention of Y. Noritaka et al., 2005 [115]. The focus of their research was the reconstruction of stress corrosion in pipes of nuclear plants. The inspection was carried out at a frequency of 20 kHz using a pancake probe. The study objectives were the sizing of stress corrosion and the modelling of crack using finite element and the application of a novel reconstruction algorithm with a stochastic approach. An ill-posed problem was investigated by Yusa et al. [116] a three-dimensional simulation was carried out to study the effect of lift-off and the dimension
of the coil probe in the ill-posed problem. A pancake coil was considered to correlate the experimental data with the simulation results in order to characterise the flaw depth.

A study pertaining to multi-frequency excitation was addressed by Yin, W. and Peyton, A. [117]. Their analytical model focused on the imaginary part of the inductance change when a non-magnetic material is approached by the multi-frequency eddy current sensor. The change was proportional to the thickness of the object under investigation. The study was also extended to ferrite core coils.

The implementation of the eddy current technique using a Hall effect sensor or GMR has also been carried out. A magnetoresistive sensor was the focus of the study in [118]. The eddy current detector enabled the acquisition of the information to detect stress. Another branch of study is the reconstruction of 3D images using EC testing. The approaches taken for the 3D reconstruction of a flaw include modelling the flaw using numerical software and applying, for example, edge elements or the finite element method, which was the focus of [119]. Besides the implementation, a variable in eddy current inspection is the sensor, which can come in different shapes, sizes and in some cases depends on the application. A popular type of sensor is the coil or so called pancakes. This type of sensor consists of a single multi-turn coil, usually in a circular shape, that comes in varies dimensions; also, the sensor can be designed to have an air core or a ferromagnetic core. Miniaturization is an issue when it comes to this type of sensor. A study using a pancake coil as the main focus was conducted by Lopes Ribeiro et al. [100], the setup of the experiments included the coil and a GMR. The study objective was the determination of the material thickness and the experimental setup consisted of a coil with 300 turns with a coil diameter of 30 mm, an internal diameter of 11 mm and a height of 8 mm. The experiment used the GMR due to its sensitivity at lower frequencies, which in the report was 250 Hz in order to have more field penetration into the material. The study showed good results up to 5 mm of penetration. Absolute coils are also popular in EC, this was the focus of a study carried out by Miorelli et al. [120]. The coil size used in this study had the following dimensions and specifications: inner radius 9.33 mm, outer radius 18.04 mm, length 10.05 mm, number of turns 1910 and frequency 1kHz. Two crack dimensions were investigated. The first crack had a depth of 1.27 mm, a length of 10 mm and an opening of 0.2mm and the second crack had a depth of 0.508 mm, a length of 10 mm, and an opening of 0.2mm, respectively. The results presented good agreement between modelling and
experimentation, showing that by using this type of arrangement the crack can be detected no matter its orientation.

Figure 3.9 Air coil probe shapes, can be fabricated in relatively different shapes
Source: [121]

Other types of coils have been investigated, such as flat coils, these can be spiral coils or rectangular coils, presented in Figure 3.10. This type of coil present an advantage in the miniaturization of the probe. As depicted in the following picture, the shape is usually spiral or rectangular. As an example, Figure 3.10b shows a printed-circuit technology coil fabricated on a 25 μm (=1 mil) thick polyimide substrate, each spiral turn was about 76 μm wide and 10 μm thick. The spacing between each turn was 102 μm (=4 mil). The main disadvantage of the rectangular coil is the orientation of the coil with respect of the crack. In a study reported by Ditchburn, R. J., and Burke, S. K. [122] they showed a difference of 3:2 when the long axis of the coil was either parallel or perpendicular to the slot.

Figure 3.10 Flat coil, usually printed on a PCB, a) spiral coil over a material, b) rectangular of miniaturized coil
Source: [123], [122]

The differential coil has also been studied, this type of sensor is usually used to reject the ambient noise when the measurement is disturbed. The sensor usually consists
of two coils connected differentially, using this probe it is possible to measure the small distortion caused by a small crack in the material. This type of probe can also be found in printed circuits like in Figure 3.11. The study showed the capability of this type of sensor to detect a small crack in the order of mm, it also demonstrated that this sensor is sensitive to crack orientation and that the coil must remain balanced.

Figure 3.11 Differential coil miniaturised, fabricated on a printed circuit board (PCB)
Source: [124]

3.8.2 Corrosion

The Eddy Current Method is also applied to corrosion detection in different metals. Pulsed Eddy Current is a variation of the technique used in corrosion detection. He et al. [125] investigated Pulsed Eddy Current (PEC) to characterise steel corrosion. The atmospheric corrosion on a steel sample was used during their investigation. A marine environment was simulated. The corrosion samples were generated from 1 to 10 months, which meant that the corrosion was spread over a wide area i.e. in the dimension of centimetres. Detection and sizing quantification were the aims of the study conducted by Hur et al. [126]. The study applied a rotating probe with a rotation rate of 5.08 mm/s at 300 rpm. Testing frequencies were 35, 100 and 300 kHz. The defect was a drilled hole of 1.32 mm in diameter. Using a differential probe to detect thinning was the focus of a study conducted by Angani et al. [127]. The EC system consisted of a waveform generator, two hall sensors, two excitation coils, a differential amplifier with a data acquisition card and processing software. The sensor was constructed to have a coil of 160 turns with a ferrite core. The Hall sensors were used as detection elements.
Davoust et al. proposed an approach using machine learning to estimate the size of corrosion [128]. The study created a database using the reference flaws and the Finite Element Method (FEM). Using this approach, an estimation of about 1mm² was achieved. In their simulation, the flaw estimation error was less than 10%.

To detect pitting corrosion at an earlier stage, the sensitivity is important. Background noise is usually a challenge when eddy currents are applied. One approach to reduce this problem is using a uniform field. The approach was proposed by Yusa et al. [129] to detect the flaws in austenitic stainless steel 316L with a uniform magnetic field. The study used an array of 23 detectors and one exciter. The uniform situation was due to the fact that the exciter was larger than the 23 coils of the detector and the exciter was above the 23 detectors. Using this configuration, the detectable cracks were in the order of 10 mm in length with a 1.1 mm depth. Corrosion cracking was the focus of the study carried out by Yusa et al [130], the size of the stress was in the order of 15.5 mm to 20 mm in length, presented in Figure 3. The study proposed a differential probe configuration; by loading several plates, stress corrosion in a stainless steel specimen was induced. The behaviour of the signal response in an eddy current inspection was evaluated and the results showed a good detection of the cracks and stress corrosion.
Figure 3. Eddy current detection of stress corrosion, a) stress corrosion sample, b) coil configuration
Source: [130]

A study of the resistance of stress corrosion was presented by Yusa and Hashizume [131], this included the evaluation of the measurement using a pancake coil and differential coils. The coils used in the experiments had the following dimensions: external diameter of 5mm, internal diameter of 1mm and a height of 5 mm for the pancake coil; the differential probe was 10 mm long, 0.3 mm wide and 5 mm deep. The study concluded that the resistance of the stress corrosion depended on the probe that a larger coil resulted in the resistance of the crack being smaller, and that pancakes coils tended to have better results than the rectangular differential coils.

Figure 3.13 Stress corrosion used in Yusa and Hashizume, left picture is a destructive evaluation and right is a picture of stress corrosion evaluated
Source: [131]

3.8.3 Others applications

A Magnetic Induction Tomography (MIT) is an application of image reconstruction to an object under investigation using EC testing. The system is composed of at least an array sensor, the electronics and a host or analyser in [132]. A
MIT planar system to detect flaws in metallic plates was presented. The system consisted of an array of 6 cylindrical air coils perpendicular to the testing object. The study was compared to a traditional EMT sensor arrangement are the system reconstructed the sensitivity map using frequencies of 10 kHz and 100 kHz.

Researchers progressed to explore the MIT system based on digital systems. A system based on a FPGA was presented in [104]. The system was composed of 8 coils that generated 56 measurements. The study showed two different reconstruction algorithms: the Tikhonov regularisation and total variation method. Other digital based MIT systems were reported in [133]. The system provided a solution for a digitalised MIT system, and an image reconstruction of the distribution of the object. The detection consisted of 16 coils and 16 strips to generate the excitation magnetic field. As a result, the study showed that the system could be reduced in size and made portable.

The following chapter will give an overview of the classical modelling proposed by Dodds and Deeds and the numerical analysis. The simulation contributes to the understanding of the effect of the defects, and the quantitative information of the flaws.

### 3.9 Conclusions

This chapter explored the Eddy Current Method as an NDT technique. Several variables and their effects, modelling approaches, sensors and instruments, and the capability of the technique were reviewed.

Eddy Current has been applied to corrosion detection in industries such as aerospace, automotive, and in power plants; Table 3.3 presents a comparison of coil arrangements in crack and corrosion detection. For all these industries, it is vital to detect corrosion while in its early stages. This presents a challenge for the eddy current techniques due to the fact that the most dangerous type of corrosion is pitting corrosion, which starts with a tiny dimension. This characteristic of pitting corrosion makes it a challenge for Eddy Current testing. Literature has reported the detection of pit corrosion in the order of a few millimetres. This is the problem addressed in this research.
Table 3.3 Sensor arrangement, advantages and limitations in cracks and corrosion detection

<table>
<thead>
<tr>
<th>SENSOR SIZE/ARRANGEMENT</th>
<th>ADVANTAGES</th>
<th>LIMITATIONS</th>
<th>DEFECTS</th>
</tr>
</thead>
</table>
| Circular (pancakes) coils | - Several analytical models (Dodds and Deeds, based Fourier superposition, and transformer model)  
- Simplicity in the fabrication  
- Sensor independent of the crack orientation  
- Air and ferrite core coils | - Noise sensitive  
- The coil size is critical for crack detection  
- Sensitive to lift-off and inclination | Stress corrosion, surface crack in order the of mm |
| Planar rectangular coils | - Good performance in conductivity measurement at high frequency  
- High sensitivity to defects surface scratches  
- Shallow imperfection  
- Possibility of inspection in complex surfaces | - Second order potential approximation  
- Limited in space area, response is in function of no. of turns and width of conductive wires  
- High dependency of the application. | Surface marks  
More sensitive for conductivity assessment in the order of mm |
| Spiral coils            | - Better response for long EDM  
- Reduce size sensor, due to printed circuit  
- Flexibility of curved form | - Low response at low frequency  
- Application for a specific NDT | Surface marks  
More sensitive for conductivity assessment in order of mm |
| Coil probes arrays      | - Increases the sensed area | - The complexity of modelled and computation response | Surface cracks and deformations |
| Encircling coils        | - Used to test tubes, bars and circular material  
- Internal or external application  
- Sensitive to parallel discontinuity to the axes of material | - Sensitive to non centred tests  
- Limited to the size  
- Noise sensitivity | Heating tubes for Corruption  
Cracks  
Conductivity assessment |
| Differential coils      | - Rejection of background noise  
- Detection of small discontinuities | - Difficult detection of gradual variations  
- Dependent of direction and size. | Cracks, stress corrosion possible in the order of mm or less |
Chapter 4 Simulation Techniques

4.1 Introduction

This chapter explores the simulation techniques used for eddy current testing. Simulation is a key piece of engineering. In our case, the simulation allows us to examine the effect of different variables in a particular problem. In particular, the simulation will allow us to study the eddy current probes, the magnetic field generated by the alternating current flowing in the probe in the presence of the conductive material and, most importantly, to predict the effect of a pitting corrosion defect. In addition, two essential problems pertaining to eddy current testing will be explored; these are a) a circular coil over a conductive plate and b) a cylindrical coil encircling a cylinder. These two geometries are essential for studying pit corrosion on plate and pipe surfaces. Moreover, a simulation of a novel probe proposed by the author will be presented. This novel probe was composed of two excitation coils, which had a receiver coil between them. The simulation of the novel probe was wholly analytical.

The simulation provided a better understanding of the generated magnetic field from the proposed novel probe and its interaction with the object under testing. This is the role of modelling done in relation to eddy current problem. The results using the wholly analytical method were compared with a numerical technique. Thusly, the author ensured that the results were sufficiently consistent and accurate. The comparison between the analytical solution and the numerical technique was carried out for a) circular coil over plate and b) a cylindrical coil encircling a cylinder. The numerical solution was carried out with the aid of a commercial software i.e. COMSOL Multiphysics® 4.4. The analytical solution proposed by Dodd and Deeds [71], [78] was used and computed in MATLAB®.

The outline of the chapter is as follows: a) the analytical and numerical simulations are presented separately, b) the simulations are followed by the comparison of the analytical and numerical approaches, c) the last part of the chapter explores the
simulation of the novel probe, giving the calculation procedure and sensitivity maps for an optimization of the probe and d) a discussion is presented.

4.2 Analytical approach

A classical analytical solution was proposed by Dodd and Deeds [95]. The construction of the analysis was based on some initial assumptions, such as axial symmetry, sinusoidal current passing through the coil, a circular coil with a rectangular cross-section, the conductive material was considered as linear, isotropic and homogeneous and finally, the problem was divided into several regions. Once the problem was divided into several regions and by solving a linear differential equation (4.1), superimposing could be done depending on the parameters of the coil.

\[
\frac{\partial^2 A}{\partial r^2} + \frac{1}{r} \frac{\partial A}{\partial r} + \frac{\partial^2 A}{\partial z^2} - \frac{A}{r^2} - j\omega \mu \sigma A = 0
\]  

(4.1)

The succeeding subsections explore two classical problems, a) a planar problem which involves a coil of N-number of turns above a plate of conductive medium; and b) a coil encircling a cylindrical conductor. The results of the analysis are presented.

4.2.1 Planar Eddy Current problem

The most common geometry of interest involves excitation coils near a plate. A typical example is shown in Figure 4.1. When a coil is placed near a conductive material and an Alternating Current (AC) is passing through the coil, a magnetic field is produced [134] and eddy currents are generated. Any defects in the conductive plate produce variation in the electric field and hence, eddy currents.

Theoretical work in this area has been conducted over the past decades. Dodd and Deeds [78]–[80] proposed an analytical method based on integral expressions of the magnetic vector potential in several regions, using Bessel functions. Figure 4.1 shows four different regions (I to IV) and an extra region (I-II), which is actually the coil. Cylindrical coordinates are used and the conductive material surface is set to be \( z = 0 \). Distance \( \ell_1 \) is the lift-off distance. The coil parameters \( r_1, r_2, \ell_2 - \ell_1 \) are the inner and outer radii, and coil height respectively.
Figure 4.1: Cross-section schematic of a circular coil over a conducting plate. Parameter: \( r_1 \) = inner radius, \( r_2 \) = outer radius, \( l_1 \) = distance between coil to conducting plate and \( l_2 - l_2 \) = coil height. Modified from: [88]

The analytical expression for the magnetic vector potential at the surface of the conductive material (region III in Figure 4.1) is defined as:

\[
A^{(iii)}(r, z) = \mu K \int_{a=0}^{\infty} J_1(\alpha r) f(\alpha r_2, \alpha r_1) \left( e^{-\alpha l_1} - e^{-\alpha l_2} \right) e^{\alpha_1 z} \frac{\alpha}{\alpha^2(\alpha + \alpha_1)} \, d\alpha
\]  

(4.2)

Where \( K \) and \( \alpha_1 \) are defined as

\[
K = \frac{NI_e}{(r_2 - r_1)(l_2 - l_1)}
\]  

(4.3)

\[
\alpha_1 = \sqrt{\alpha^2 + j\omega\mu\sigma_e}
\]  

(4.4)

In equation (4.2), \( J_1 \) is the Bessel function of the first kind and from equation (4.3) \( N \) and \( I_e \) are the number of turns in the coil and the electrical current passing through the coil, respectively. In the next subsection, the calculation of a planar problem is presented.

**4.2.1.1 Eddy Current solution for a planar problem**

The problem definition discussed in this subsection is depicted in Figure 4.1. The parameters of the problem are presented in Table 4.1. The calculation of the magnetic vector potential in (4.2) uses the Quadrature numerical method. This method can be implemented in MATLAB® by applying the integral function.

The Quadrature method solves the integral by dividing the problem into a finite interval \( a \leq x \leq b \). The method solves the integration by finding the area underneath the curve. The accuracy of the solution is a function of the number of intervals, which
means that approximation can be improved by increasing the interval. This integration method and some variations thereof can be found in MATLAB®.

Table 4.1 Coil parameters, problem planar model to solve, from equation (4.2)

<table>
<thead>
<tr>
<th>MODEL PARAMETER</th>
<th>PARAMETER IN EQUATION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius</td>
<td>( r_1 )</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Outer radius</td>
<td>( r_2 )</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>Lift-off</td>
<td>( \ell_1 )</td>
<td>1 mm</td>
</tr>
<tr>
<td>Coil top</td>
<td>( \ell_2 )</td>
<td>3 mm</td>
</tr>
<tr>
<td>Coil height</td>
<td>( \ell_2 - \ell_1 )</td>
<td>2 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>( N )</td>
<td>300</td>
</tr>
<tr>
<td>Electrical current</td>
<td>( I_e )</td>
<td>1 A</td>
</tr>
<tr>
<td>Working frequency</td>
<td>( f )</td>
<td>1 kHz, 3 kHz, 6 kHz, 30 kHz, 60kHz</td>
</tr>
</tbody>
</table>

Aluminium was simulated as a conductive plate with an electric conductivity of \( \sigma_e = 3.87 \times 10^7 \, S/m \). The magnetic vector potential \( A_\varphi \) was calculated at the surface of the conductive plate. \( \mu_0 = 4\pi \times 10^7 \) was the permeability in free-space. The analytical calculation of the magnetic vector potential \( A_\varphi \) at the surface of the conductive material with the described parameters is presented in Figure 4.2; from which reasonable conclusions about the simulation could be extracted. These conclusions are: a) the value of \( A_\varphi \) at the initial position (\( r = 0 \)) of the simulation was 0, which made sense because the current density at the centre of the coil was 0; b) the peaks from the simulations were almost at the same distance, \( r = \text{mean coil radius} \), which was reasonable because the current density was higher at the mean coil radius.
In a similar fashion to the planar problem, Dodd and Deeds theoretically studied the eddy current cylindrical problem; they proposed an analysis based on the magnetic vector potential. The problem was described as a coil with a rectangular cross-section, encircling a cylindrical conductor. A schematic description of the problem is depicted in Figure 4.3. As with the planar problem, the cylindrical problem was divided into several regions, which are depicted as I and II in the figure. The configuration can be described by material I with the radius “$a$” as the inner material and material II with the radius “$b$” as the outer material. The lift-off, which is the distance from the outer material to the coil’s inner radius, is defined as $r_1 - b$. $\ell_2 - \ell_1$ is the coil’s height. The present example focuses on the magnetic vector potential solution on the surface of the cylindrical material.
The magnetic vector potential for the cylindrical problem configuration is slightly different from that of planar problem. The solution is based on the Bessel function of the second order. The following expressions given by [79] can be used to calculate the magnetic vector potential on the surface of the object being tested.

\[
A^{(III)}(r, z) = \frac{\mu l}{\pi} \int_0^\infty r_0 K_1(\alpha r_0) F_d(\alpha, \alpha_1, \alpha_2, a, b, r) \cos(\alpha - z_0) d\alpha
\]  
(4.5)

\[
F_a(\alpha_1, \alpha_2, a, b) = \frac{K_1(\alpha_2 b)}{bDK_1(ab)} \left( \alpha_1 I_1(\alpha_2 a)l_0(\alpha_1 a) - \alpha_2 I_1(\alpha_1 a)l_0(\alpha_2 a) \right)
\]  
(4.6)

\[
F_b(\alpha_1, \alpha_2, a, b) = \frac{l_1(\alpha_2 b)}{bDK_1(ab)} \left( \alpha_2 K_0(\alpha_2 a)l_1(\alpha_1 a) + \alpha_1 K_1(\alpha_2 a)l_0(\alpha_1 a) \right)
\]  
(4.7)

\[
F_c(\alpha_1, \alpha_2, a, b) = \left[ F_a(\alpha_1, \alpha_2, a, b) - F_b(\alpha_1, \alpha_2, a, b) + \frac{l_1(ab)}{K_1(ab)} \right]
\]  
(4.8)

\[
F_d(\alpha, \alpha_1, \alpha_2, a, b, r) = \{ l_1(\alpha r) - F_e(\alpha_1, \alpha_2, a, b)K_1(\alpha r) \}
\]  
(4.9)
Where the function $K_1(\cdot)$ from (4.5)-(4.9) is the modified Bessel function of the second order, $I_1(\cdot)$ is the modified Bessel function of the first order, and $I$ is the current passing through the coil. The next subsection presents the solution of the magnetic vector potential $\mathbf{A}_q$, for a specific encircling eddy current problem.

The cylindrical problem presented in the next section is part of the present research work, due to the that fact of some restrictions of the fabrication of realistic samples, the generation of pitting corrosion technique for cylindrical material presents more complexity. The simulations were included in the present thesis because the aims of the research were to investigate the novel sensor in the planar and cylindrical configuration (specially pipes).

**4.2.2.1 Eddy Current solution for a cylindrical problem**

The problem discussed in this subsection is similar to the one depicted in Figure 4.3. The parameters of the problem are presented in Table 4.2. Computation of the magnetic vector potential was carried out in MATLAB® by using the `integral()` function. As mentioned before, the function applied the Quadrature numerical method.

Table 4.2 Coil parameters, cylindrical model parameters to solve, from equation (4.2)

<table>
<thead>
<tr>
<th>MODEL PARAMETER</th>
<th>PARAMETER IN EQUATION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil Inner radius</td>
<td>$r_1$</td>
<td>9 mm</td>
</tr>
<tr>
<td>Coil Outer radius</td>
<td>$r_2$</td>
<td>10 mm</td>
</tr>
<tr>
<td>Coil bottom</td>
<td>$\ell_1$</td>
<td>2 mm</td>
</tr>
<tr>
<td>Coil top</td>
<td>$\ell_2$</td>
<td>-2 mm</td>
</tr>
<tr>
<td>Coil height</td>
<td>$\ell_2 - \ell_1$</td>
<td>4 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>$N$</td>
<td>400</td>
</tr>
<tr>
<td>Electrical current</td>
<td>$I_e$</td>
<td>1 A</td>
</tr>
<tr>
<td>Working frequency</td>
<td>$f$</td>
<td>1 kHz, 3 kHz, 6 kHz, 30 kHz, 60 kHz</td>
</tr>
</tbody>
</table>

An aluminium cylinder was simulated as the conductive cylindrical material with an electric conductivity of $\sigma_e = 3.87 \times 10^7 \, \text{S/m}$, the outer material diameter was $b = 8.5 \, \text{mm}$ and the inner material diameter was $a = 7.5 \, \text{mm}$. The magnetic vector potential $\mathbf{A}_q$ was computed at the surface of the cylindrical material, $\mu_0 = 4\pi \times 10^7$ was the permeability in free-space. The analytical computation of the magnetic vector
potential $A_\varphi$ at the surface of the conductive material was performed using the described parameter and is presented in Figure 4.4. The problem was solved using a cylindrical coordinate system. The geometry was located in the $rz$-plane. Therefore, the $\varphi$ component of the magnetic vector potential $A_\varphi$ had to be computed in order to calculate the physical quantities.

![Magnetic Vector Potential](image)

Figure 4.4 Magnetic vector potential curves for 1 kHz, 3 kHz, 6 kHz, 30 kHz, and 60 kHz of a cylindrical problem

### 4.3 Numerical approach

In addition to the analytical solutions, numerical tools e.g. Boundary Element Method (BEM), Finite Element Method (FEM), and Finite Integration Technique (FIT) can be used to address the problem of eddy current modelling. Nowadays, there are several computation software available for modelling. For this project, the selected software was COMSOL Multiphysics® 4.4. This section presents a solution to both the planar and cylindrical configurations, as discussed in sections 4.2.1 and 4.2.2.

The calculation was carried out using modelling software in a 2D axisymmetric configuration comparing different mesh refinements. A comparison with the analytical solution was conducted for validation purposes and is also presented. The next subsection presents the planar solution followed by the cylindrical solution.

#### 4.3.1 Planar numerical simulation

As defined in the problem described in section 4.2.1.1 (the planar eddy current problem), the coil had $N = 300$ (number of turns), an inner radius of $r_1 = 0.5 \text{ mm}$, an
outer radius of \( r_2 = 2.5 \text{ mm} \), a distance of \( \ell_1 = 1 \text{ mm} \) from the conductive material to the coil and the height of the coil was \( \ell_2 - \ell_1 = 2.5 \text{ mm} \), the electric current was \( I_e = 1 \text{ A} \) and the working frequency was \( f = [1 \text{ kHz}, 3 \text{ kHz}, 6 \text{ kHz}, 30 \text{ kHz}, 60 \text{ kHz}] \). The conductive material was set to be aluminium. The material had a the thickness of \( d = 5 \text{ mm} \) and an electrical conductivity \( \sigma_e = 3.87 \times 10^7 \text{ S/m} \).

In COMSOL Multiphysics® the solution was set to 2D-axisymmetric, which was similar to the analytical solution assumption. The calculation used the magnetic fields option with dependent variables \( A_r, A_\theta \) and \( A_z \). The study was carried out in the frequency domain. Figure 4.5 presents the geometry constructed in COMSOL®

![Figure 4.5 Planar geometry problem drawn in COMSOL Multiphysics®](image)

Three different labels are depicted in Figure 4.5. \( r_2 \) was the simulated coil, \( r_1 \) was the aluminium plate and the \( sq1 \) was the air surrounding the model. For the time harmonic quasi-static formulation, the reduced PDE formulation for \( A \) was as follows.

\[
(j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)A + \nabla \times (\mu^{-1}\nabla \times A) = J_e
\]

\[(4.10)\]

\[
B = \nabla \times A
\]

\[(4.11)\]

where \( \sigma \) was the conductivity, \( \varepsilon \) the permittivity and \( \mu \) the permeability.

The method used to solve the model was FEM, which divided the problem into a large number of mesh elements. The accuracy of the solution depended on the number of utilised mesh elements. A greater number of elements meant higher accuracy was
reflected in the solution. For the computation of the magnetic vector potential, a different refinement of the mesh was made. The meshes used to solve the problem were normal, fine and extremely fine, which are presented in Figure 4.6. The properties of the meshes are presented in Table 4.3

Table 4.3 Mesh size properties COMSOL Multiphysics®

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>VALUE</th>
<th>PROPERTY</th>
<th>VALUE</th>
<th>PROPERTY</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular elements</td>
<td>799</td>
<td>Triangular elements</td>
<td>2105</td>
<td>Triangular elements</td>
<td>26068</td>
</tr>
<tr>
<td>Edge elements</td>
<td>99</td>
<td>Edge elements</td>
<td>152</td>
<td>Edge elements</td>
<td>506</td>
</tr>
<tr>
<td>Vertex elements</td>
<td>12</td>
<td>Vertex elements</td>
<td>12</td>
<td>Vertex elements</td>
<td>12</td>
</tr>
</tbody>
</table>

The solution was configured in the frequency domain. The frequencies were selected to be similar to those of the analytical solution, which were 1 kHz, 3 kHz, 6 kHz, 30 kHz and 60 kHz. The computations took 38 seconds to simulate the planar problem using the parameters presented above. The PC used to run the simulation had
an Intel Core i5 CPU 3.40 GHz, with 8 GB RAM, and ran 64-bit Windows 7; COMSOL registered 984 MB as virtual memory. The magnetic vector potential $A_\phi$ was calculated at the surface of the plate as shown in Figure 4.7. The magnetic vector potential was approximately the same, but a more visual picture could be obtained, Figure 4.7a presents the visual representation of the magnetic vector potential. It can be seen that the peak of the magnetic vector potential matched with that of Figure 4.7b and the analytical solution presented in Figure 4.2.

![Figure 4.7 Phi component of magnetic vector potential calculated by COMSOL 4.4, a) surface plot of the magnetic flux density at 60 kHz, b) Magnetic vector potential, $A_\phi$](image)

**4.3.2 Cylindrical numerical simulation**

This problem was described in Section 4.2.2.1. The coil parameters were: $N = 400$ (number of turns), inner radius $r_1 = 9$ mm and outer radius $r_2 = 10$ mm. The conductive material was simulated as a layered conductive object. The inner material i.e. material 1, was set to have a radius of $a = 7.5$ mm. The outer material was set to have a radius of $b = 8.5$ mm. The lift-off was defined as $r_1 - b = 1$ mm. The height of the coil was $\ell_2 - \ell_1 = 4$ mm. The electric current through the coil was set to be $I_e = 1$ A. For the excitation frequency, the simulation took several frequencies, i.e. $f = [1$ kHz, $3$ kHz, $6$ kHz, $30$ kHz, $60$ kHz, $1$ MHz]. The conductive material was set to be aluminium with an electrical conductivity of $\sigma_e = 3.87 \times 10^7$ S/m. The magnetic vector potential $A_\phi$ at the outer surface of the conducting cylinder was computed using COMSOL Multiphysics®. Figure 4.8 shows the geometry constructed in COMSOL and Figure 4.9 presents the different mesh sizes constructed to carry out the model solution.
Figure 4.8 Cylindrical geometry problem drawn in COMSOL Multiphysics®.

Figure 4.8 shows four different labels, $r_1$, $r_2$, $r_3$ and $sq_1$, which represent the coil, the inner cylindrical material, the outer cylindrical material and the air surrounding the model, respectively. The computation of the quasi-static problem was done in the same fashion as that of the planar one. The equations for the magnetic vector potential are (4.10) and (4.11). The simulation was carried out using the same methodology as the previous configuration. Three meshes were generated to solve the problem and are depicted in Figure 4.9.
Figure 4.9 Mesh sizes for the cylindrical configuration, a) Normal Mesh, b) Finer Mesh and c) Extremely Fine Mesh.

The parameters for the mesh sizes are presented in Table 4.4 with the shapes of the elements set to a triangular form. The study was conducted in the frequency domain and the frequencies were 1 kHz, 3 kHz, 6 kHz, 30 kHz and 60 kHz.

Table 4.4 Mesh size of cylindrical simulations

<table>
<thead>
<tr>
<th></th>
<th>NORMAL MESH</th>
<th></th>
<th>FINER MESH</th>
<th></th>
<th>EXTREMELY FINE MESH</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PROPERTY</td>
<td>VALUE</td>
<td>PROPERTY</td>
<td>VALUE</td>
<td>PROPERTY</td>
<td>VALUE</td>
<td></td>
</tr>
<tr>
<td>Triangular elements</td>
<td>1592</td>
<td>Triangular elements</td>
<td>2926</td>
<td>Triangular elements</td>
<td>26476</td>
<td></td>
</tr>
<tr>
<td>Edge elements</td>
<td>176</td>
<td>Edge elements</td>
<td>223</td>
<td>Edge elements</td>
<td>539</td>
<td></td>
</tr>
<tr>
<td>Vertex elements</td>
<td>14</td>
<td>Vertex elements</td>
<td>14</td>
<td>Vertex elements</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

The computation took 56 seconds to simulate the cylindrical problem under the parameters presented. The PC configuration was the same as mentioned in previous section. The magnetic vector potential $\mathbf{A}_\phi$ was calculated at the surface of the cylinder; Figure 4.10 shows these calculation results. The curves show that the magnetic vector
potential had its highest value at the centre of the coil, which is visually is presented in Figure 4.10a. The figure shows the concordance of both simulations, the analytical and numerical calculations. The higher the distance from the centre, the more the magnetic force decays, which was the expected behaviour. The magnetic vector potential decays the farther it is from the magnetic source.

![Figure 4.10 Phi component of magnetic vector potential calculated by COMSOL 4.4, a) outer cylindrical material using 1kHz, b) Magnetic vector potential, $A_\phi$](image)

4.4 Comparison of results from the analytical and numerical solutions

4.4.1 Planar configuration

A comparison of the magnetic vector potentials from the analytic and numerical solutions can be seen in Figure 4.11. The working frequency of the simulation presented was 1 kHz. From Figure 4.11a, it can be seen that the calculation showed a good agreement with the simulation when a relatively low frequency was applied.
Figure 4.11 Comparison between analytic and numerical simulations, a) at working frequency 1 kHz, and b) the working frequency 1 MHz.

Figure 4.11b presents a comparison between the analytical and the numerical calculation when the working frequency was 1 MHz. The calculations of the magnetic vector potential differed significantly when the working frequency was higher. The numerical approach presented a lower accuracy at a higher frequency even with a relatively simple geometry.

The developed numerical solutions consisted of a mesh with 53537 elements, which took 38 seconds to solve. In comparison, the analytical approach, in Matlab took 15 seconds to solve the problem. The difference between the simulations was less than 0.1%, at lower frequencies, which serves as validation for both the analytical and the numerical techniques.
4.4.2 Cylindrical configuration

The numerical approach for the cylindrical case consisted of 53537 elements and took 56 seconds to solve. In comparison, the analytical approach in Matlab takes 26 seconds to solve the cylindrical problem. The difference between the simulation with a low frequency was again less than 0.1%, which gave a good correlation between the simulations. As in the planar problem, when the solution was carried out using a higher frequency (1 MHz), it tended to diverge significantly. Figure 4.12 presents the comparison of the analytical and numerical approach, i.e. 1 kHz in Figure 4.12a and 1_MHz in Figure 4.12b.

![Magnetic Vector Potential](a)

![Magnetic Vector Potential](b)

Figure 4.12 Comparison between analytical calculations (Matlab®) and numerical (COMSOL®) calculations for a cylindrical configuration, a) working frequency of 1 kHz and b) working frequency of 1MHz
4.5 Novel sensor configuration

This section presents the simulation of a novel eddy current sensor proposed by the author. The sensor consisted of three coils, creating a differential electromagnetic configuration. The subsequent subsection presents the description of the sensor, simulation and calculation of the magnetic vector potentials, a prediction of the signal due to different pits sizes and finally, a sensitivity map generation. The construction of the solution was wholly analytical and hence accurate even at high frequencies. This was made possible due to the geometry of the sensor design. During the modelling, each coil could be treated as axisymmetric. A sensitivity map was also generated from 2D simulations.

4.5.1 Sensor description

A differential sensor design is the main purpose of this section. The sensor consisted of three coils; two of them served as the excitation source and the remaining coil acted as the receiver. A layout of the sensor is presented in Figure 4.13. From the schematic, it can be seen that the electric current passing through coils 1 and 2 was in opposite directions but had the same amplitude. The distance between the excitation coils was the diameter of the receiver coil plus \( d_{c1} \) as labelled in the figure. Therefore, the novel sensor remained symmetrical in the proposed design. The excitation field generated by the excitation sources, i.e. coils 1 and 2, could be optimised to be uniform in the region between them. The receiver coil was set to be half the size of the excitation coils.
Figure 4.13 Sensor proposed schematic; Coil 1 and Coil 2 as excitation source, Coil 3 as receiver.

With this configuration, when a conductive plate is presented, the induced background voltages in the receiver coil due to the excitation source are ideally cancelled out, or should be practically minimal. The implication of this configuration is significant as the receiver coil registers small changes in the magnetic field generated by a defect.

The analysis was constructed using a purely analytical solution, which was based on the eddy current problem solution proposed by Dodd and Deeds [95]. The analysis addressed coils with a rectangular cross section. Several assumptions were made; such as the current density flowing in the coil was proportional to the vector potential so that each turn had the same magnitude and phase. It was also assumed that the configuration remained symmetric since in each turn magnitude and phase remained the same. Thus, superposition could take place. The problem statement presented in this thesis held the same form as Dodd and Deeds’ model; the methodology is depicted in Figure 4.14. The subsequent section will describe the analytical solution and will present the calculations. Several simulations for the prediction of the signal due to a pit are presented and sensitivity maps were generated.
4.5.2 Solution of Magnetic Vector Potentials

In this section, a description of the solution is presented. The excitation coils and the receiver coil were treated separately for the solution of the magnetic potentials. From this point of view, the solution could be regarded as three different coils.

The excitation coils had the same parameters e.g. number of turns, electric current and so on, but the injecting current was in the opposite direction. That resulted in a similar computation but in the opposite direction. The coils were separated by the distance labelled $d_c2$. The procedure to solve this part of the problem was: a) calculate the magnetic vector potential at the surface of the conductive material due to coil 1 (left coil), b) mirror the solution from step a and c) calculate the sum of the two magnetic
vector potentials calculated previously. The magnetic vector potential due to coil 1 could be calculated using the following equation.

\[
A^{(ii)}(r, z) = \mu K \int_{a=0}^{\infty} f_1(\alpha r) f_2(\alpha r_2) \frac{(e^{-\alpha r_1} - e^{-\alpha r_2})e^{a_1 z}}{a^2(\alpha + a_1)} \, d\alpha
\]

where

\[
K = \frac{NI_e}{(r_2 - r_1)(\ell_2 - \ell_1)}
\]

\[
a_1 = \sqrt{a^2 + j\omega \mu \sigma_e}
\]

Coil 1 had the same parameters as in Table 4.1. The radius of the simulation coil was 6.9 mm. The solution of the magnetic vector potential on the surface of the plate is depicted in Figure 4.15.

Using this computation, the magnetic vector potential for the two-excitation coils could be built. The second coil could be solved in the same fashion as coil 1. In the case of the present sensor, the coil 2 had the same parameters as coil 1. The main difference was the direction of the current flowing through the coils. To reduce the calculation complexity, a mirror operation of the magnetic vector solution of coil 1 could be performed. The solution for the coil 2 is presented in Figure 4.16.

![Magnetic Vector Potential](image.jpg)

Figure 4.15 Computation of the magnetic vector potential magnitude of the left coil sensor proposed in Figure 4.13, labelled as Coil 1.
Figure 4.16 Calculation for the second excitation coil (right coil), labelled as coil 2. The calculation is rotated in comparison to coil 1.

Following the computation of each of the excitation coils, the magnetic vector potential for the novel electromagnetic sensor could be constructed. A summation of both magnetic vector potentials could be carried out, and the magnetic vector potential will approximate constant at the in centre of the coil, which is the most sensitive part. The overall computation of the magnetic vector potential due to both excitation coils is presented in Figure 4.17.

Figure 4.17 Two excitation coils producing a quasi-uniform field. The present picture presents the magnetic vector curves for the sensor proposed.

The remaining calculation was of the vector potential of the receiver coil. In the same fashion, the magnetic vector potential of the receiver coil could be obtained. The parameters for the receiver coil are presented in Table 4.5.
Table 4.5 Receiver coil parameters (coil 3), electromagnetic model sensor

<table>
<thead>
<tr>
<th>MODEL PARAMETER</th>
<th>PARAMETER IN EQUATION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius</td>
<td>( r_1 )</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Outer radius</td>
<td>( r_2 )</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Lift-off</td>
<td>( \ell_1 )</td>
<td>1 mm</td>
</tr>
<tr>
<td>Coil top</td>
<td>( \ell_2 )</td>
<td>3 mm</td>
</tr>
<tr>
<td>Coil height</td>
<td>( \ell_2 - \ell_1 )</td>
<td>2 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>( N )</td>
<td>169</td>
</tr>
<tr>
<td>Electrical current</td>
<td>( I_e )</td>
<td>1 A</td>
</tr>
<tr>
<td>Working frequency</td>
<td>( f )</td>
<td>1 kHz, 3 kHz, 6 kHz, 30 kHz, 60 kHz</td>
</tr>
</tbody>
</table>

Using the aforementioned parameters, the magnetic vector potentials were calculated; the results are presented in Figure 4.18.

Figure 4.18 Real component of the vector potential, coil 3 receiver differential model

4.5.3 Sensor optimization

This section presents an optimization of the proposed new design based on simulations. The sensor has been optimized in terms of coil sizes, number of wire turns and the distance between the coils. There is a trade-off between the sensor size and the smallest defect that can be detected, which is related to the spatial resolution. A higher area can be covered with a bigger sensor, but the resolution decays, and smaller objects could be harder to detect. Conversely with a smaller sensor, a smaller object could be
detected but less area is covered. For the purpose of this thesis, a relatively small sensor is proposed, due to the fact that the pit corrosion remains in range of μm to mm.

The first optimization carried out was the distance between the excitation coils, which is presented in Figure 4.19. For the sensor proposed it is important to generate a uniform field, and also, the sensor had a constraint which is that the receiver coil must be in the middle. For this reason it is important to have less distance between the excitation coils but to have enough space to build the receiver coil with the appropriate number of turns to detect the small variation due to defects. Figure 4.19a depicts the simulation of the distance between the excitation coil using 1 kHz, the distance range simulated goes from 6.9 mm to 14.9 mm. It is clear that the closer the coils, the close to uniform field is. Figure 4.19b presents the same simulation using 60 kHz and the quasi-uniform field generated remains better at a distance of 6.9 mm.

Some conclusions can be extracted from the distance simulation. a) The distance between the excitation coil should be the minimum, in order to generate a uniform field, which is a key of the configuration to reject the background noise. b) The space limitations for the construction had to be considered, to construct the receiver coil the best option was 6.9 mm depicted in Figure 4.19. c) At higher frequencies the uniform field decays in comparison with lower frequencies, this can be seen from Figure 4.19a and 4.19b. To make a uniform field the distance between the excitation coils should be reduced. This remains a limitation since the construction of coils of 6 mm in diameter is complex, and reducing this dimension further complicates the task.

The other important variable to consider is the number of turns. The selection of this variable was made considering the space where the sensor will be encapsulated and the wire used to fabricate the coils. This was of 0.8mm radius which allowed the advantage of using a greater number of turns, which was selected to be 400. The receiver coil was limited to the space of 6.9mm and the number of turn selected for the receiver coil was 169. The values in Table 4.5 were selected from these simulations and the limitation in physical space in the receiver coil.
Figure 4.19 Simulation of distance between the centre of the excitation coils and the quasi-uniform field. 6.9mm is the optimum distance for achieving quasi-uniform field, a) Simulation using 30 kHz, b) Simulation using 60 kHz.

Using these calculations the sensitivity maps have been computed and are explained in the next section.
4.5.4 Sensitivity map generation

The analytical calculations presented in the preceding section were used to generate the sensitivity maps of the probe. Transformation matrices, i.e. rotation and translation, were used to generate the sensitivity maps from the analytical calculations.

Sensitivity analysis was reported in [135]–[138]; it can be derived from Maxwell’s equations and used for the inverse problem in the eddy current method. The calculations in the preceding section were used to build the sensitivity map for the sensor presented. To study the sensitivity of the sensor in relation to pits at different positions and depths, a sensitivity formula was proposed:

$$\frac{\Delta Z_{12}}{\delta \sigma} = E_a \cdot E_b$$  \hspace{1cm} (4.15)

The magnetic vector potential due to the excitation coils could be obtained using the superposition principle, i.e. summing \( A \) due to Coil 1 and due to Coil 2 (Figure 4.13 p. 93). This excitation strategy resulted in a quasi-uniform electric field in the area between the two excitation coils, indicated by the plateau parts in Figure 4.17. Using these calculations, the analysis of the effect of the distance between the two excitation air-coil sensors could be optimized as was previously mentioned. The sensitivity map (Figure 4.20) for the novel sensor defined earlier was calculated at a working frequency of 60 kHz.
Figure 4.20 Maps of: (a) A field for the receiver coil, (b) A-field YZ view of the receiver (c) 3D A-field of a dual excitation air coil, (d) XZ view of excitation coil A field, (e) 3D sensitivity map for the sensor proposed, (f) XZ view sensor sensitivity map and (g) XY view sensitivity map
4.5.5 Prediction of induced voltage due to a pit

From the theory proposed by B. A. Auld and J. C. Moulder [96], the change measured due to a flaw can be expressed as the difference in the impedance of a flawless material and the presence of a defect in the tested piece:

\[
\Delta Z = \frac{j\omega}{l^2} \int_{V_F} E_a \cdot \delta \varepsilon \cdot E_b dV
\]

(4.16)

where \( j = \sqrt{-1}, \) \( \omega \) is the angular frequency, \( E_a \) is the electric field in the test piece without a flaw, \( E_b \) is the electric field of the test piece in the presence of a flaw and \( V_F \) is the volume of the flaw. Both electric fields (\( E_a \) and \( E_b \)) are excited by \( I \) and the conductivity change due to a crack is

\[
\delta \varepsilon = \delta \varepsilon + \frac{\delta \sigma}{j\omega} \approx \frac{\delta \sigma}{j\omega}
\]

(4.17)

The approximation in (4.17) is due to negligible displacement currents [95], [96]. The approximation of \( \Delta Z \) in (4.16) by applying (4.17) is

\[
\Delta Z = \frac{1}{l^2} \int_{V_F} E_a \cdot \delta \sigma \cdot E_b dV
\]

(4.18)

As in the previous definition, \( E_a \) and \( E_b \) are the electric fields for the test piece with and without a flaw respectively, \( \sigma \) is the conductivity and \( V_F \) is the volume of the flaw. From [95]:

\[
\Delta V = \Delta Z I
\]

(4.19)

Where \( \Delta V \) is the voltage change in the test piece due to a flaw, which is excited by current \( I \). The change of induced voltage can be calculated by applying equations (4.18) and (4.19).

The purpose of this simulation was to predict the voltage changes due to a pit. The present section focuses on the signal changes due to the pitting corrosion of several sizes. Pitting corrosions in the present section are shown in Table 4.6. The generations of pits of these sizes is explained chapter 5. For the present section it is sufficient to take the parameters of each pit in order to introduce the simulation so that the prediction of the signal due to the volume of the pit can be obtained.

~ 102 ~
Table 4.6 Pitting corrosion parameter, metrology using confocal microscope

<table>
<thead>
<tr>
<th>CARBON STEEL (hr)</th>
<th>DIAMETER (µm)</th>
<th>DEPTH (µm)</th>
<th>VOLUME (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>592</td>
<td>148</td>
<td>0.0279</td>
</tr>
<tr>
<td>3</td>
<td>633</td>
<td>198</td>
<td>0.0458</td>
</tr>
<tr>
<td>6</td>
<td>756</td>
<td>100</td>
<td>0.0203</td>
</tr>
<tr>
<td>10</td>
<td>925</td>
<td>559</td>
<td>0.3139</td>
</tr>
<tr>
<td>10</td>
<td>890</td>
<td>451</td>
<td>0.1439</td>
</tr>
<tr>
<td>15</td>
<td>887</td>
<td>279</td>
<td>0.1057</td>
</tr>
<tr>
<td>20</td>
<td>1016</td>
<td>385</td>
<td>0.2454</td>
</tr>
<tr>
<td>25</td>
<td>1015</td>
<td>442</td>
<td>0.1972</td>
</tr>
</tbody>
</table>

From the voltage change in equation (4.18), the induced voltage in the presence of a perturbation of $V_F = 0.0279$ mm³ is shown in Figure 4.21.

![Real induced voltage graph](image1)

![Imag induced voltage graph](image2)

Figure 4.21 Induced voltage due to a flaw of volume of 0.0279 mm³ using 60 kHz.
4.5.6 Lift-off simulation

Lift-off variation was also explored. The lift-off simulation used a range of 0 to 5 mm. Figure 4.22 shows the curve of the induced voltage due to the variation of the lift-off. This result was compared to those of the experimental measurements. The calculation was as expected from the general EM theory, which states that high lift-offs reduce eddy current density in the inductive material. The simulation setup remained the same as in the previous section.

![Graph showing induced voltage vs. lift-off distance](image)

Figure 4.22 Real induced voltage of lift-off variation between the range from 0 to 5mm

4.6 Conclusions and discussion

EM Modelling can be divided into two approaches, a) analytical and b) numerical. Each approach presents advantages and disadvantages. On the one hand, when a simple coil geometry is involved, the analytical solution is a very good option. The closed form proposed by Dodd and Deeds presents a very good correlation between theory and experiments. The comparison between the analytical and the numerical methods showed good agreement at a lower frequency, when being applied to simple coil geometries such as the planar and the cylindrical problems. However, at a higher frequency a discrepancy arose. Thus, the analytical solution becomes a better option. On the other hand, the numerical approach is an option when a complex coil geometry is involved.
This chapter focused on two basic problems, i.e. planar and cylindrical coils, and solutions were presented using both analytical and numerical techniques. A comparison between these techniques was also presented. The numerical solution could also be constructed in 3D. The major drawback to applying 3D simulation lies in its low computational performance and inferior accuracy. The conclusion using the numerical solution in COMSOL presented the opportunity to construct the solution a purely analytical manner.

This chapter also presented the study of a novel differential probe. The solution when simulating this was based on wholly analytical techniques. The methodology to construct the analysis of the novel probe was presented.

A prediction of the signals due to realistic pitting corrosion was carried out. Parameters for the pits, such as diameter, depth and volume were presented in Table 4.6. The diameter range of the pitting corrosion was in the order of a few hundredths of a micron for the smaller pits and of the order of a millimetre for the larger pits.

The rapid analytical solution allows the probe to be optimised for better features. The solution constructed in MATLAB® remains able to solve the problem within a few seconds. The rapid analytical solution was used to study the lift-off effect in the configuration mentioned. The next chapter presents the sample preparation and the experimental procedure to verify the novel probe in practice.
Chapter 5 Experimental evaluation

5.1 Introduction

This chapter presents the experimental results from actual pitting samples. The first stage of the work was preparing the pitting samples by using a micro-capillary with a Galvanostatic device. This method used a corrosive accelerator and an electrical current to promote the corrosion process. After the pitting generation, evaluation using a confocal microscope was carried out. The samples generated for this project could be divided into two categories: a) mixed samples which included pits with the same generation time and b) individual samples that contained the same generation time.

This chapter also presents experimentation using the developed Eddy Current instrument. The aim of the experimentation was to evaluate not only the performance of the instrument but also several variables that could impact the test results. Those variables were the lift-off and the speed variation when carrying out the scan.

The chapter is divided as follows. The first section gives a description of the instrument, i.e. hardware, sensor and software to acquire the measurement. In addition, the first section presents the sample preparation and its evaluation using an optical method. The second section details the experimentation. A range of experiments were carried out to evaluate the pitting detection, from 1 hr to 20 hr pit generation. A test taking into account the lift-off variation was also carried out. These experiments assessed the limitations of the instrument to detect the pitting corrosion in spite of the lift-off, which had a significant impact during the experimentation. During the experiment, a sweep of lift-off was carried out. The results showed the impact of lift-off on the detectability of a flaw under the conditions presented in this chapter. Another variable tested was the working frequency. Two working frequencies were used, 30 kHz and 60 kHz. The motivation behind using those frequencies is presented in the second part of this chapter. Finally, the conclusions are presented.
5.2 System description, software and hardware validation

Eddy current techniques have previously been applied to characterise biological tissues, measure fluid levels and for metal evaluation (thickness and cracks), amongst others [104], [139]–[142]. The instrument developed by W. Yin, et al. [143] was based on a Field Programmable Gate Array (FPGA); and a planar configuration system for metallic plates was described by W. Yin and A. J Peyton [144]. It applied a forward solution based on analytical methods.

The research presented in this thesis took advantage of the benefits presented by digital systems, especially using a FPGA [145]–[147]. The FPGA performed several tasks, including the generation of a digital signal that was used as the signal injected into the coil probe, data acquisition (DAQ) through an analogue to digital converter (A/D) device, and communication between the host (a PC) and the instrument.

5.2.1 Equipment

The Eddy Current instrument proposed to carry out the experimentation was Field Programmable Gate Array (FPGA) based. The instrument was divided in to two main boards. Figure 5.1 presents a schematic representation of the instrumentation. As mentioned, the main device was a FPGA using a Spartan III from Xilinx®. The FPGA was the most important component in the instrument, it performed the signal generation, demodulation and data acquisition amongst other tasks. For this thesis, the hardware was previously built (Figure 5.1a and b), and the firmware was a part of the contribution of this thesis. The synchronization of the signal generation and the demodulation was vital to the detection success and instrument sensitivity. For the development of the firmware, the author applied some of the IP cores available from Xilinx® to ensure synchronization, reliability and to reduce the development time. The Xilinx® IP cores employed were the Direct Digital Synthesiser (DDS), Multiply Accumulator (MAC), and Digital Clock Manager (DCM’s). In the succeeding sections, a brief explanation of the features used and their implementation is presented. The system has the capability to generate a large range of frequencies. The selection of the frequencies for the experiments were due to the fact that the instrument had better behaviour in those frequency and the simulations presented in previous chapter include those frequencies (30 kHz, 60 kHz). Some others like 1kHz, 3kHz, 6 kHz, are also considered here, and the
main motivation is the comparison with the experimentation and to have an overview of a possible behaviour of the system using other frequencies.

![Diagram of the electromagnetic instrument](image)

Figure 5.1 Schematic description for the electromagnetic instrument. a) Processing/DAQ board in red, b) Conditioning board in green, c) Sensor and d) Host in blue

The high processing speed of the FPGA allowed for practically real time data acquisition, which was an advantage of the new instrumentation. The embedded processes such as data acquisition interfacing, D/A and A/D converters, the interface for USB communication, sinusoidal signal generation using IP cores, and some other modules could be found in the FPGA. The FPGA board is depicted in Figure 5.2.
Several devices were integrated on the main board (processing/DAQ board). A microcontroller (CY7C68013A) worked as an interface for the USB communication between the instrument and the PC host with a 16-bit data width. The signal generation was performed inside the FPGA using a Direct Digital Synthesizer (DDS) from Xilinx® IP Core. The data conversions were carried out using AD924 and DAC9754 A/D and D/A respectively. The demodulation process mainly used several Multiply-Accumulators from a Xilinx® IP Core. The next section gives more details about the integration of the different devices used in the instrument.

VHDL language was used to programme the FPGA. The RTL design using Xilinx® ISE 9 is presented in Figure 5.3. In the next subsections, the method and the parameters used to implement the signal generation, data conversion and demodulation, and communication with the host PC are explained.
Figure 5.3 RTL design of the function blocks and their connection on the FPGA

5.2.1.1 FPGA

The FPGA presented a very powerful advantage over other devices, e.g. the Microcontroller (MCU), because it had useful features such as parallel execution. For FPGA programming, two approaches can be followed, a) Verilog and b) VHDL. VHDL was the programming language applied in this thesis, which implemented several key modules in the EC instrument. Another advantage of the FPGA was that the pins could be assigned depending on the circuit needs, and the translation in the PCB design.

The hardware used was a Spartan-3, a family of Field-Programmable Gate Arrays by Xilinx. Some of the features are presented below, and more information can be found in the datasheet [148].

- Densities up to 74,880 logic cells
- SelectIO™ interface signalling
- Up to 633 I/O pins
- 622+ Mb/s data transfer rate per I/O
- 18 single-ended signal standards
- 8 differential I/O standards including LVDS, RSDS
- Termination by Digitally Controlled Impedance
- Signal swing ranging from 1.14V to 3.465V
- Double Data Rate (DDR) support
- Digital Clock Manager (up to four DCMs)
- Eight global clock lines and abundant routing.
In this thesis two Digital Clock Managers (DCMs) were used to generate the clocks for the converters and to synchronise the data transmission from the USB to PC with the MCU in charged of the USB communication (FX2LP). The next sections explain the signal generation, demodulation process, and other functional modules embedded in the FPGA.

5.2.1.2 Signal generator

A sinusoidal signal was used to inject current into the excitation coil which produced the magnetic field in the object under investigation. There is an approach to generate an arbitrary signal by using an FPGA, which also allows varying the signal frequency and phase. The approach is known as the Direct Digital Synthesis (DDS). A description of DDS is depicted in Figure 5.4. Another advantage of using the FPGA, or more specifically a Xilinx® FPGA, was the wealth the libraries (so-called IP Cores) written by Xilinx®. These libraries improve the efficiency of the programming by reducing the time and effort during the development and debugging of an application. The library is known as the IP Core and is supplied by Xilinx®.

![Figure 5.4 Block diagram of the DDS Xilinx © IP core](Source: [154])

The DDS is a Xilinx® IP core embedded in the FPGA. Basically, the output of the DDS was a digital waveform which was passed to the Digital-to-Analogue Convertor (D/A). The interfacing of the D/A converter is explained in a subsection presented later in this chapter.

The digital signal generated from the DDS can be described as follows:

\[ S(t) = A_s \cdot \cos(2\pi f_m t + \varphi_s) \quad (5.1) \]
where \( A_s \), \( f_m \) and \( \varphi_s \), are the amplitude, the frequency and the phase of the excitation signal \( S(t) \) respectively. The generated digital signal was converted to an analogue signal through the D/A converter and then amplified and applied to the excitation coil. The excitation current had the form:

\[
M_i(t) = A_{mi} \cdot \cos(2\pi f_m t + \varphi_{im})
\]  

(5.2)

where \( A_{mi} \) was the amplitude, \( f_m \) was the frequency, and \( \varphi_{im} \) was the phase of \( M_i(t) \) as the current passed through the coil. The system response modulated the induced voltage in the receiver coil which was attenuated in magnitude and shifted in phase compared to the excitation signal. The induced voltage signal could then be described as:

\[
M_v(t) = A_{mv} \cdot \cos(2\pi f_m t + \varphi_{vm})
\]  

(5.3)

Where \( M_v \) was the voltage induced in the receiver signal, \( A_{mv} \) was the amplitude, \( f_m \) was the frequency and \( \varphi_{vm} \) was the phase. The induced voltage was captured and then digitised by the A/D converter, which was then demodulated to extract the amplitude and phase. The signals (5.2) and (5.3) had the discrete form of:

\[
M_i[n] = A_{mi} \cdot \cos\left(\frac{2\pi f_m n}{f_s} + \varphi_i\right), \quad 0 \leq n \leq N_s - 1
\]  

(5.4)

\[
M_v[n] = A_{mv} \cdot \cos\left(\frac{2\pi f_m n}{f_s} + \varphi_{vm}\right), \quad 0 \leq n \leq N_s - 1
\]  

(5.5)

where \( n \) was the number of samples in a cycle, \( f_s \) was the sampling frequency, \( f_m \) was the signal frequency, and \( N_s \) was the total number of samples.

### 5.2.1.1 Demodulation process

The demodulation process employed a multiply-accumulate process (MAC). The demodulation was performed by multiplying the digitized signal of (5.2) and (5.3), with the reference signal from the DDS (sine and cosine), and storing the result in a look-up table in the FPGA [104]. The stored values are given by

\[
l_i[n] = M_i[n] \times \cos\left(\frac{2\pi f_m n}{f_s}\right)
\]  

(5.6)
\[ Q_i[n] = M_i[n] \times \sin \left( \frac{2\pi f_m n}{f_s} \right) \]  
(5.7)

\[ I_v[n] = M_v[n] \times \cos \left( \frac{2\pi f_m n}{f_s} \right) \]  
(5.8)

\[ Q_v[n] = M_v[n] \times \sin \left( \frac{2\pi f_m n}{f_s} \right) \]  
(5.9)

where \( I_i[n] \) and \( Q_i[n] \), represent in-phase and quadrature components of the current and in the same fashion, \( I_v[n] \) and \( Q_v[n] \) represent the in-phase and quadrature components of the voltage. The signals from (5.6)-(5.9) were fed into low pass filters. The results represented the real and imaginary parts of the demodulated signal [104].

\[ X_i[n] = I_i[n] \otimes F[n] \approx \frac{1}{2} A_{mi} \cos (\varphi_{im}) \]  
(5.10)

\[ Y_i[n] = Q_i[n] \otimes F[n] \approx \frac{1}{2} A_{mi} \sin (\varphi_{im}) \]  
(5.11)

\[ X_v[n] = I_v[n] \otimes F[n] \approx \frac{1}{2} A_{mv} \cos (\varphi_{vm}) \]  
(5.12)

\[ Y_v[n] = Q_v[n] \otimes F[n] \approx \frac{1}{2} A_{mv} \sin (\varphi_{vm}) \]  
(5.13)

where \( X_i[n] \) and \( Y_i[n] \) are proportional to the real and imaginary induced voltages and \( F[n] \) is defined as the low pass filter [104]. A schematic of an I/Q demodulation process is depicted in Figure 5.5.

![Figure 5.5 Simplified signal connection for a digital I/Q demodulator. DDS and MAC components are embedded on FPGA](image)

Source: [149]
5.2.1.2 Analogue – Digital Converter

In order to record the measurements from the sensor, Analogue to Digital converters A/D were employed. A high-speed A/D converter (10 Mega Samples Per Second (MSPS)) was used, from Analogue Devices [150]. Hence, an issue arose from the difference in the clock frequencies between the FPGA and A/D converter.

5.2.1.3 Digital – Analogue Converter

After the signal generation using the DDS, the output had to be converted to an analogue signal. For this purpose, a Digital to Analogue converter (D/A) was required. In this work a 14-bit converter was used. Some important features of this converter are listed below:

- 14-bit resolution
- Parallel interface
- High-speed conversion 165 MSPS

The DAC904 from Texas Instrument [151] was used for high-speed instrumentation, control and waveform generation [151]. The DDS and the D/A had to be synchronised. The actual clock for the D/A in this design was 50 MHz.

To overcome the difference in clock rates between the D/A and FPGA, it was necessary to synchronise the FPGA clocks for the A/D and the D/A. The FPGA worked at 50 MHz and the A/D worked at 10 MHz. The implementation of a Digital Clock Manager (DCM) was the methodology used for the synchronisation. This module divided the system clock by a factor of 5. A DCM was a primitive in the Xilinx© FPGA and was used to implement a divider for the generation of different clock rates.

5.2.1.4 USB Interface (CY7C68013A)

An 8-bit microcontroller (FX2LP) [152] was responsible for performing the USB communication. The MCU FX2LP needed some minimal connections with the FPGA, which can be seen in Figure 5.6. The FPGA monitored the flags A and D to generate the control signals. The FX2LP was used in slave mode, which meant that the FPGA needed to generate the control signals for the communication.

The FX2LP worked at 48 MHz and the FPGA system clock at 50 MHz. The main challenge was to synchronise the MCU and FPGA in order to send and receive the information in a proper way.
5.2.1.5 Signal generation evaluation

This section presents the signal generation results. Three experiments were performed and generated three different signals, as presented in Figure 5.7-Figure 5.12 at a single frequency and at multiple frequency. For the experiments, an Agilent oscilloscope Infinium 9000 series was used to record the signal and analyse the signal in spectrum by FFT. During an experiment with a single frequency, the signal was at 833 kHz. For multi-frequency experiments, the frequencies were: a) two components: 416 kHz and 833 kHz and b) for components frequencies: 833 kHz, 416 kHz, 208 kHz and 104 kHz.

The first tested signal was a single frequency at 833 kHz. A screenshot of the signal is depicted in Figure 5.7. The spectrum was analysed using the FFT; the result is presented in Figure 5.8. Using the FFT the frequency components of the signal could be identified. As can be seen in Figure 5.8, a pulse (spike) was at 833 kHz and the horizontal scale had 1 MHz per division. In the same figure, the other spikes were at low levels as spurious noises. The signal level was approximately 52 dB and the next spike was more than 30 dB. For the experiment with two frequencies, the high spur level was around 48 dB, more than 30 dB away from the spurious frequencies.

![Figure 5.6 Interface signals between MCU FX2LP and controller FPGA to allow USB interfacing. Source: Figure Depicted in [152]](image-url)
Figure 5.7. Signal generated at 833 kHz
Source: Experiments results

Figure 5.8. Signal spectrum recorded 833 kHz
Source: Experiments results
Figure 5.9. Multi-frequency signal recorded 416 kHz and 833 kHz
Source: Experiments results

Figure 5.10. Spectrum recorded 416 kHz and 833 kHz
Source: Experiments results
Figure 5.11. Signal recorded 104 kHz, 208 kHz, 416 kHz, and 833 kHz
Source: Experiments results

Figure 5.12. Signal spectrum recorded, 104 kHz, 208 kHz, 416 kHz, and 833 kHz
Source: Experiments results

5.2.1.6 Demodulation Experiments

For the demodulation process, the experiments were carried out for a single frequency case and for a dual frequency case. A sinusoidal signal was generated and the demodulated data were sent to the host PC and recorded by a C++ program using a GUI
on the host PC. For all the experiment, a series of 1000 demodulated samples were recorded and evaluated. The experiments were performed using a closed loop as depicted in Figure 5.13 (the D/A was the feedback to the A/D).

![Figure 5.13 Experimentation in feedback connection](image)

The signal to noise ratio quantisation relates the signal corrupted by noise and is given by

\[
SNR = \frac{\mu}{\sigma}
\]  

where \( \mu \) is defined as the mean value of the data series and \( \sigma \) is defined as the standard deviation of the samples. The Median Relative Error (MRE) is used to evaluate the quality of the signal generated. The MRE for the evaluation is given by

\[
MRE = \frac{\sum_{i=1}^{L}|V(i) - V_0|}{L \cdot V_0} \times 100\%
\]  

where \( V(i) \) are the samples, \( V_0 \) is the expected value and \( L \) is the length of the data series. The next subsections will present a single frequency of 10 kHz. The second experiment used a multi-frequency demodulation at 10 kHz and 20 kHz. The third experiment was the composite signal of 10 kHz and 50 kHz and the last experiment used a signal at 10 kHz and 100 kHz.

For the first experiment, the selected frequency was 10 kHz. 1000 samples were recorded to evaluate the generated signal. In Figure 5.14, the samples’ demodulated amplitude is plotted. Using equation (5.14), the SNR was calculated and was
approximately 88 dB. The Mean Relative Error (MRE) for the signal was approximately 5.25%.

For the generated signal, the phase was also modulated. The demodulation for the phase is presented in Figure 5.15.

![Image of Figure 5.14: Signal recorded amplitude-demodulated 10kHz](image1.png)

**Figure 5.14.** Signal recorded amplitude-demodulated 10kHz  
Source: Experiments results

![Image of Figure 5.15: Signal recorded phase-demodulated 10kHz, 500 samples](image2.png)

**Figure 5.15** Signal recorded phase-demodulated 10kHz, 500 samples  
Source: Experiments results
Figure 5.14 and Figure 5.15 presents raw data demodulated, with the amplitude and phase respectively. It is clear that the small amplitude variation, for example, Figure 5.14 shows a variation of the third significant number, which is an indicator of a good SNR of the system. In Figure 5.15 the demodulated phase is presented, and similarly it shows a low variation in phase, which indicates a small noise in the phase and presents a good feature of the signal generation. This indicates that the stable signal can be injected into the object under investigation. In comparison with the previous section, Figure 5.8 presents a demodulation using a scope, and the SNR drops up to 55 dB, which implies that the system can operate better in some frequencies, which are a multiple of the bits of resolution used in the DDS. As a conclusion, even if the system can generate a wide range of frequencies, some of those are the optimum, and these will be the multiples of the bits of resolution in the DDS IP core.

5.2.2 Sensor

The sensor was constructed using three coils. The coils formed a gradiometer configuration and as in the Novel sensor configuration, presented in section 4.5. The coils were encapsulated in a plastic enclosure. Figure 5.16 shows a picture of the probe created in this research, the dimensions thereof are explained in section 4.5.

Figure 5.16 Novel sensor probe proposed, sensor encapsulated in a plastic box and sealed with a non-conductive glue.
5.2.3 Software

The FPGA-based Eddy Current instrument was connected to a PC host. The communication between the PC host and the instrument was USB serial communication. Two variations of the GUI were used in this work a) the GUI devoted to control the number of frequencies used in the experiment and b) the GUI used to record data from the experiment. The software was C++ based. Figure 5.17 presents the two GUIs.

![a)](image1)

![b)](image2)

Figure 5.17 C++ based software. a) GUI to communicate the PC host with the Eddy Current System, b) Software used to record the experiment measurement.

The software in Figure 5.17a communicated with the instrument and selected the number of frequency components in the generated signal. Figure 5.17a shows a signal with two components being generated. The second software was used to show the measurements in real time and to record the measurement data in a text document. The
data processing was carried out in MATLAB®. The complete system, which included the probe and the eddy current instrument, is depicted in Figure 5.18.

![Figure 5.18 Complete system, host, instrument and probe](image)

### 5.3 Sample preparation

An electrochemical micro-capillary technique, which was operated under galvanostatic control, was used to generate pits of controlled sizes.

The micro-capillary cell is presented in Figure 5.19. The counter electrode was a platinum sheet, the reference electrode was a Saturated Calomel Electrode (SCE) and the working electrode was a carbon steel plate itself. An example of a carbon steel sample is depicted in Figure 5.19b. The area which was affected by the corrosion process could be controlled using this microcell. Both the size of the pit and its location in the carbon steel sample were known. The diameter of the capillary was 460 microns. The circuit was closed through the electrolyte inside the microcell and a current of 0.6 mA flowed between the carbon steel sample and the counter electrode.
Figure 5.19 Schematic of the electrochemical test. The circuit was closed throughout the electrolyte inside the microcell and the current source: [153]

Different pit generation times of 1, 3, 6, 10, 15 and 20 hours were used to generate pits of varying sizes. The location of each pit was equally spaced at 2.5 cm and was more than 2.5 cm from the edge. An example can be seen in Figure 5.20a. After the tests were conducted, all the pits were examined using a confocal laser-scanning microscope (Keyence VK-X210) where accurate 3D images and morphology information were obtained. Surface optical images and 3D images of the pits are presented in Figure 5.21 from which the generated pits on the surface are semispherical. For the pits that were generated within 6 hours, the edge of the pit is very clear and less corrosive product was observed around the pits as compared to the pits with with longer generation times.

Figure 5.20 Example of the metallic plates, (a) schematic and scanning direction, (b) photo of plate
Figure 5.21 Optical images (left) and 3D images (right) of pits on carbon steel with different generation times. a) 0.6 mA for 1 hour b) 0.6 mA for 3 hours, c) 0.6 mA for 6 hours, d) 0.6 mA for 10 hours, e) 0.6 mA for 15 hours, f) 0.6 mA for 20 hours.

5.4 Experimental results

5.4.1 Scan speed variation

To assess the capability of the instrument in detecting pits, experiments were carried out using the carbon steel plate samples described in section 5.3. The movement of the probe was performed using a closed loop XYZ positioning system with micrometre resolution (M470 Uniscan Instrument). For a particular setup the lift-off variation between the probe and the sample could be minimised while a constant speed of inspection of 2000 μm/s, 1500 μm/s, or 1000 μm/s were maintained. It also enabled accurate control of lift-offs so that the lift-off effect could be studied. The set-up of the experiment is depicted in Figure 5.22.
Figure 5.22 Experimental set-up for the experiment using the M470 Uniscan XYZ positioning system and a carbon steel plate.

During the scan of the metallic plates, 25 k and 15 k data samples were saved using the frequencies selected. The decision to save the specified amount of data was based on the time required to complete a scan of the plate under investigation. The scan started near the left edge of the plate, but far enough to avoid edge effects, as shown in Figure 5.20a. The controlling software used to save the data was developed in C++ as part of a custom package [104].

The inspection occurred near the surface of the metallic plate. The working frequency was selected to carry out a closed loop-back experiment to assess the SNR of the instrument at several frequencies. The working frequency used in this study was 60 kHz.

At each time, a single pit was tested using the set-up explained above. The probe scanned over each pit four times (forward and backward) for each test. This produced 12 measurements for each pit.
Figure 5.23 One hr. pit labelled as A in TABLE 5.1, a symmetrical pattern in the behaviour of the curves is seen. a) Real part and b) Imaginary part

The signals from the same pit showed a resemblance in shape with similar amplitudes and phases. When reversing the scan direction, a symmetrical signal shape was obtained. In Figure 5.23, the scan was carried out on a 1 hr pit at a speed of 2000 μm/s, the signal presented a symmetrical pattern in both the real and imaginary components. The peaks presented in the figure could be related to the dimension of the pit. The same characteristics were present in a 10 hr pit at a speed of 2000 μm/s
depicted in Figure 5.24. Mean filtering was applied to the raw signal to obtain a clear signal (the light green line in Figure 5.23 and Figure 5.24). This filter was selected due to its easy implementation and effectiveness in smoothing the signals.

Figure 5.24 Symmetrical signal from the experiments using a 60 kHz as a working frequency and 2000 µm/s as the scanning speed. Pit D from Table 5.1. a) Real part and b) Imaginary part

Figure 5.24a and Figure 5.24b present the voltage change due to a pit of 10hrs exposure time at a scanning speed of 2000 µm/s. Each peak represented a detected pit. The metrology of this plate indicated that the pit had a diameter of 925 µm and a depth of 559 µm.

The instrument was calibrated a ferrite material and recording the response. In MATLAB® the signal of the object under investigation was subtracted from the ferrite
signal and the air response signal. By applying this process, a high inductance response was obtained. The calibration was conducted by calculating the angle ($\theta$) variation due to the ferrite material and finally multiplying this angle with the recorded voltage.

Table 5.1 Relationship — average— between signal amplitude, depth and diameter

<table>
<thead>
<tr>
<th>Pit</th>
<th>VOLTAGE VARIATION (REAL PART) mV</th>
<th>VOLTAGE VARIATION (IMAG PART) mV</th>
<th>DIAM. ($\mu$m)</th>
<th>DEPTH ($\mu$m)</th>
<th>VOL. ($mm^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.700</td>
<td>2.550</td>
<td>592</td>
<td>148</td>
<td>0.0279</td>
</tr>
<tr>
<td>B</td>
<td>6.546</td>
<td>1.288</td>
<td>633</td>
<td>198</td>
<td>0.0458</td>
</tr>
<tr>
<td>C</td>
<td>6.003</td>
<td>2.504</td>
<td>756</td>
<td>100</td>
<td>0.0203</td>
</tr>
<tr>
<td>D</td>
<td>11.534</td>
<td>4.502</td>
<td>925</td>
<td>559</td>
<td>0.3139</td>
</tr>
<tr>
<td>E</td>
<td>10.758</td>
<td>4.764</td>
<td>887</td>
<td>279</td>
<td>0.1057</td>
</tr>
<tr>
<td>F</td>
<td>11.150</td>
<td>4.54</td>
<td>1016</td>
<td>385</td>
<td>0.2454</td>
</tr>
</tbody>
</table>


**Column Diam. Mean diameter of the pit.

The amplitude results from the experiments are shown in Figure 5.25; the average of the amplitude values for the real part of the measured signals are presented. From Figure 5.25 it can be observed that the signal amplitude for a particular pit at each test remained stable, giving a variation of less than 5% in amplitude. The width of the peak in the signal should be related to the scanning speed. Experiments were carried out at 1000, 1500 and 2000 $\mu$m/s using the 1 hr, 3 hrs, 6 hrs and 10 hrs pits. From Figure 5.26, it can be seen that the width of the peak was inversely proportional to the scanning speed which was as expected.

![Real Amplitude Measurement Signal: 60 kHz](image)

Figure 5.25 Signal from pits produced using different generation times
Figure 5.25 presents the repeatability of the system using different pit sizes. In similar fashion the Figure 5.26 presents the test for 1, 3, 6 10 hrs. pits sizes changing the scan speed. The two main aims for the scan repeatability are: a) the repeatability of the scan detection, this was depicted in Figure 5.25 which shows the amplitude variability; b) determination of the signal variation, this also was the subject of variation of scan speed, which is depicted in Figure 5.26. This result also presents a good performance, for example, comparing the 1000 μm/s result of with the 2000 μm/s result the width of the peak is approximately half of the width at 1000 mm/s. This is the behaviour presented in Figure 5.26. There is one important point to note, that the scan speed was kept constant. The reason is due to the fact that the analytical model presented in previous chapter does not include the variable of the scan speed, but the author assumes the behaviour is important for the reason stated previously.

To show the stability of the system an experiment was carried out by moving the object and keeping the sensor still. this configuration is similar as in Figure 5.16. The result is presented in Figure 5.27, which presents the measurement vs time. Figure 5.27a shows in blue the raw data of the measurement. This has to be calibrated, and is presented in red, where the amplitudes can be seen to remain almost without variation. Conversely Figure 5.27b shows the imaginary part of the raw data, and it can be seen that the system needs some time to reach an stable state. The main reason is the DDS, which need some time to stabilise and synchronize with the working frequency.
Figure 5.27 stability of the system in a long period using 60 kHz. a) Is the real part of a raw signal in blue and calibration in red, and b) is the imaginary part of the recorded and the calibrated signal

5.4.2 Lift-off variation

Lift-off experiments were also carried out. The experiments were performed to assess the effect of lift-off. The probe was placed in a wide range of lift-off distances from 0 μm to 500 μm in steps of 100 μm, from 1000 μm and 1500 μm in steps of 100 μm, and 1500 μm to 5000 μm in steps of 500 μm (see Figure 5.28). The distance was controlled by the XYZ positioning system mentioned in the previous section.
Figure 5.28 Probe and carbon steel sample, evaluation of lift off using a Keyence system.

Figure 5.29 Measurement results of lift-off variation using the FPGA-based system, a) lift-off from 0 to 0.5 mm and b) 0 to 4 mm, step increments of 0.5 mm.
For the results presented in Figure 5.29a, 48 experiments were carried out and arranged as: 4 replication x 2 directions (forward and backward) x 6 lift-off steps. For the result presented in Figure 5.29b, 72 experiments were carried, and arranged as 4 replication x 2 directions (forward and backward) x 9 lift-off steps. These numbers of experiments are the same for the comparison, presented in the following section, in Figures 5.31a and b.

5.5 Comparisons

The comparisons between the model of the novel sensor and its predicted realisation are divided into two sections, the comparison between the amplitudes and the lift off variations.

5.5.1 Amplitude comparison

A strong correlation between the simulation results and measurement results was observed and is shown in Figure 5.30. As mentioned in previous chapters, certain assumptions are made during modelling though these are not necessarily true in practice. The variation could be caused by several factors: excessive corrosive products around the pit area, slight variation in the EM properties of the samples slight errors in volume calculation using the coherent optical method, environment EM noise during the test, inherent instrument noise, or sensor noise due to their components such as resistors and coils. Despite the variation, the detection of pit corrosion was successful even for the smallest pit of the order of 0.0279 mm$^3$ in volume.
The experiments carried out for Figure 5.30 were 56, arranged as: 4 replications x 2 directions (forward and backward) x 7 pit sizes.

### 5.5.2 Lift-off variation

In real world testing, it is difficult to avoid lift-off variations. In addition, for Corrosion Under Insulation (CUI), the coating thickness may present variations. The aim of this section is to evaluate the measurement of the instrument in the presence of lift-off. Two experiments were carried out, a) the first experiment had a lift-off variation from 0 to 0.5 mm in step increments of 0.1 mm and b) the second experiment had a lift-off variation range from 0 to 4 mm in step increments of 0.5 mm. Both experiments were compared with lift-off simulations. From Figure 5.31 it can be seen that the amplitude of the real part of the voltage presented a decreasing trend, which was as expected. A discrepancy of approximately 15% was observed, which may be due to the same reasons stated in the previous section.
Figure 5.31 Lift-off variations in the real part of the predicted signal and the measurement, a) experiment and simulated signal in a the range of 0 to 0.5 in step increments of 0.1 mm and b) experiment and simulated signal in the range of 0 to 4 mm in step increments of 0.5 mm
5.6 Conclusions

This chapter presented firmware development and the experiments conducted during this research. The system described in the presented thesis shows an approximate 80 dB SNR when a single frequency is generated, and the detection carried out using a speed of 1000 μm/ – 2000 μm/s. It has a high sensitivity when a lift-off is considered, and demonstrate the opportunity to detect pits despite lift off variation of up to 5 mm. The SNR drops when a multi-frequency technique is intended to used, as presented in section 5.2.1, Figure 5.9 – Figure 5.12. The main reason of this decay is due to the fact of the truncation of the signal generated. For example at the moment of a dual frequency generation it necessary to truncate some of the less significant digital bits of the final signal. A description of the FPGA-based system, experimental setup and sample preparation was presented. Different variables were studied, such as the scanning speed, working frequency, defect sizes and lift-off. The stability and the sensitivity of the FPGA-based eddy current system was verified to be adequate for the detection of pit corrosion. The amplitude variation measured for particular pits remained less than 5% across repeated tests, which indicated the stability of the instrument and showed the consistency of the measurements. As the scanning speed changed, the signal length decrease due to the pit was as expected, i.e. inversely proportional to the scanning speed. The experiments on the study of lift-off variation showed the response to be as expected.

The correlation between the pit generation time and the signal strength/pit size was weak. This can be related to the imperfect process of pit generation. For example, it is likely that corrosive liquid leakage could have occurred resulting in a wider area of change of EM properties around the intended pit site. Future work could further investigate these aspects of the variation.

Finally, a comparison with a commercial probe is difficult, this is due to: a) the probe in this thesis is designed to be used with the system explained, so the proposed probe could work with a commercial equipment but is likely that the performance of the probe and equipment will substantially decay, b) some of the important parameters like sensitivity, fabrication or accuracy are not presented in all cases. This could compromise several factors like the sensitivity which much of the time depends on the material under investigation, such as conductivity, permeability, EM noise, temperature
and some other factors. However in the following table some parameters of an Olympus commercial bobbin probe are presented.

Table 5.2 Commercial probes parameters, diameter and frequency

<table>
<thead>
<tr>
<th>PART ID</th>
<th>ITEM NUMBER</th>
<th>DIAMETER FREQUENCY</th>
<th>CENTER FREQUENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>mm</strong></td>
<td><strong>in.</strong></td>
</tr>
<tr>
<td>TEB-132-250</td>
<td>U8280455</td>
<td>13.2</td>
<td>0.520</td>
</tr>
<tr>
<td>TEB-134-050</td>
<td>U8280457</td>
<td>13.4</td>
<td>0.528</td>
</tr>
<tr>
<td>TEB-140-050</td>
<td>U8280566</td>
<td>14</td>
<td>0.551</td>
</tr>
<tr>
<td>TEB-148-015</td>
<td>U8280459</td>
<td>14.8</td>
<td>0.583</td>
</tr>
<tr>
<td>TEB-148-050</td>
<td>U8280628</td>
<td>14.8</td>
<td>0.583</td>
</tr>
<tr>
<td>TEB-158-015</td>
<td>U8280461</td>
<td>15.8</td>
<td>0.622</td>
</tr>
<tr>
<td>TEB-158-250</td>
<td>U8280629</td>
<td>15.8</td>
<td>0.622</td>
</tr>
</tbody>
</table>

Some other features presented for these commercial bobbin probes are: lightweight, solidly built, coil protected by a plastic sleeve, economical solution, with stainless steel wear guides at front and rear ends, which can be compared with the probe presented in this thesis. Additionally, the novel probe is handmade, resulting in an economical solution due to the fact that the coil is constructed with copper wire and protected with a plastic material. As mentioned previously, the novel probe is specifically designed to fit the custom built FPGA instrument.
Chapter 6 Conclusions and future work

The application of the eddy current method for pitting corrosion detection has been presented in this thesis. The work combined the analysis and optimization of a novel probe, validation of analytical solutions, generation of representative corrosion samples, FPGA programming and experimental validation amongst other works. This chapter summarises the work presented throughout this thesis, and presents the conclusions based on the achieved objectives during the research. Finally, potential future work is discussed.

6.1 Conclusions

The aim of this thesis was to contribute to the detection of pitting corrosion at its early stages. This research designed an FPGA-based eddy current instrument and a novel differential probe. In combination, they increased the sensitivity to detect pits in the range of hundredths of micrometres to millimetres. To the best knowledge of the author, this is the smallest detectable pit for current eddy current methods. The developed firmware for the FPGA consisted of VHDL modules which generated the excitation signal, converted the received signal from analogue to digital, demodulated the received signal and transmitted the demodulated I/Q data to a PC through USB communication. All these processes had to be precisely synchronised so that the instrument could deliver its best performance in terms of sensitivity. Pitting corrosion is considered to potentially be the most dangerous type of corrosion amongst the different corrosion types. The major challenge was to increase the sensitivity of the instrument to detect the pitting corrosion, particularly during its early stages.

Thus, the main aim of this thesis was to design an instrument with superior sensitivity. This aim was divided into two aspects; firstly, proposing, constructing and analysing a new sensor and secondly, realising key functions in a FPGA in a synchronised manner. Thusly, coherent data was acquired and the noise was minimised in the D/A, A/D and demodulation processes. To achieve this aim, several objectives
were proposed and accomplished which contributed to the positive detection of pitting corrosion in the range of hundredths of micrometres. By reviewing the main objectives outlined in Chapter 1, the contribution of this research is summarised and final comments are provided.

- **Proposing, designing, analysing and optimising a novel probe for corrosion detection.**

  A novel differential sensor was proposed which minimised the background signal for plate scanning. In addition, the designed probe had an advantageous feature in that the sensor response could be analysed using a closed form analytical solution. The analysis was based on an adaptation of the analytical solution proposed by Dodd and Deeds. The analytical solution was based on the calculation of magnetic vector potentials in several regions. Two classical geometries were treated in section 4.2. The two classical problems, a) a planar sensor coil and b) a cylindrical sensor coil were solved using MATLAB®. They were extended for the analysis of the novel probe proposed by the author. The final analytical model for the designed sensor involved the integration of a variable in an infinite range. The range of the variable was selected to optimize a trade-off between the accuracy and the computation time/effort of the problem. By selecting an optimum value for the integration variable, the solution provided an accurate analysis.

  The validation of the analytical solution was done by comparing the analytical and numerical solutions. The numerical solution was constructed in COMSOL® and discussed in section 4.3. The conclusion suggested that the analytical and numerical solutions presented good agreement at lower frequencies. However, at higher frequencies, the analytical solution had superior performance both in terms of accuracy and computation time. It should be noted that it was a deliberate choice of the sensor design, which enabled the application of a wholly analytical solution. Needless to say, numerical approaches have their advantages when other complex coil geometries are involved.

  The discrepancy that arose in the validation of the approaches when a higher frequency was used was the main motivation behind adapting the analytical solution to the proposed novel probe. The sensor proposed in this research consisted of three coils. Two of them served as the excitation source. The remaining coil acted as the receiver,
which registered the induced voltage changes during the test. The previous established analytical solution could not be applied directly to the described probe configuration. Instead in this research a methodology was proposed to apply on analytical solution to the novel probe. The methodology was discussed in section 4.5 and it provided positive results for the novel probe. A prediction of signals due to realistic pitting corrosion was carried out. Having the analytical solution for the novel probe, an optimisation was carried out to select the distance between the two excitation coils to produce a uniform excitation field. The substantial advantage was the time consumed and the accuracy. The analytical solution took the order of a couple of seconds, while a 3D numerical solution would require many minutes and still deliver the results with inferior accuracy.

- **Optimising an FPGA-based Eddy Current instrument capable of detecting pitting corrosion in the range of hundreds of microns.**

Pit sample generation was achieved by applying an electrochemical micro-capillary technique operating under galvanostatic control (section 5.3). Applying this generation technique presented two characteristics. Firstly, the geometry and the chemical conditions of the generated pit simulated realistic pit corrosion. Secondly, the pit dimensions achieved by the micro-capillary technique remained in the ranges of early stage pitting, which was the range of detection targets for this thesis. The pitting samples were generated using a microscope confocal laser Keyence VK-X210.

The development of the firmware in VHDL was carried out for the operation of the eddy current instrument. The firmware provided precise synchronisation of key electronic components in the eddy current instrument. The FPGA and D/A worked at 50 MHz, the A/D worked at 10 MHz and the communication was implemented at a much slower rate. To overcome the difference in clocks rates, it was necessary to synthesise and implement a Digital Clock Manager (DCM). The developed firmware showed successful end results in the sensitivity and stability of the instrument for reliable pitting corrosion detection.

Two frequencies were used in the experiments, these were 30 kHz and 60 kHz. These frequencies were selected by evaluating the best SNR from a set of experiments using the instrument itself as presented in section 5.2.
In conclusion, the developed instrument and the novel probe accomplished the goals of the Ph.D. research work, i.e. the detection of early stage pitting corrosion. The next subsection will present possible future work.

6.2 Future work

Besides the novel sensor and instrument for effective pitting corrosion detection, design and simulation, some additional work could be done to complement the work done to date and continue the research contribution. As mentioned before, effective pitting corrosion detection of a few microns was presented. Quantification and shape reconstruction is work that could be extended using the result from this research.

Shape reconstruction and quantification would give a better understanding of the damage due to pitting corrosion. The unknowing shape and estimation of the flaw parameters lead to better actions to mitigate the corrosion problem. In addition, the pitting corrosion considered in this research was semi-spherical in shape. In the corrosion literature, several shapes of pitting corrosion can be found. The shape of the pitting corrosion could be studied using the FPGA-based instrument with the presented novel probe. Extraction of the geometrical features of the defects could then be explored.

The FPGA allows for reconfiguration of the instrument. Multi-frequency operation could be validated in future work. Some work using a multi-frequency mode was carried out during this research. However, due to the time limitations of the research, the scope was limited to a single frequency mode. The work using a multi-frequency technique was published using the generation of the working signal. Future work remains in experimenting using this setup and having up to seven components in the generated signal.

Chapter 4 presented the simulation of two configuration problems in relation to the Eddy Current Method i.e. planar and cylindrical. This thesis’ aim was the corrosion detection in a planar configuration. This work could be expanded to a cylindrical configuration. Some simulation work has already been done and so it would only be natural to expand this work to the cylindrical configuration.
Finally, as previously mentioned, the experiments were carried out at 30 kHz and 60 kHz. In the future, more experiments could be carried out using a wider range of frequencies and studying the instrument-probe response.
References


[143] W. Yin, G. Chen, J. Jiang, and Z. Cui, “The design of a FPGA-based digital magnetic induction tomography (MIT) system for metallic object imaging”, in


