



Assessment and validation of the Lyft System for detection and sizing of CUI with FE modelling

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A dissertation submitted to the University of Wales Trinity Saint David in accordance with
the requirements for the award of MSc Non-Destructive Testing and Evaluation.

September 18, 2017

DECLARATION/STATEMENTS PAGE

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Dedicated to my family, for having given me all the support and love throughout all this
year and all my life.

Acknowledgements

I would like to thank my tutor, Peter Charlton, who has been alongside me throughout all of this year, and who has proven to be a vital source of knowledge and inspiration that helped me to complete this investigation and the course in general.

I would also like to thank the kind people of Oceaneering and more specifically Richard Granville for having allowed me to perform all the tests and experiments required for this work in the company's facilities, as well as having provided me with training and capacitation in the use of the Lyft system without which I would have struggled to complete this dissertation.

I would also like to express my gratitude towards Liam, Ashley and Luca who were always there to assist and guide me no matter how many questions I came up with, and who made my stay in Swansea a lot more pleasant.

Abstract

Corrosion under insulation (CUI) represent one the unresolved issued that many industries face. It appears on the surface of carbon steel components that are under insulation and a weather jacket, when there is a presence of moisture and oxygen. CUI can cause many economic losses when undetected. Pulsed eddy current testing is a relatively new technique used for the inspection of electrically conducting and ferrous materials, it contains a lot more defect information when compared to conventional eddy current techniques, due to the use of an excitation pulse that contains broadband frequencies. PEC inspections can be performed without the need of removing the insulation and non-ferrous cladding. One limitation when using PEC systems is that undersizing of defects occurs when a lift-off is present. The Lyft system is an innovative technology created by Eddyfi, especially developed for the detection of CUI. Lyft has a new and unique tool that helps to compensate the undersizing effect. The CWT tool is underdevelopment, thus the importance of this thesis, which contains a validation and assessment of the screening tool in order to observe how accurate are the calculated results with the CWT tool when those are compared with the uncorrected data from an inspection in contact with the same Lyft system. This thesis also includes a transient eddy current analysis of PEC testing through finite element analysis using Quickfield. The software allowed to simulate the Lyft system capability by performing a circuit analysis of a simple send-receive type probe over a carbon steel plate and through insulation and cladding. The simulation in contact showed the differences between the signals from defects with different length and depth and the signal from the nominal wall thickness (no defect); whereas the simulation through insulation and cladding showed how the presence of lift-off affects the circuit analysis.

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Chapter 1

Introduction

1.1 Motivation

Carbon steel is one of the most used materials by many industries despite its low corrosion resistance. Industries such as oil and gas, mining, construction, transportation, nuclear power and offshore plants take advantage of the low prices of this material and use it in different equipment, pipelines, columns, tanks and vessels, which most of the time work at elevated temperatures (-4 °C to 175 °C), therefore an insulation needs to be installed to avoid heat loss, to protect workers and maintain an efficient process. By insulating those components, corrosion could appear if there are moisture and oxygen between the component surface and the insulation material. Corrosion can be avoided if the proper protection system is used, but in the end, corrosion is a natural process that all materials face when in contact with oxygen to go back to its stable form. Insulated pipes are covered with an insulation material and a non-ferrous cladding, the latter is installed to avoid contact between water and the pipe surface. The optimum conditions for corrosion under insulation (CUI) to appear are water, oxygen, chlorides and moisture from the insulation material.

In the recent years, pulsed eddy current (PEC) systems were developed to inspect CUI, one of the costliest problems that many industries face. In contrast with standard eddy current

techniques, PEC has more penetration and the given results are more accurate and easier to understand. Lyft is a new system developed by Eddyfi to inspect corrosion under insulation on ferrous pipelines without the need of removing the insulation. Lyft is a user-friendly and less operator-dependent system; one of the new features that make it stand out from old PEC systems is the wall thickness compensation tool (CWT), a new algorithm which helps to minimise the problem of under sizing defects. This led to set the aim of this thesis, validate the CWT tool by comparing the remaining wall thickness of the corroded areas with and without the compensation from the new tool, when the insulation is installed and when removed. The Lyft system is relatively new and is still under development, thus the importance of performing an assessment and validation before it is widespread in the industry. The study also includes a parametric transient electromagnetic simulation to evaluate and understand several variables involved in a process.

1.2 Pulsed eddy current testing

Eddy current testing (ECT) is based on the principle of electromagnetic induction, discovered by Michael Faraday in 1831. Electromagnetic induction is the current developed in a conducting surface when the magnetic field of an eddy current instruments coil is in contact with that conducting object (Hellier, 2003). Technicians are well trained to read the received signals on the equipment screen, if there are any discontinuities in the material there will be some disturbances in the circulation of the eddy currents and these are seen in the screen receiver. The EC probes use a continuous wave at a single frequency. For the detection of deep sub-surface defects, lower frequency or higher excitation current needs to be applied to those probes, but this leads to the heating of the probes (Arjun et al., 2015). Pulsed eddy current techniques are used to overcome this problem, it uses a square wave pulse (multi-frequency) as the exciting source, which gives stronger penetration and high accuracy (Liu et al., 2010). This allows inspecting materials under insulations and weather jackets. Pulsed

eddy current testing is a relatively new technique. Studies started in the late 70's, but commercial equipment was not yet available at that time (NDT-Resource-Centre, 2017). This thesis is based on the study of a relatively new equipment developed by Eddyfi, a reinvented technology known as Lyft. Undersizing is a typical problem in PECT, a new algorithm was developed to provide a better estimate of defect sizes, this Lyft tool is assessed and validated in this research. By using QuickField, a transient magnetic module can be used to simulate the behavior of PEC system, as it can create pulses generated by the electric field of the probe and it can also calculate the eddy currents and the resulting field, for then to observe and interpret its behavior in the wall thickness of the pipe (TeraAnalysis, 2016).

1.3 Aims and objectives

The research literature suggests that the principal limitation of the new PEC system, Lyft, is that it under sizes the depth of the defects when they are smaller than the footprint of the probe. Under sizing avoids the reporting of accurate remaining wall thickness readings. The owners state that this problem is reduced by the new Compensated Wall Thickness (CWT) tool.

The problem leads to define the principal hypothesis of the thesis, the compensated wall thickness (CWT) tool from Lyft helps to improve smaller-than-averaging-area defect sizing. The aim of this thesis is the assessment and validation through experimental methods of the unique Lyft tool, used for the inspection of corrosion under insulation (CUI).

The sample was provided by Oceaneering, a carbon steel pipes with corrosion scabs covered with an insulating material and a weather jacket. The inspections will be performed through the insulating material and cladding and in contact with the pipe. Results from both tests will then be compared. This leads to defining one first objectives of this thesis:

- Perform the validation of results through POS (probability of sizing) statistical analysis using the data obtained from the PEC system. POS analyses will be used to accurately

determine the dimensions of all defects.

To aid in interpreting the outcomes of the experimental validation work and to compare real results with an ideal situation, simulations will be performed, which leads to defining the second and last objective:

- Undertake a parametric transient electromagnetic simulation study to help with the interpretation of the results.

After achieving all aims and objectives, a report will be written with a validation of pulsed eddy current corrosion mapping tool used to detect corrosion under insulation. A set of recommendations based on the collection of data will also be given for it to be considered in future investigations at both the academic and industrial levels.

1.4 Research methodology

To achieve the aims and objectives of the thesis, the company allowed to use their premises and the Lyft kit to inspect a carbon steel pipe with and without insulation and cladding, the location of defects was unknown to the operator. Through the desktop version of the newest Lyft system, the compensated wall thickness (CWT) of all scabs has been calculated and a comparison with the results obtained before the compensation, with and without the insulation has been carried out. The comparison has been performed by carrying out a suitable statistical analysis through the probability of sizing (POS).

For further analysis of PEC techniques, a transient magnetic module has been performed using Quickfield software, which has helped understand and compare the real results from the PEC inspection with an ideal situation. The model has been capable of simulating the magnetic field distribution calculated outside and along the pipe, as well as the generated eddy currents in the conductor.

1.5 Contribution of the thesis

This thesis contains the following contributions:

- An assessment and validation of the unique compensated wall thickness (CWT) tool of Lyft, which is used to reduce the under-sizing effect when using pulsed eddy current to inspect corrosion under insulation - study needed before the system is used across the industry.
- A suitable statistical analysis through POS to show how accurate are the CWT measurements.
- A transient electromagnetic simulation using Quickfield to compare and understand the inspection results with an ideal situation. Quickfield proved to be powerful software for the study of pulsed eddy currents and to simulate the Lyft system.

1.6 Organisation of Thesis

The main parts of this thesis are Corrosion under insulation of carbon steel, Nondestructive testing, Eddy current, Pulsed eddy current, Lyft system and PEC simulations. Each one of these parts is contained in Chapter 2, where the respective literature review are carried out. The principle of Eddy Current (EC) and Pulsed Eddy Current (PEC) techniques are thoroughly explained, as well as the history, advantages and limitations of PEC and some previous studies which are mentioned to provide relevant background to this thesis. The description of the system used for this study is given in section 2.5. The last section 2.6 gives vital information about the parametric transient electromagnetic simulation performed. The second part in Chapter 3, shows all the real data obtained from the PEC system with its suitable statistical analysis to validate the hypothesis of this thesis. Simulations are also shown and evaluated in this section. The last Chapter contains the conclusions and recommendations for future studies.

Chapter 2

Literature Review

2.1 Corrosion under insulation of carbon steel

Carbon steel is the most widely used material in engineering. In 2015, the UK produced 11 million tons of steel (see figure 2.1) and it is estimated that 80-90% of that steel goes to the production of carbon steel. The EU produced 166 million tons of steel in the same year, the UK is the fifth biggest producer of steel in the EU (Rhodes, 2016). Carbon or mild steels have less than 2% (in weight) of alloy content, which makes the material susceptible to corrosion. Despite the relatively low corrosion resistance of carbon steel, the production of this material remains high as it is used by many industries such as marine, oil and gas, transportation, mining, construction, manufacturing and others. Because of the high demand of carbon steel, it is easy to understand that the cost of metallic corrosion is measured in millions of pounds per year. All those industries work hard to provide the correct protective system to avoid corrosion or to at least prolong the lifecycle of the material.

Corrosion under insulation (CUI) is an electrochemical process that occurs because of the presence of oxygen and moisture (Silva et al., 2014). CUI generally appears in the form of general or localised corrosion in a range of 24 to 120 °C, but the most severe temperatures are between 45 and 95 °C.

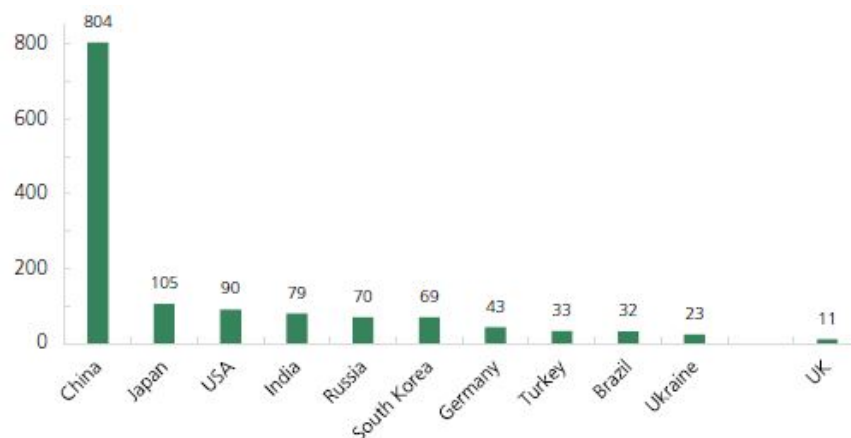


Figure 2.1: Top ten producers of steel and UK (Rhodes, 2016)

CUI is one type of corrosion that has received great attention in the recent years by the operators in gas, chemical-processing, and petroleum plants. A substantial number of vessels, pipelines, tanks, heat exchangers are often insulated to conserve energy by keeping hot processes hot and the cold processes cold or to protect the components from the harsh marine environment. There was one time that once the insulation was installed and the component worked properly, the condition of the metal under the insulation was forgotten. It was not until the late 1970's that the problem of corrosion under insulation was observed when the operators changed the 10 to 20-year-old insulation, only to conserve more energy (Committee, 1987).

Insulation is everywhere in any plant. For example, in a small-size petrochemical industry insulated carbon steel pipework, exposed to a marine environment, could reach 1.2 km long, whereas a medium-size oil refinery contains an approximate of 360 km of insulated piping and more than 25 football fields of insulated tanks, equipment and vessels (see an example in figure 2.2). It is estimated that 10% to 30% of the insulation gets damaged within one to three years of the installation. The damage of the insulation cladding could allow water to penetrate into the material insulation, which causes corrosion.



Figure 2.2: a) Insulated pipework and b) Insulated vessels

This is why inspections and repairs, which could be performed during operation, is so important and the costs of it are insignificant compared to the potential savings if no insulation was installed or if no inspection and repairs were carried out (ROXUL).

Carbon steel corrodes when water and a free supply of oxygen are present. Without oxygen, corrosion would be insignificant. Insulation is installed to avoid any space for water to collect and any access of oxygen (air). Some of the active spaces for water and oxygen to enter through the insulation is when steel passes through the insulation material to, for example, an insulation support rings, ladders, platforms, etc; other active places are when the insulation terminates at flanges or other components, when the insulation is damaged, etc. The figure 2.3 shows a typical CUI cycle on a horizontal pipe with the hot product inside of it, where water enters through the insulation cladding and gets trapped on the bottom side. When the cycling temperatures vary to room temperatures, the corrosion rates are high. The corrosion rate of carbon steel is controlled by temperature and presence of oxygen.

To prevent corrosion under insulation there are two options, one is to add a corrosion inhibitor (water soluble) to the insulation, such as Na_2SiO_3 . But laboratory tests show that this has no benefit for the long-term protection as if water runs through the insulation, the water-soluble inhibitor will be extracted. Another option is to rely on a more effective waterproofing, however, these systems do not prevent water vapour and air from contacting the

The CUI Cycle

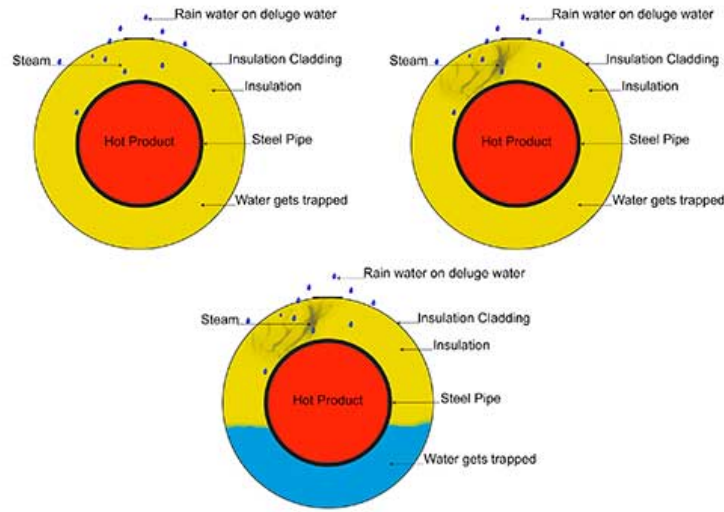


Figure 2.3: The CUI cycle

annular space. Therefore, an inhibitor and a waterproof insulation are not the most effective solutions to prevent corrosion. Instead, the surface of the steel could be covered with a high-quality protective coating and this will be the best long-term solution (Committee, 1987).

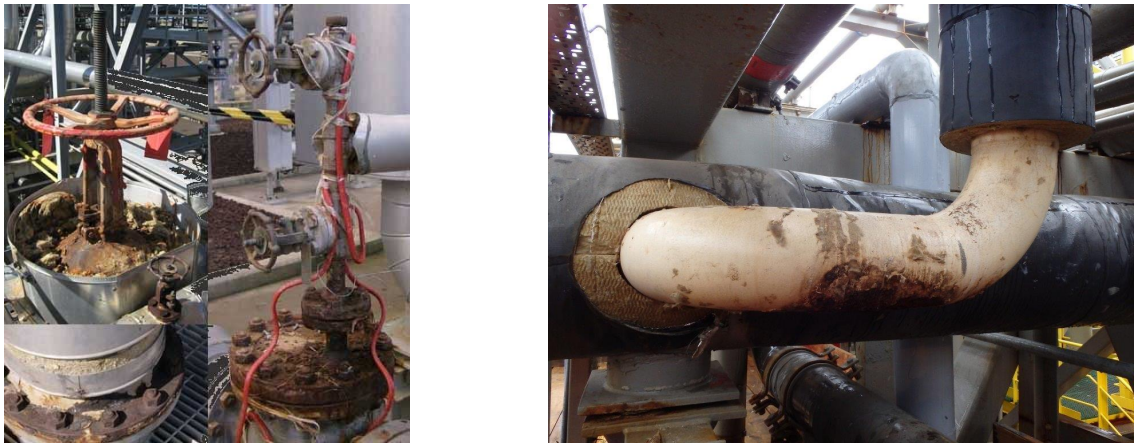


Figure 2.4: Severe corrosion under insulation

Some insulating materials available in the market are fibreglass, mineral wool, ceramic fibre and calcium silicate (Silva et al., 2014).

If corrosion under insulation is not detected at the right time, it could cause catastrophic

effects, costly plant shutdown and in some rare cases, safety incidents. Maintenance, monitoring and inspections every now and then are key to avoid these undesirable effects. There are several non-destructive techniques available nowadays, such as visual and ultrasound inspection, radiographic examinations, ultrasonic guided wave, which have their advantages and disadvantages.

The Visual inspection, which could eliminate any misinterpretation from nondestructive techniques, however, is very impractical, especially if the insulation material is toxic and expensive as the insulation would need to be removed. Ultrasound wall thickness measurements are also an impractical technique, insulation would also need to be removed as the probes need to be in contact with the test piece and are difficult to apply at high temperatures (Grenier et al., 2016). In both cases, insulation would need to be reinstalled properly because it could cause areas for water ingress.

Radiographic inspection can easily be used for the detection CUI but is limited to inspect small areas at a time so inspecting long insulated pipe lengths would take too long, access to both sides of the component is also needed and safety issues are involved as this technique is a form of electromagnetic radiation, which is harmful to the inspectors and those around them (Caines et al., 2013; Cheng and Komura, 2012).

Ultrasonic guided wave is another useful technique that only needs a small portion of insulation removal to install the equipment, it can detect external and internal corrosion in long-distances pipelines, however, the detection sensitivity is not high, because of the external noise and attenuation of the guided wave at long distances (Lai et al., 2015). Ultrasonic guided wave inspection can be used in combination with pulsed eddy current, the technique under evaluation in this thesis; both techniques are under development and need assessment and validation before it is adopted on mass in industry.

2.2 Nondestructive testing

Non-destructive testing (NDT) technologies are not commonly known by the average person although it has been in use by engineers and technicians in many industries for decades. The main purpose of these tests is to detect and evaluate any flaws within a material without causing any damage (BINDT, 2017). However, they not only involve the process of finding discontinuities or the presence of other conditions that affect the serviceability of the material, they could also evaluate other characteristics such as grain size, dimensions, alloy content, hardness, internal stress, etc.

Most of the NDT techniques appeared in the late 1920's but it has shown a rapid growth in the last 40 years and it keeps on growing because of its importance in many industries. It can be applied to an automated production process or to evaluate a specific area that is known to be prone to failure. These methods basically help to keep our world safe; however, this does not mean that NDT inspections will guarantee that the material will not fail, all of the techniques have limitations, some more than others, this is why it is so important to understand the technique, the material itself and the nature of the discontinuities under the specific conditions (Hellier, 2003).

All of the nondestructive testing techniques that are in use nowadays include visual testing (VT), liquid penetrant testing (PT), magnetic particle testing (MP), radiographic testing (RT), ultrasonic testing (UT), thermal infrared testing (TIR), acoustic emission testing (AE) and eddy current testing (EC). In this thesis, a type of eddy current testing, known as pulsed eddy current testing is analysed.

2.3 Eddy current

2.3.1 Basic principles of eddy current inspection

It is important to review the basic principles before explaining the eddy current theory, this following section is focused on the scientific principles of electricity and magnetism.

- **Electricity**

All materials are made of atoms (the smallest unit of any element), these contain a maximum of eight electrons on the outer shell. If the atom contains seven or more, the material will not conduct electricity (insulator). On the other hand, if the atom contains three or fewer electrons, the material is a conductor. If the number of electrons is between four and seven, the material is known as a semiconductor. This ability to conduct electrons is called conductivity. This is key in EC testing, as only conductive materials can be inspected.

If a voltage (also known as an electromotive force, EMF) is applied, there will be a movement of electrons, called electricity or current. There will always exist some opposition to the current flow as electrons will be attracted to their atoms, this opposition is known as resistivity.

Conductance is the ability of a body to the flow of electricity, resistance is the opposition to this flow; both depend on the conductivity, length and cross section area of the body.

After explaining the previous principles, all can be related thanks to Ohm's law, which states:

"The electrical current (I: Amperes) flowing in a circuit is proportional to the voltage (V: Volts) and inversely proportional to the resistance (R: Ohms)"

$$I = \frac{V}{R}$$

- **Magnetism**

Is the phenomenon that exists because of the motion of electrons in an atom, therefore a force of attraction or repulsion between materials will appear. A magnet has two opposite

ends called north and south poles, usually known as dipoles as they always exist in pairs. Magnets have a force field in form of closed loops, called magnetic flux (Φ in Webers). See figure 2.5. The number of lines per unit area is called flux density (B), the Maxwell (Mx) is one line of force, 1×10^8 Maxwells or lines is a Weber (Wb), one line of force per square centimeter is a gauss (G) and a Tesla (T) is one Weber per square meter.

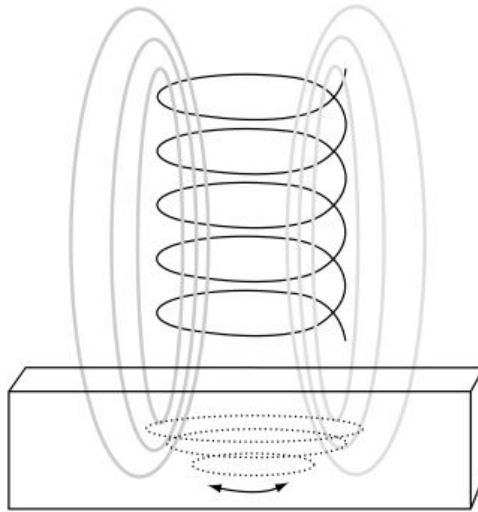


Figure 2.5: Flux density distribution. Hellier (2003)

To calculate the amount of magnetic flux that passes through a cross-sectional area, the following formula can be applied:

$$\Phi = BA$$

The intensity of a field depends on the flux density. By applying the inverse square law, the flux density is inversely proportional to the square of the distance from the poles of the magnet, therefore, as the distance from the magnet increases, the flux density decreases. Materials can be magnetic or nonmagnetic. Magnetic materials are classified depending on their response to external magnetic fields, such as ferromagnetic, paramagnetic and diamagnetic. Diamagnetic materials are not susceptible to magnetic fields (examples are gold, copper, silver); paramagnetic materials are slightly magnetised and do not retain the magnetic properties (examples are aluminium, platinum). Ferromagnetic materials are strongly magnetised and retain the magnetic properties after the magnetic field is removed (examples are iron, car-

bon steel, nickel). When ferromagnetic materials are magnetised, all the domains are aligned. Domains exist in the grain structure of these materials, they are small magnets consisting of groups of atoms. When a material is solidified, each domain is randomly orientated.

- **Permeability**

Another important property to describe, permeability is known as the ability of a material to be magnetised. The process of magnetisation of a ferromagnetic material follows a hysteresis loop, see figure 2.6, (AspenCore, 2017), which shows the relationship between the flux density (B) or magnetisation (M) and the magnetising force (H).

$$\mu = \frac{B}{H}$$

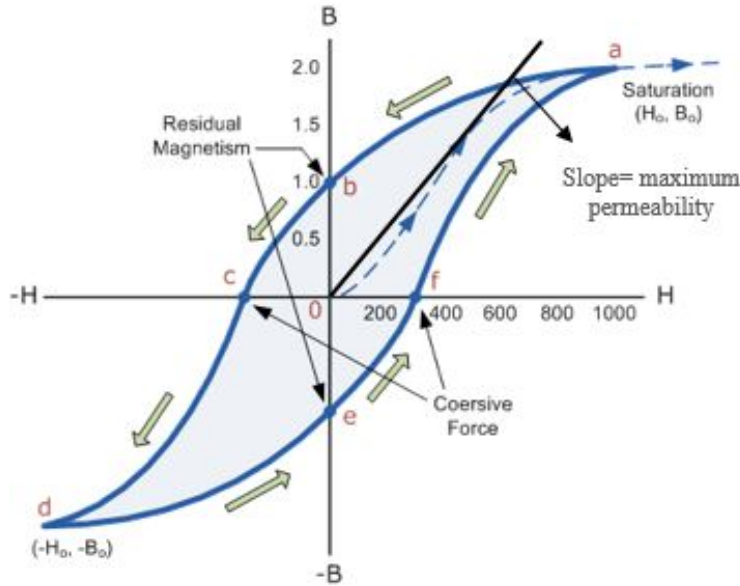


Figure 2.6: Magnetic hysteresis loop

If the ferromagnetic material is magnetised for the first time, it will follow the dashed line until saturation is reached, at this point all domains are aligned, any changes in the magnetizing force will not cause any changes in flux density. When the magnetizing force is removed, the material would retain some flux density; the appropriate property that describes this

remaining magnetic field is retentivity. The retentivity and remaining flux are only the same when saturation is reached, otherwise, the remaining flux could be less than the retentivity. The coercive force is the required force to unmagnetise the material; demagnetization is a very important process as residual magnetism can: attract debris or cutting machines and interfere with electronic equipment.

Relative permeability is the most used term and is found by dividing the permeability of the material by the permeability in free space or air ($4\pi \times 10^{-7}$ H/m).

$$\mu_r = \frac{\mu_{material}}{\mu_{air}} = \frac{\mu}{\mu_0}$$

Relative permeability of paramagnetic materials is $\mu_r > 1$; diamagnetic materials is $\mu_r < 1$ and of air is $\mu_r = 1$.

- **Electromagnetic induction in eddy current testing**

The process of induction is explained below with a pair of coils, a primary coil (multiturn) that represents the eddy current test coil and a secondary coil (single turn) that represents the sample to be tested:

1. An alternating voltage is applied to the coil circuit thanks to an alternating current generator. The resistance voltage V_R , part of the total voltage, is applied to move current through the resistance of the coil wire.
2. A current I_P (the primary current) is generated in the coil thanks to V_R .
3. An alternating magnetic field Φ_P is developed because of the alternating current; this is known as electromagnetism.
4. Electromagnetic induction occurs in the coil wire, in other words, self-induction occurs because of Faraday's law that states that the amount of induced voltage is proportional

to the rate of change of flux variation:

$$V_L = \frac{d\Phi}{dt}$$

That induced voltage, called back emf, V_L , is the additional voltage created by the alternating magnetic field, induced 90° out of phase with the coil current and flux. See figure 2.7.

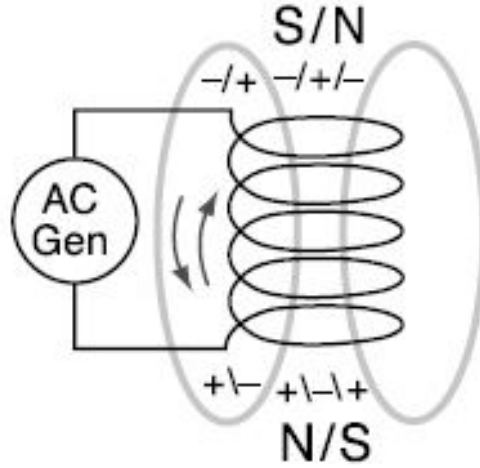


Figure 2.7: Self-induction process, back voltage is developed. Hellier (2003)

5. An opposition to the changes in the coil current will occur because the back emf is out of phase. The opposition of alternating current flow is known as inductive reactance, X_L , this resistance can only occur in an AC circuit and different to R, which can occur in a DC or AC circuit.

$$V_L = IX_L$$

$$X_L = 2\pi fL$$

Where X_L : inductive reactance, V_L : induced voltage, f: test frequency and L: coil inductance (which is derivitted from Faraday's law and is shown later).

6. When the secondary coil is placed near the primary coil, mutual inductance occurs,

Φ_P induces a voltage V_S in the secondary circuit, induced 180° out of phase with the primary flux.

7. A current I_S is induced in the secondary circuit by V_S (same phase); I_S represents the eddy currents. See figure 2.8.

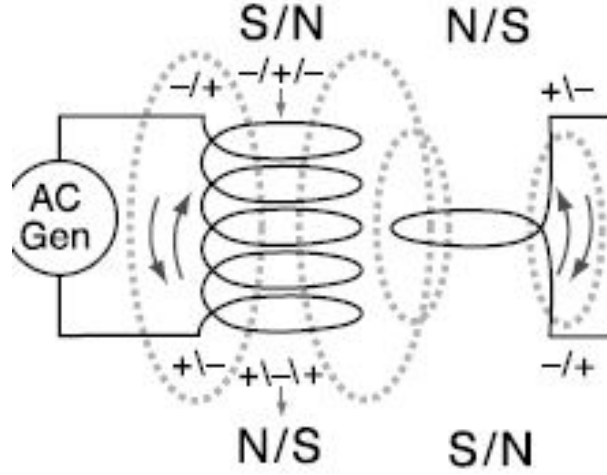


Figure 2.8: Mutual induction process. Hellier (2003)

8. A secondary flux, Φ_S , is developed by the flow of the currents in the secondary circuit with the phase of the secondary current.
9. Heinrich Lenz's law states that the induced current has a direction to make the secondary magnetic field to oppose the primary magnetic field, therefore the minus in Faraday's law:

$$V_L = -N \frac{d\Phi}{dt}$$

This is observed in the 180° phase difference between the two circuits. The opposition causes a reduction of the primary field, therefore a reduction of the net flux of the two coils.

From the modified Faraday's law, the coil inductance (L) can be derived:

$$V_L = -N \frac{d\Phi}{dt}$$

$$V_L = -N \frac{dBA}{dt}$$

By assuming the area of B is uniform:

$$V_L = -NA \frac{dB}{dt}$$

$$V_L = -NA \frac{d}{dt}(\mu H)$$

From Ampere's law (see appendix for derivation), H is:

$$H = \frac{NI}{l}$$

$$V_L = -NA \frac{d}{dt}(\mu \frac{NI}{l})$$

$$V_L = -\frac{N^2 \mu A}{l} \frac{dl}{dt}$$

Therefore, the coil inductance, L is:

$$L = -\frac{N^2 \mu A}{l}$$

Where A: cross-sectional area of the coil, N: number of turns, l: coil length and μ : permeability of the coil core ($\mu = \mu_r \mu_0$).

During an eddy current inspection, V_L and V_R change with the properties of the tested sample. Changes in V_R do not occur because of a change in the resistance of the coil, it changes because when the eddy current flow through the material, friction is present, so there is an energy loss from electrical energy to thermal energy, that loss through heat is counteracted by an increase in V_R only to keep the coil current constant (Hellier, 2003).

- **Impedance plane**

If the phase difference between V_L and V_R is 90° they can be vectorially added to produce

V_T , which is the net voltage in the primary circuit:

$$V_T = \sqrt{V_R^2 + V_L^2}$$

And just as V_L and V_R , X_L and R can also be vectorially added to calculate the impedance Z of an eddy current system (see figure 2.9):

$$Z = \sqrt{R^2 + X_L^2}$$

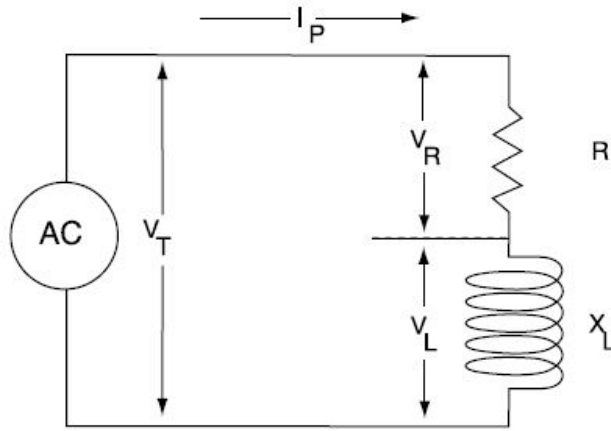


Figure 2.9: Circuit of an eddy current system. Hellier (2003)

If there is more inductive reactance than resistance, the impedance line will be closer to the resistance line and the phase shift will decrease. If there is more resistance than inductance reactance, the phase will increase and the impedance line will be closer to the inductive reactance. See figure 2.10

The phase angle of the circuit is the proportional relationship between the resistance and the inductive reactance:

$$\phi = \arctan \frac{X_L}{R}$$

It is important to understand that Ohms law can be adapted to calculate X_L and R

$$X_L = \frac{V_L}{I}$$

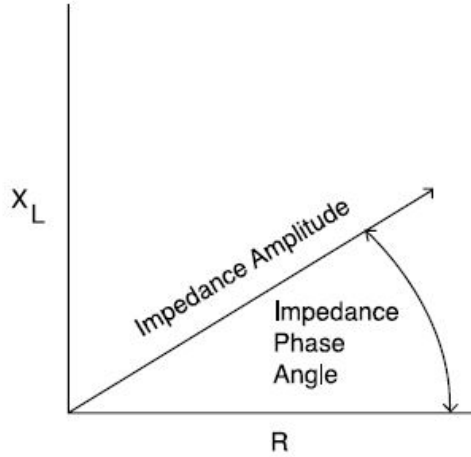


Figure 2.10: Impedance angle and phase angle. Hellier (2003)

$$R = \frac{V_R}{I}$$

$$Z = \frac{V_T}{I}$$

Where I [Amps] is the same across the circuit; V_L , V_R and V_T : [Volts] and X_L , R and Z : [Ohms] (Hellier, 2003).

- **Eddy current testing**

Eddy current testing is based on the principle of electromagnetic induction, discovered by Michael Faraday in 1831. Electromagnetic induction is the voltage developed in a conducting surface when the magnetic field of an eddy current instruments coil is in contact with that conducting object. See figure 2.11. A current is generated in the test object, known as eddy currents (Hellier, 2003). Technicians are well trained to read the impedance changes picked up on the equipment screen, if there are any discontinuities in the material there will be some disturbances in the circulation of the eddy currents and these are seen on the screen receiver.

The below figure shows the basic principle of eddy current testing, in other words, when the alternating current (AC) from the probe (with a known impedance Z), which contains the primary magnetic field, gets in contact with an electrically conductive material, circular eddy currents are induced. This current generates a secondary magnetic field that weakens

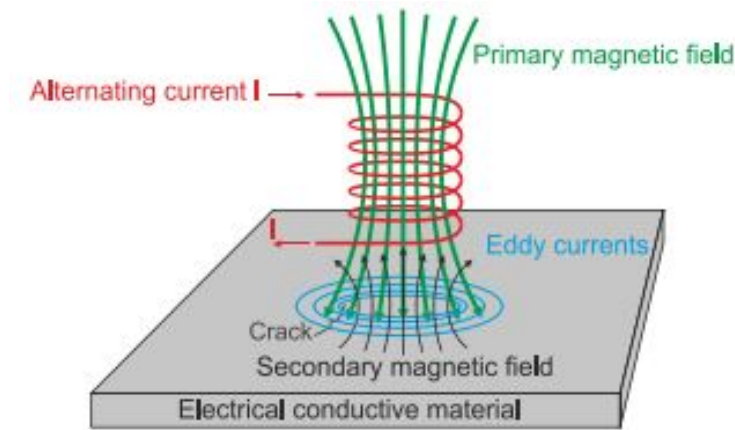


Figure 2.11: Principle of Eddy Current. Garcia-Martin et al. (2011)

the primary field (changing the coil's impedance to Z_c) as it is in the opposite direction. The probe will then receive the magnetic flux from the eddy currents created in the test component. The changes in impedance can be plotted in an XY graph with the voltage signals.

Eddy current probes are not sensitive to oil, dust, dirt, humidity, temperature (up to 1,200 °C), therefore no preparation or cleaning of the test component surface is needed to obtain accurate results from an Eddy current inspection.

Eddy current testing has been widely used since the 1950's because of many other advantages, some of them are: it allows to detect defects in several types of materials such as ferromagnetic and non-ferromagnetic, whereas other nondestructive methods are limited to only one of them. Probes do not need to be in contact with the material of interest, it can also calculate the thickness of non-conductive materials, determine hardness, composition and quality control in almost every industry.

Eddy current testing is one of the oldest non-destructive methods that was discovered and applied in field services. This type of testing is currently at its best potential because of the development of new portable and lightweight equipment with user-friendly software; test results are given almost immediately, it is a safe method (radiation is not involved) and the material surface does not need any cleaning or preparation. Even though the method is at its best potential, researchers are still developing and experimenting with new probes, in-

strumentation and techniques to obtain even higher quality results and to detect defects at an early stage, which would translate into lower costs of inspections for industries (Garcia-Martin et al., 2011).

Many industries accept inspections with eddy current equipment because the method is sensitive to the following variables: detection of defects, variations in conductivity, material thickness, cladding thickness, gaps between conductive layers, variations in permeability (Hellier, 2003).

2.3.2 Equations governing eddy current technique

The phenomena of eddy current are described by Maxwell's equations. To simplify the equations is assumed that the material inspected is a good conductor and that the electromagnetic wave propagating in the specimen is a plane wave. Maxwell's equations can be explained by:

$$\nabla \times E = \frac{\delta B}{\delta t} \text{ (Faraday's law of induction)} \quad (2.1)$$

$$\nabla \times H = J \text{ (Ampere's law)} \quad (2.2)$$

$$\nabla \cdot B = 0 \text{ (Gauss's law for magnetic fields)} \quad (2.3)$$

$$\nabla \cdot D = 0 \text{ Gauss'law for electric fields} \quad (2.4)$$

Where $\nabla \times$: curl operator, E: electric field, B: magnetic field, H: field intensity, D: electric field intensity, J: current density.

With the equations from above, eddy current problems can be solved but the partial differential equations need to be modified to other differential equations that are simpler to solve. Equation 2.3 can be expressed using A, a magnetic vector potential, even though it is not

real, a good approximation can be given to the potential in a space with a finite volume, where the magnetic field is uniform.

$$B = \nabla \times A \quad (2.5)$$

Two cases need to be considered. For the static case (non-charging), Equation 2.1 is simplified to $\nabla \cdot E = 0$, the electric field (E) can be expressed by $E = -\nabla\Phi$, where Φ : electric voltage. However, for the non-static case, Equation 2.5 needs to be substituted in Equation 2.1, therefore, for the relation describing the electric field (static case + non-static case) is:

$$E = -\nabla\Phi - \frac{\delta A}{\delta t} \quad (2.6)$$

Since $D = \epsilon E$, Equation 2.4 can also be expressed as $\nabla \cdot E = 0$, for then substitute in Equation 2.6

$$\begin{aligned} \nabla(-\nabla\Phi - \frac{\delta A}{\delta t}) \\ -\nabla^2\Phi - \frac{\delta A}{\delta t} = 0 \end{aligned} \quad (2.7)$$

The remaining equation to be used is Equation 2.2, it can be expressed by using $B = \mu H$ and $B = \nabla \times A$, therefore:

$$\begin{aligned} \nabla \times (\frac{1}{\mu} B) &= J \\ \nabla \times (\nabla \times A) &= \mu J \end{aligned}$$

By applying the identity of the curl of a curl:

$$\nabla(\nabla \cdot A) - \nabla^2 A = \mu J$$

The analogous of Ohm's law is $J = \sigma E$, where $\sigma=1/R$, thus:

$$\nabla(\nabla \cdot A) - \nabla^2 A = \mu\sigma\left(\frac{\delta A}{\delta t}\right) \quad (2.8)$$

One important gauge in electrodynamics is the Coulomb gauge, which helps dealing with stationary problems, it can also be used for non-stationary cases. The gauge sets that $\nabla \cdot A = 0$. By using this gauge, Equation 2.7 (static case) can be simplified to:

$$\nabla^2 \Phi = 0 \quad (2.9)$$

And Equation 2.8 (non-static case) can be simplified to:

$$\nabla^2 A = \mu\sigma\nabla\Phi + \mu\sigma\left(\frac{\delta A}{\delta t}\right) \quad (2.10)$$

Equation 2.9 is the Laplace's equation. Equation 2.10 (like the heat equation) is a partial differential equation showing that there is a process of diffusion. The latter can also be expressed using current densities

$$\nabla^2 A = \mu(J_s) + \mu\sigma(J_e) \quad (2.11)$$

Where J_e is the induced eddy-currents $J_e = -\delta A/\delta t$, and J_s is the external source current density $J_s = -\sigma\nabla\Phi$, which governs the properties in the eddy current technique (Giguere, 1999).

$$J_s = -\sigma\frac{\delta A}{\delta t} - \frac{1}{\mu}\nabla^2 A$$

$$J_s = -\sigma J_e - \frac{1}{\mu}\nabla^2 A$$

2.3.3 Characteristics

- Eddy currents flow in closed loops, the flow paths are circular unless a discontinuity is present causing a disturbance. The flow paths are parallel to the turns of the coil.
- Discontinuities are hard to detect when they are parallel to the eddy current flow paths and easy to detect when the longest dimension is perpendicular to the flow paths. See figure 2.12 (Hellier, 2003).

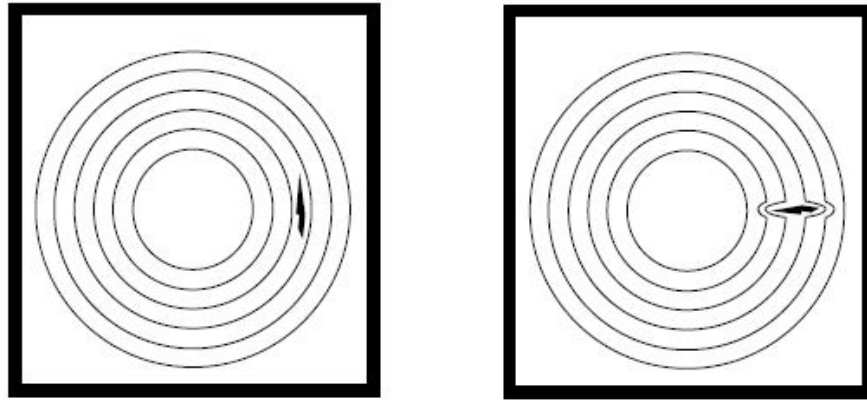


Figure 2.12: Eddy current flow paths with discontinuity, parallel to flow paths and perpendicular to flow paths. Hellier (2003)

- **Edge effect**

This effect occurs at the end of the inspected material. Eddy current paths are disturbed when the boundaries are reached as eddy currents cannot flow there. Inspections with eddy current technique are limited to near edges. This effect can be reduced by reducing the diameter of the coil, for encircling probes (Garcia-Martin et al., 2011). See figure 2.13.

- **Depth of penetration and current density**

Eddy currents show a phenomenon known as the skin effect. The current density is at its maximum at the surface decreases exponentially with depth. Standard depth of penetration is another name for skin depth (δ), is known as the depth at which eddy current density has decreased to $1/e$, e is the natural logarithm (2.71828). For example,

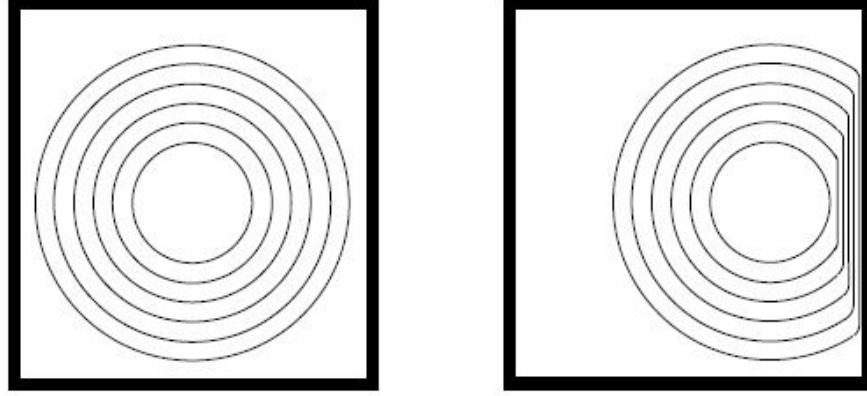


Figure 2.13: Edge effect. Eddy currents undisturbed and eddy currents disturbed by material boundaries. Hellier (2003)

the eddy current density for one skin depth ($1\delta=1/e$) is 37% of its surface value. At two skin depth ($2\delta=1/e^2$) the eddy current is at 13.5% and at three skin depth ($3\delta=1/e^3$) is 5.0%. Eddy current testing cannot work beyond three skin depths as the eddy current density is too small to develop sufficient secondary flux to change the coil impedance by a significant amount (Hellier, 2003).

$$\delta(mm) = \frac{661}{\sqrt{f\mu_r\sigma}} = 25\sqrt{\frac{\rho}{f\mu_r}}$$

Where: δ : standard depth of penetration (mm)

f: frequency (Hz)

μ_r : relative permeability (dimensionless, $\mu_r=1$ for non-ferrous materials)

σ : electrical conductivity (% IACS)

ρ : resistivity

The sensitivity of eddy current testing depends on the eddy current density. As the above equation shows, eddy current inspections depend on the frequency, material permeability and conductivity. These parameters cannot be increased as desired because of the limiting factor of the skin effect. The thickness of the specimen under inspection has to be two or three times the standard depth of penetration to avoid the eddy cur-

rent flow from showing on the other side of the specimen (Garcia-Martin et al., 2011). Pulsed eddy current (PEC) technique is performed to overcome this problem, it uses a pulsed excitation current that contains broadband frequencies that gives much more information about the defects on the inspected specimen (Arjun et al., 2015).

- **Phase lag** Eddy currents also show a linear phase lag (θ) with depth; as the latter increases, the eddy current activity is progressively delayed. Phase lag is the time between the eddy current response from a defect on the surface and another defect at some distance below the surface. Eddy currents below surface take a longer time to form than those at the surface.

Phase lag is an important parameter as it helps to calculate the depth of a defect and its rough size (Hellier, 2003). Phase lag can be calculated using:

$$\theta = \frac{x}{\delta}.57.3$$

Where: θ : phase lag (degrees), x : distance below the surface (mm)

2.4 Pulsed eddy current

2.4.1 Principle of pulsed eddy current testing

The conventional eddy current technique utilises a probe with a single frequency excitation which allows inspecting surface and subsurface defects. To inspect deeper sub-surface defects, one option is to increase the excitation current but this could lead to heating of the probe, another option is to lower the frequency but this leads to the decreasing of the sensitivity because of the limiting factor of the skin effect. Pulsed eddy current (PEC) testing was developed to analyse more parameters, such as defect location, defect size, probe lift-off and to allow deeper penetration into the test piece. The latter is achieved because PEC technique has a probe that utilises short pulses with a high current that contains a wideband frequency

spectrum (Arjun et al., 2015). In other words, the coil inside the probe is driven by a square wave. According to the Fourier transform, any function can be expressed as the summation of an infinite number of sine and cosine terms with different frequencies (Yoo, 2001). See the following figure 2.14.

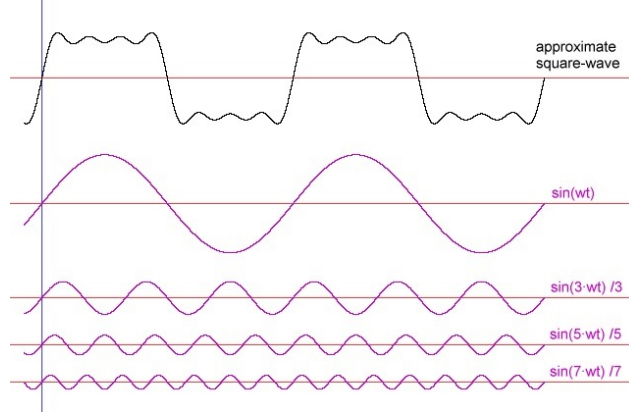


Figure 2.14: Approximation of a square wave

The idea of adding together a fundamental frequency and harmonics of various amplitudes is called Fourier synthesis, named after Joseph Fourier who first developed the idea in early 1800. Multiple sines and cosines could be added to model any function, as in the following expression:

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{[\infty]} A_n \cos nw_0t + B_n \cos nw_0t$$

Where $A_0/2$ is a constant divided by two to avoid counting it twice, A_n and B_n are the Fourier coefficients that will change depending on the function that needs to be modelled, and w_0 is the angular frequency ($w=2\pi f$ $f=2\pi/T$) (James et al., 1996). Thus, a pulse signal (odd function) could be expanded using an infinite sinusoidal function (harmonics) thanks to Fourier series:

$$f(t) = C + \sum_{n=1}^{[\infty]} \frac{1}{n} \sin nt$$

Where $n=1,3,5 \dots (2k-1)$ and C is the offset.

2.4.2 Typical signal response

The square shape current excitation (figure 2.15A) gives a broad band of frequency excitation that travels through a component, the wave is attenuated and it is governed by the diffusion equation which was explained in section 2.3.2. The presence of discontinuities makes some electromagnetic radiation to be scattered back to the sensor, so the characteristics of these indications can be recorded to analyse through the wall thickness of the test piece (figure 2.15B).

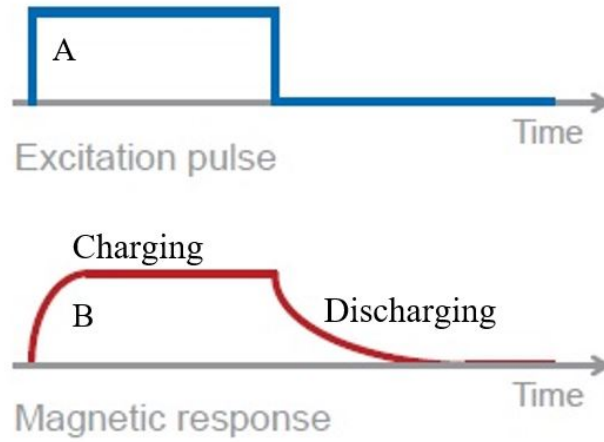


Figure 2.15: A) Excitation pulse and B) Magnetic response. Eddyfi (2017)

To mathematically solve and understand how the current and voltage behaves in the coil inside a PEC probe, an RL circuit (see figure 2.16) needs to be explained. An RL circuit (electric circuit) is formed of an inductor and a resistor driven by a voltage or current source. If the voltage source is a pulsed wave, there will be two important phases in the circuit, a charging and a discharging phase (see figure 2.15B).

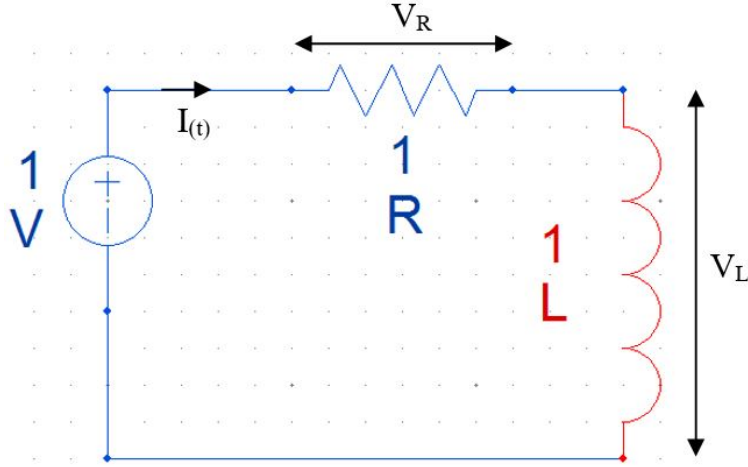


Figure 2.16: Series RL circuit

The current in the charging phase will start to build up and it will take some time to reach its maximum value (equivalent to 5-time constants or 5τ , known as transient time), the current has a form like a growth graph and it can be calculated using Kirchhoff's law (see appendix for derivation). So, the current in the circuit can be calculated with the following equation:

$$i = I_{max}(1 - e^{-\frac{t}{\tau}})$$

$$i = \frac{V_S}{R}(1 - e^{-\frac{t}{\tau}})$$

Where τ is the time constant $\tau=L/R$, and is the value when the I_{max} is at its 63% of the total.

The discharging phase occurs because of a sudden cut-off of the excitation pulse, so the current saved in the circuit will start to decay until it reaches zero. The form of the current is a decay graph (see appendix for derivation from Kirchhoff's law):

$$i = I_{max}(e^{-\frac{t}{\tau}})$$

$$i = \frac{V_S}{R}(e^{-\frac{t}{\tau}})$$

Where τ is the time constant $\tau=L/R$, and is the value when the I_{max} is at its 37% of the

total.

The second phase of discharging is the most important phase for PEC inspections, but instead of the current, the voltage in the resistor is measured, which has the same behaviour:

$$V_R = V_S(e^{-\frac{t}{\tau}})$$

Where V_S is the voltage in the source.

2.4.3 Previous studies

- There are several studies of insulated pipes and equipment that have used pulsed eddy current testing (PECT). For example, W. Cheng (Cheng and Komura, 2012) evaluated the wall-thinning of a carbon steel pipe under insulation through PECT, this article focused on the size of the footprint generated by the coil to evaluate local wall-thinning; it is mentioned that in order to evaluate local wall-thinning, a small footprint needs to be generated by using a specific arrange of coils in the probe. Using PECT signal at one location was not enough to calculate the local wall-thinning; W. Cheng and I. Komura recommended to use a scanning mode, which was under development at that time.
- Another study was made by S. Lai (Lai et al., 2015), using a ferromagnetic pipe with machined pittings, groove corrosion and thinning large area. The experiments were carried out to optimise and improve sensibility of the pulsed eddy current system when detecting inner flaws of a pipe under insulation. Corrosion usually appears in the outer layer of the material that is in contact with the insulation, but when high temperatures, erosion, pressure, toxic products are present the corrosion can reach the inner layer of a pipe. S. Lai et al. showed that PECT can detect the inner wall thinning of 10% of a pipe with a diameter of 159mm and insulation of 110mm in thickness, can also detect localised corrosion of 300mm² and 2mm of area and depth, respectively.

- The latest study was made by M. Grenier (Grenier et al., 2016), the experiments were carried out on a lab-machined carbon steel plate and on an insulated pipe with real internal defects. M. Grenier used a new development of pulsed eddy current testing, known as Lyft system, created by Eddyfi. The study showed that with the smart tool (which allows to filter and calibrate automatically) a dynamic mode could be applied to obtain quality data at a faster rate. The major findings were that the dynamic scanning mode allowed to increase spatial resolution to obtain better defects detection, even when these were in places that were hard to reach (nozzles or pipe supports). Lyft system proved to accurately detect defects under insulation of different materials and showed that it is immune to lift-off variations when in the presence of scab corrosion or blister.
- There are investigations that only involve simulations, using finite element analysis. The purpose of this is to evaluate several variables involved in a process and compare them with the real problem. An example of this is the study performed by S. Liu Liu et al. (2010), where the purpose was to evaluate the relationship between the corrosion on low-carbon steel pipes and the signals obtained from the simulation with ANSYS, using the time-domain difference method. Different length, width and depth of corrosion areas were analysed and the results showed that the negative peak of the differential induced voltage-time curve was completely comparable when the corrosion parameters were changed. These results provide an important reference when detecting corrosion and when determining the corrosion parameters.
- Another important variable when performing inspections with eddy current techniques is the lift-off effect, this is assessed by G. Yun T. (Tian and Sophian, 2005) where it is mentioned that this effect is also found when applying pulsed eddy current techniques. Different approaches have been studied to reduce the lift-off effect, but G. Yun used a two-stage process and normalisation technique. The first stages purpose was to reduce the lift-off effect whereas the second stage involved the feature finding that corresponds

to the defect. Air and defect-free sample measurements were two important references to reduce the lift-off effect by the proposed technique. Results showed that surface defects may present as a liftoff, therefore, the approach was mainly appropriate for sub-surface corrosion detection and some sub-surface defects as surface defects present as a lift-off.

- In order to analyse pulsed eddy current problems, H. Tsuboi (Tsuboi et al., 2004) compared Fourier transform method and time-stepping method to a simple transient EC problem. The results using a coarse and a fine mesh were compared, showing that the time-stepping method depended on the mesh more than those of the Fourier transform method, as it showed larger amplitude errors, therefore the Fourier transform method showed to be more accurate for PEC problems. Calculated results showed a good agreement with the measured data.
- One last study worth mentioning was performed by V. Arjun Arjun et al. (2015) where the design and dimension optimisation for PEC testing was discussed, to detect sub-surface defects (2, 3, 5 and 6mm below the surface) in stainless steel plate. Three probes were designed and analysed using finite element method through COMSOL Multiphysics, commercial software. The numerical modelling was preferred to trial and error experimental investigations, the result showed that the send-receive probe with ferrite core for exciter and pickup coils without shielding presented the highest induced current density. The outer diameter of the probes (11, 15, 19 and 25mm) was also investigated, the 19-mm diameter probe showed the highest induced current density and it also showed the best detection sensitivity for sub-surface defects located at 5mm below the surface, as the peak amplitude of the voltage gradually increased up to 19mm and then decreased. After the model predictions, the probe was fabricated and it could detect defects located up to 6 mm below the surface in an 8 mm thick stainless steel plate.

2.4.4 Advantages and limitations

Some of the advantages of using pulsed eddy current technique are:

- It uses short duration pulses with high excitation current that contains broadband frequencies, which allows greater depth of penetration when comparing it with the conventional eddy current testing and it also allows for better suppression of noise.
- The greater depth of penetration gives more information about defects.
- Inspections with PEC technology can be carried out in service and it is not affected by the temperature of the medium inside the pipe. The temperature range is approximate: -100 °C to 550 °C.
- There is no need for the probe to be in contact with the test piece, as the magnetic field injected by the probe can penetrate through any non-conducting material, such as insulators, coatings.
- No preparation of the surface is needed
- It can detect inner or outer corrosion without the need of removing the insulation.
- The inspections are simple, quick, the excitation signal is stable and the readings are repeatable.
- There are no health and safety issues.
- It can also be applied to stress evaluation, material property characterization, defect reconstruction and to heat the tested piece to perform a fast and large area of thermography testing (Huang and Wang (2016); Xie et al. (2011)).
- It gives accurate results even when the test component is under concrete, metallic mesh or polymer bars.

However, even though the technique has several advantages, it has some limitations:

- It is a technique under development, so more research needs to be done to understand the signals and interpret the results.
- It can only be carried out on carbon steel and low-alloy steel.
- PEC cannot detect small pitting.
- There are some geometries of the test piece that affect the readings, such as nozzles, internal and support structures, welds.
- Probe signal could be affected by the magnetic permeability of the test piece.
- Measurements are not possible in sharp bends and near supports.

2.5 Lyft system

2.5.1 Description

Pulsed eddy current probes are usually formed of an exciting coil and a pick-up coil (Liu et al., 2010). When the probe is placed on the surface of the material to inspect (including coating, insulation and cladding material), the current generates a pulsed magnetic field that penetrates different layers (including non-magnetic materials) until it reaches the wall thickness of the material of interest and eddy currents are generated in the component. When the magnetic field penetrates, the electrical current is turned off causing a sudden drop in the magnetic field. Eddy currents decrease in strength and the magnetic field corresponding to that decay is captured by the probes sensor for then to be used to estimate the wall thickness (Cheng and Komura (2012); Giguere (1999); TV (2012)). See figure 2.17, an example of a PEC probe over an insulated pipe, which is the case of interest of this thesis.

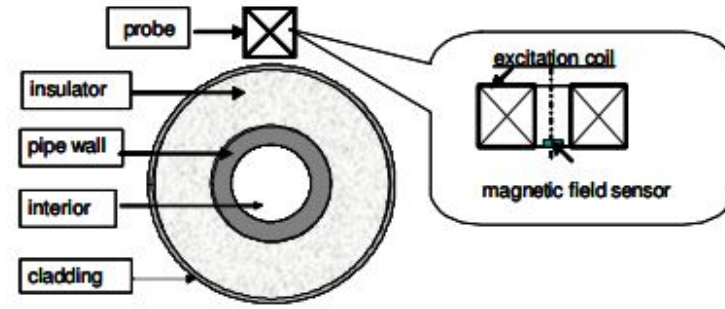


Figure 2.17: PEC probe over insulated pipe. Cheng and Komura (2012)

This thesis is for the assessment and validation of the Lyft system, created by Eddyfi. Eddyfi is a company established in recent years and it is focused on the development of eddy current technologies.

There are 3 important phases when using PECT:

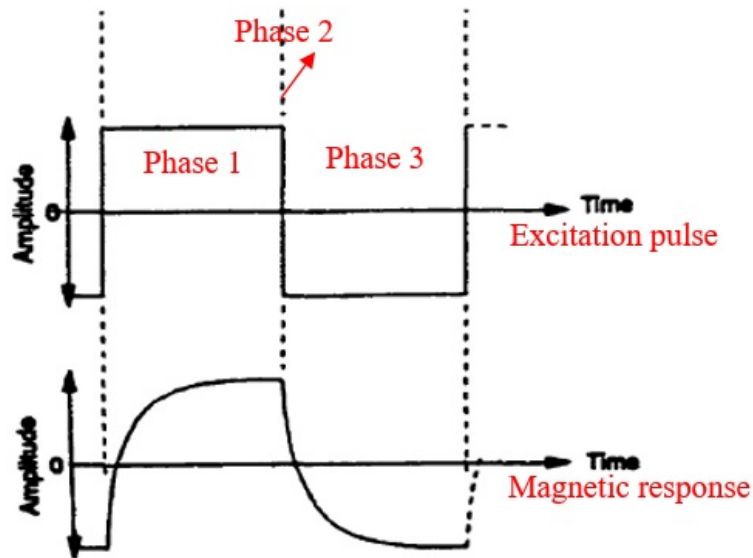


Figure 2.18: Probe coil drive and magnetic response. Giguere (1999)

1. The emission of the primary magnetic pulse (see phase 1 in figure 2.18), when the magnetic field, generated by the probe, penetrates all layers, including the non-magnetic materials (cladding sheet and insulation) until it reaches the component wall thickness and stabilises.

2. The second phase is when the electrical current is turned off, the eddy currents are generated in the wall thickness due to the change in the magnetic field. (see phase 2 in figure 2.18)
3. The reception of the secondary magnetic field through the probe (see phase 3 in figure 2.18), after the eddy currents decay in the wall thickness. The magnetic sensor measures the decay rate of the eddy currents.

The region of interest for the measurements during PECT is phase 3, the decay of the eddy currents is related to the thickness of the test piece. Old systems like the RTD-INCOTEST, where one measurement could take up to 10 seconds, were focused on the analysis of the magnetic response in a Log-Log scale. See figure 2.19 (Scottini, 2002).

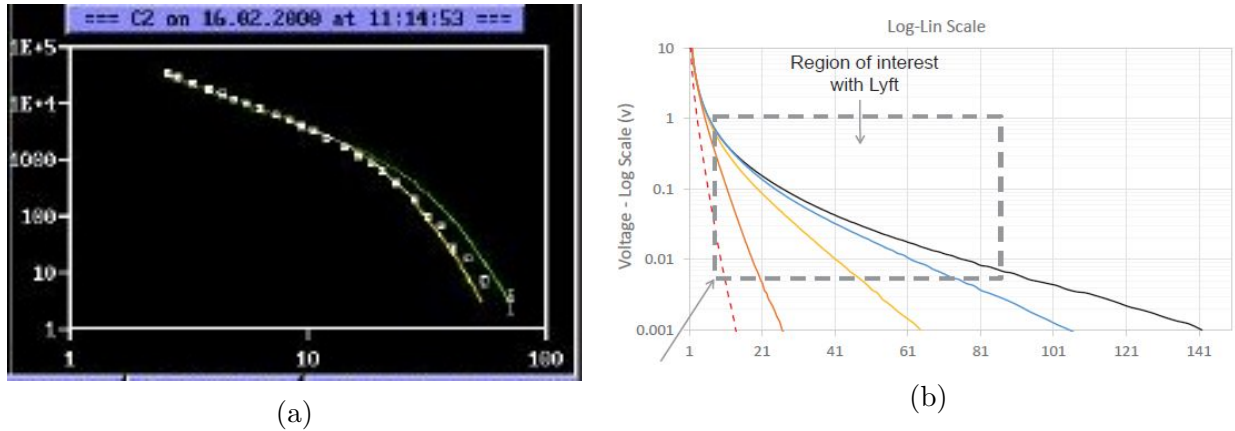


Figure 2.19: Decay of eddy currents on display of a) RTD-INCOTEST. Scottini (2002) b) Region of interest with Lyft. Eddyfi (2017)

The figure 2.19a shows the abrupt drop-off in the curve, new systems like Lyft (figure 2.19b) use a Log-Linear scale to observe a rapid drop at the beginning of the signal and then a straight line at the end of the signal, the region of interest is also observed.

2.5.2 Footprint

The footprint is the area covered by the probe, the footprint size changes with the probe size, thickness of insulation, cladding material and the thickness of the test piece. The maximum

intensity of the signal is at the centre of the probe footprint. It is important to know the footprint to set the grid spacing or resolution. One footprint is said to ensure 50% overlap between readings.

To determine the footprint (FP) of the probe in the specific case, Lyft uses:

$$FP = 0.65xLO + FP_0$$

Where LO: lift-off, FP_0 : footprint at lift-off = 0

Lyft has three probes and FP_0 depends on the size of the probe:

PEC-0.25-G2: 35

PEC-089-G2: 62 mm

PEC-152-G2: 100 mm

Selection of the probe is affected by the lift-off and the wall thickness of the component.

As PEC is affected by edge effect, is also important to know the footprint to calculate the distance when measurements begin to vary, that distance is one footprint.

Each probe reading to determine the wall thickness is an average of the wall thickness within the averaging area. To calculate this averaging area (AvgA), Lyft uses:

$$AvgA = 1.8xFP$$

If the discontinuity is smaller than the averaging area, the size will be underestimated. Using the footprint size is also important when setting the resolution, this will change depending on the selected mode and if the scan is carried out using fast- screening or hi-resolution. For this thesis, a hi-resolution scan is preferable, so the acquisition resolution is:

- Footprint fraction of $FP/2$ is the index axis resolution.
- Footprint fraction of $FP/5$ is the scan axis resolution (Eddyfi, 2017)

2.5.3 Compensated wall thickness tool

The compensated wall thickness (CWT) is a unique tool in the Lyft system, the algorithm helps to minimize the problem of under sizing, which is common for all PEC systems. The CWT is calculated after the inspection is finished and it calculates the minimum wall thickness within a smaller area instead of the whole scan area. When selecting the smaller areas is important to remember:

- Include points of the nominal wall thickness and the deepest defect point.
- Selected area must include a minimum of 3 x 3 valid points.
- The centre of the cursor should be in the deepest defect point and not in the boundaries of the defect.
- If the defect is not thick enough, the CWT cannot be calculated.
- The resolution must be greater than one FP along index axis (vertical) and half FP along scan axis (horizontal).
- CWT can be calculated within a sub-component but the latter should be calibrated and the cursor should be completely inside the sub-components area.
- CWT cannot be calculated in areas where the wall thickness is greater than 100%, recalibration should be done first.
- CWT should not be calculated in very noisy data or near edges Eddyfi (2017).

2.5.4 Advantages and limitations of Lyft

Lyft is an advanced and innovative technology with a lot of advantages when used to inspect steel structures under insulation and correctly measure defects located on outer and inner layers of the material of interest. However, more studies need to be completed to evaluate

different variables and completely validate this innovative technology, and more specifically the unique CWT tool. Moreover, components that have been used in the real world need to be evaluated in labs and then perform accurate inspections on any steel component under different insulating materials. Some of the advantages are:

- Sensitive to far-side and near-side defects.
- Supports wall thicknesses up to 102 mm and insulation thicknesses up to 305 mm.
- Fast data acquisition, up to 15 readings per second with grid-mapping and fast dynamic scanning mode.
- Dynamic mode available due to a removable rugged encoder embedded at the front of the probe.
- It gives accurate results even when the test component is under non-magnetic materials, such as insulation, coatings, concrete fireproofing, marine growth.
- It can also inspect through chicken wire and rebars.
- Not affected by water or ice.
- User-friendly.
- SmartPULSE available, which executes WT calibration and PEC autoset at the same time. PEC autoset is done to adjust the equipment and avoid saturation.
- Suitable for many applications, such as corrosion under insulation (CUI), corrosion blistering and scabs, corrosion under fireproofing (CUF), surface corrosion, corrosion under coatings, waterworks, underwater and splash zones and flow-accelerated corrosion (FAC) Eddyfi (2017).

The Lyft system has limitations, some are listed below:

- Edge effect, after the size of the probe footprint, when close to metallic structures.
- Lyft cannot differentiate the location between far-side and near-side defects.
- Pittings are impossible to detect because of the small sizes.
- Hard to use on elbows smaller than 200 mm in diameter.
- Under sizing when defects are smaller than the footprint. This problem is minimized by the CWT.
- Lyft is unaffected by the lift-off effect, as soon as it is below 305 mm thick, but some extreme variations could affect the signal response. If the reduction of liftoff is significant, saturation might happen, on the other hand, if the lift-off increases too much, the amplitude might reduce below noise level (Eddyfi, 2017).

See figure 2.20 for the Lyft system.



Figure 2.20: Lyft system

2.6 PEC simulations

Quickfield software is generally used for electromagnetic, thermal and stress analysis. This thesis is focused on a transient magnetics analysis of a material with nonlinear permeability through time stepping finite element method (FEM). The software allows to insert a pulsed wave as the excitation current to perform the pertinent circuit analysis, it can also calculate the generated eddy currents and the resulting magnetic field in the conducting material.

The software uses triangular elements and it can create a smooth transition from coarse to fine mesh sizes in short times, making the simulation tool extremely efficient (TeraAnalysis, 2016).

The governing equation is:

$$J_s = -\sigma J_e - \frac{1}{\mu} \nabla^2 A$$

Which was derived from Maxwell's equations in section 2.3.2. Quickfield software adopts the finite element method to solve the numerical solution of the previous equation and after the simulation is finished, many physical quantities of the electromagnetic field can be observed for further analysis.

Chapter 3

Experimental Evaluation

After learning how to use the Lyft system, blind inspections were carried out at Oceaneering, Swansea. The component was a pipe, Schedule 20, with numerous areas of scab corrosion and wall loss, which were not artificial, the pipe was insulated with Rockwool, a man-made mineral wool, also known as mineral fibre and wrapped with an industry standard cladding of stainless steel. The company had carried out some previous tests on the component, so the number of defects was known. See table 3.1 and figure 3.1 for component dimensions.

Table 3.1: Component dimensions details for CUI test

Geometry	Pipe
Material	Carbon steel
Dimensions	273.1 mm x 40000 mm
Wall Thickness	6.4 mm
Insulation	80.0 mm
Jacket Material	Stainless Steel
Jacket Thickness	1 mm

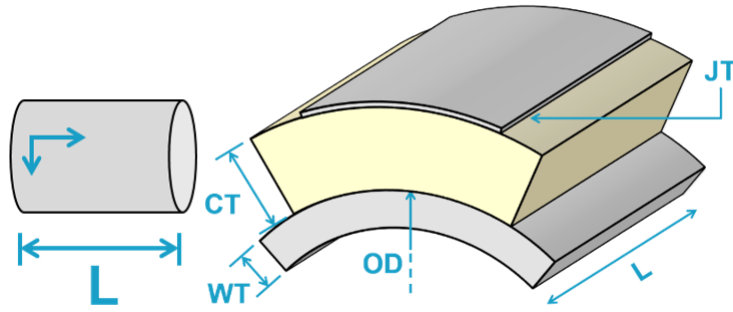


Figure 3.1: Component dimensions for CUI test

The inspections were performed twice, the first one was the inspection of the pipe under insulation and cladding and the second one was the inspection in contact with the pipe, for then to compare the results from both and see the behaviour of the CWT tool. See figure 3.2 for the inspected pipe under insulation and cladding.



Figure 3.2: Pipe under insulation and cladding

3.1 Inspection through insulation and cladding

For the inspection of the corrosion under insulation, a PEC-089-G2 (figure 3.3) probe was selected according to the lift-off and wall thickness of the pipe.

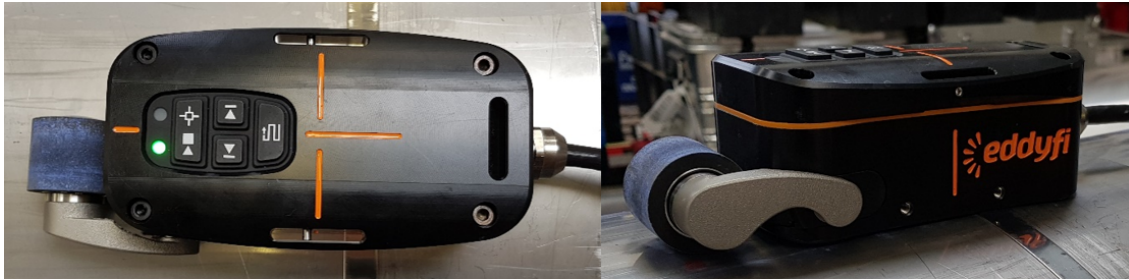


Figure 3.3: PEC-089 G2 probe

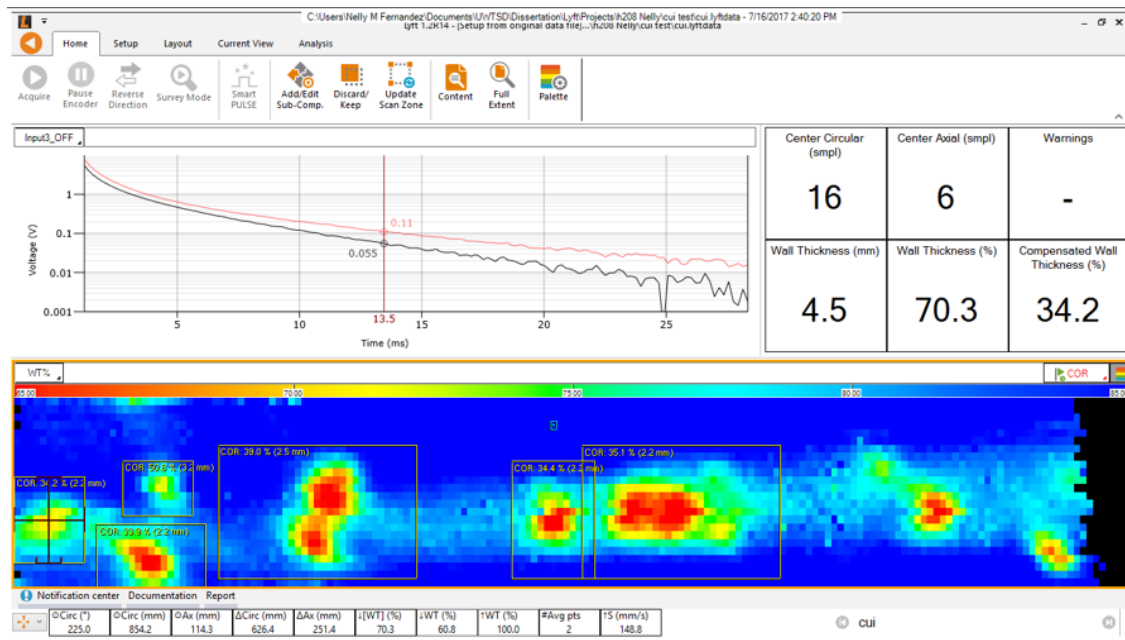
The test started by setting up the general information in the PEC system, with information about the component, scan zone and selected probe. The “Smart pulse” was used to calibrate the system and take the measurements of the nominal wall thickness, other shots were taken in “Survey mode” to ensure that the calibration was done in a defect free zone. The only preparation that was required when using Lyft in dynamic mode was to trace parallel guiding lines along the pipe in the scan axis. For the first scan, only one scan zone was generated, including the whole circumference (1366 mm) and length of the pipe (4000 mm). The inspection was carried out in dynamic mode and high resolution (index axis resolution: 56.9 mm and scan axis resolution 22.9 mm) and it took less than an hour. See test setup in table 3.2.

Table 3.2: CUI test setup

Probe	PEC-089-G2-HT05S
Probe Footprint	114.7 mm
Circumferential Footprint	182.7 mm
Pulse Duration	27.1 ms
Max. Power	10.0 W
A-Scan Start Time	1.2 ms
A-Scan Duration	27.3 ms
Characteristic Decay Time	7.0 ms
Jacket Delay	0.5 ms
PEC Autoset Main Channel	Input3_OFF
Gain	39 dB
Acquisition Rate	6.51 Hz
Line Filter Frequency	50.1 Hz
Sizing Algorithm	1.2+

After the scan was finished, good quality data of the magnetic response was observed in the A-scan and 12 corrosion areas were easily observed in the C-scan, the palette was adjusted to see from 65 to 85% wall thickness. The literature review showed that PEC systems undersize defects that are smaller than the average area, those undersized areas could appear even smaller with the presence of liftoff due to the increased footprint size. Lyft comes with the post-processing CWT tool to improve those areas smaller than the averaging area, to do this, each defect was separated in different boxing areas. Each boxing area included the nominal wall thickness and the deepest defect point, a minimum of 3 x 3 valid points and the deepest defect point in the centre of the cursor. The compensation was calculated for each of the detected defects. See the following figure 3.4 for a screenshot of the Lyft display, including the A-scan at the top left, where the red decay curve is the nominal wall thickness and the black decay curve is the decay curve where the cursor is located at that moment; at the top right, location of the cursor, remaining wall thickness in millimeters and percentage, as well as compensated wall thickness in percentage are shown. Below all of this, the C-scan can be observed.

Figure 3.4 shows a screenshot of the PEC display for scab 1, which is located at the bottom left corner of the scan, the top right values correspond to the location of the cursor,



remaining and compensated wall thickness. Red areas correspond to the greater wall loss and dark blue areas to the nominal wall thickness. See appendix for the screenshots of scabs 3 to 12 and 14.

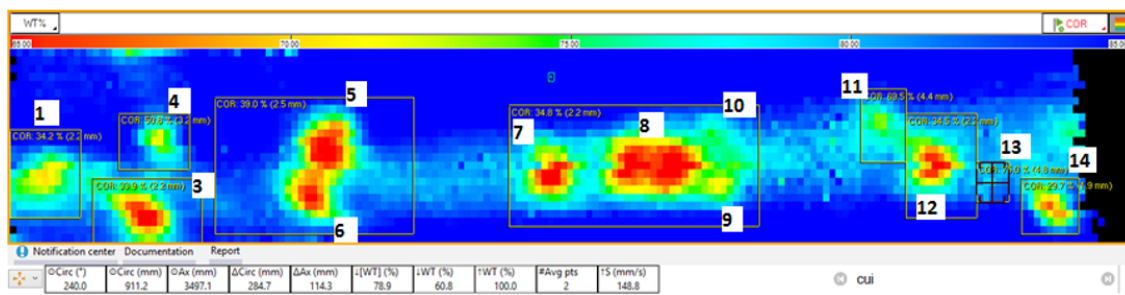


Figure 3.5 shows the screenshot of the PEC display after calculating all the compensated wall thickness in each of the defects. It can be observed that scabs 5 and 6 were closed in the same box, just like scabs 7, 8 9 and 10, this was done to include enough valid points (nominal WT and deepest defect point) when calculating the CWT.

Scab 2 and 13 were too shallow to be easily observed on the C-scan, however, the location was known so the CWT was also calculated in the area of scab 13 and some loss was observed.

Most of the defects are located in the six o'clock position (bottom of the pipe), as expected for pipes under insulation horizontally installed. The scan shows that the pipe has scabs all over its length, probably because corrosion product was held by the coating and formed other layers over the pipe. Despite Lyft not being able to differentiate between far-side and near-side defects, it can detect them, this then allowed a general wall thickness loss to be observed along the same position. That loss could be due to internal corrosion/erosion because of the product that flows inside the pipe and temperature conditions of the process.

Table 3.3 shows the calculated remaining and compensated wall thickness in percentages and in millimetres. It can be observed that the CWT is lower than the remaining WT, as expected.

Table 3.3: CUI Test

Scan Zone	Nominal (mm)	Remaining (%)	CWT (%)	Minimum (%)	Remaining (mm)	CWT (mm)	Minimum (mm)
scab 1	6.4	70.3	34.2	70.3	4.5	2.2	4.5
scab 3	6.4	63.0	33.9	63.0	4.0	2.2	4.0
scab 4	6.4	71.9	50.8	71.9	4.6	3.2	4.6
scab 5 6	6.4	70.0	39.0	62.8	4.4	2.5	4.0
scab 7 8 9 10	6.4	63.0	34.8	60.8	4.0	2.2	3.9
scab 11	6.4	73.7	69.5	73.7	4.7	4.4	4.7
scab 12	6.4	63.8	34.5	63.8	4.1	2.2	4.1
scab 13	6.4	78.9	75.0	78.9	5.0	4.8	5.0
scab 14	6.4	67.0	29.7	67.0	4.3	1.9	4.3

3.2 Inspection in contact

The second part of the tests was to carry out the inspection in contact with the pipe, for which the stainless-steel cladding and insulation was removed (figure 3.6 and 3.7).



Figure 3.6: Carbon steel pipe for in contact test

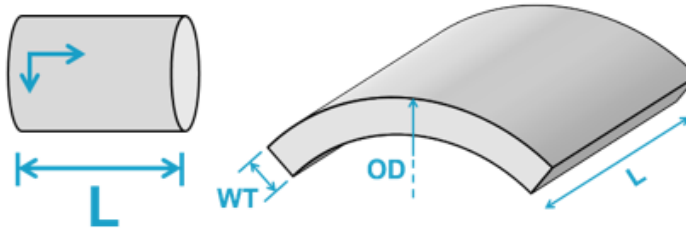


Figure 3.7: Component dimensions for in contact test

A smaller probe with smaller footprint was selected, PEC-025 G2 (figure 3.8). No guidelines were traced for this test, a rubber mat with a grid was used to allow the encoder to roll smoother when inspecting the scabs.



Figure 3.8: Component dimensions for in contact test

After setting up the equipment with the information needed (see table 3.4), calibration and measurement of the nominal wall thickness with “Smart pulse” were carried out in a defect free zone. Different scan zones were generated for each scab zone to match with each of the boxing areas in the first test. Scans were carried out in dynamic mode and high-resolution, index axis resolution: 25 mm and scan axis resolution 7 mm.

Table 3.4: In contact test setup

Probe	PEC-025-G2-HT05S
Probe Footprint	35.0 mm
Circumferential Footprint	35.0 mm
Pulse Duration	23.7 ms
Max. Power	10.0 W
A-Scan Start Time	0.7 ms
A-Scan Duration	25.9 ms
Characteristic Decay Time	6.6 ms
Jacket Delay	0.0 ms
PEC Autoselect Main Channel	Input3_OFF
Gain	27 dB
Acquisition Rate	6.99 Hz
Line Filter Frequency	50.0 Hz
Sizing Algorithm	1.2+

The following figures show each one of the scabs with the respective C-scan obtained with Lyft. Palette was set to show 65% to 95% of wall thickness. Figure 3.9b shows the screenshot of the Lyft display for scab 1, where the red decay curve corresponds to the nominal wall thickness and the black decay curve corresponds to the wall thickness measured where the



Figure 3.9: a) Scab 1 and b) Lyft display: Scab 1

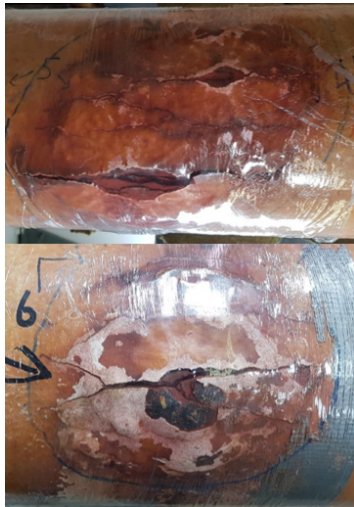


Figure 3.10: a) Scab 3 and b) C-scan: Scab 3

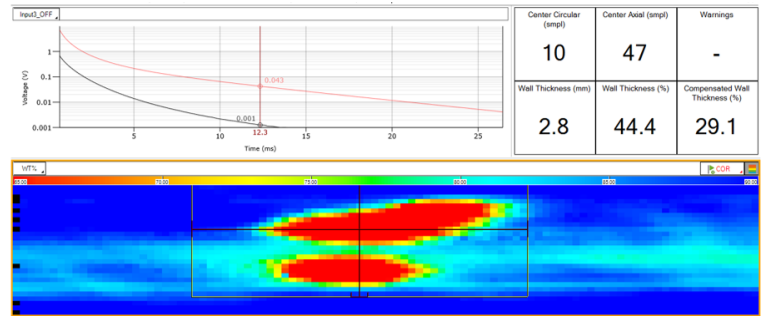


Figure 3.11: a) Scab 4 and b) C-scan: Scab 4

The following figures show the scabs that were inspected in the same scan zone. Figure shows the screenshot of the Lyft system display for the test of scab 5 and 6, showing both decay curves, like previous figures.



(a)



(b)

Figure 3.12: a) Scab 5,6 and b) Lyft display: Scab 5,6



Figure 3.13: Scab 7, 8, 9 & 10

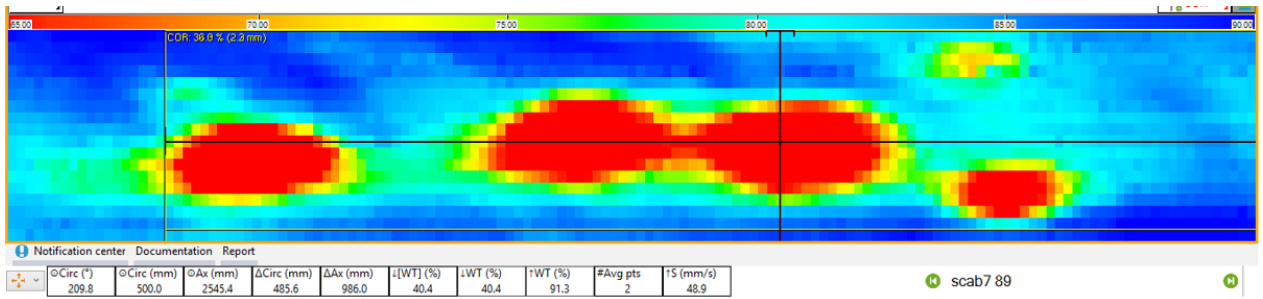


Figure 3.14: C-scan Scab 7, 8, 9 & 10

This last set of figures of the inspection in contact include the test over scab 13 (figure 3.17), even though it was not easy to differentiate in the inspection through the insulation, some wall loss is shown in the C-scan of the test in contact. Scab 13 had an area of approx-

imately $110 \times 110 \text{ mm}^2$, when performing the test through the insulation, the PEC-089 G2 probe had a circumferential footprint size of 120mm for a liftoff of approximately 89mm, this means that one reading was bigger than scab 13, so the size was underestimated by Lyft. The calculated remaining wall thickness was 78.9% and after the compensation it went down to 75%.

On the other hand, when performing the test in contact, the PEC-025 G2 probe had a circumferential footprint size of 35mm for no lift-off, so for the test in contact of scab 13, approximately 4 shots were taken, instead of one, therefore bigger differences are shown. The calculated remaining wall thickness was 72.3% and it went down to 48.6% after the compensation.

Scab 13 was also difficult to differentiate in the inspection through the insulation because it was surrounded by bigger and deeper scabs, so when calculating the remaining thickness of the whole scan, Lyft averaged out making scab 13 shallower than it was. Had scab 13 been the only defect on the pipe, it would have stood out in the scan, as it does in the inspection in contact, where no contributions from other defects are shown in the scan. It is important to mention that all defect that were present on the pipe were corrosion scabs or blisters, which can be as dangerous as CUI and sometimes even more.

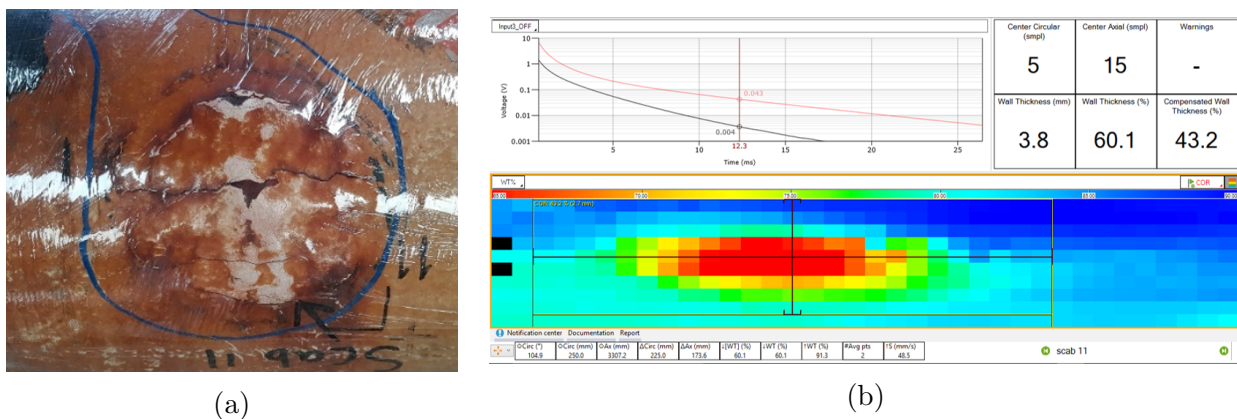


Figure 3.15: a) Scab 11 and b) Lyft display: Scab 11



Table 3.5 shows the uncompensated and compensated wall thickness in percentages and in millimetres of the inspection in contact. It can be observed that the uncompensated values are very similar to the compensated ones, this is usual as the tests were performed in contact with the pipe, so the size of the footprint was not affected by lift-off, therefore, the problem of undersizing was minor.

It is important to mention that even though this thesis is focused on the detection of CUI, all defects on the inspected pipe are scabs, a type of localised corrosion just as, or even more dangerous, than CUI. Scabs could have a very irregular form, this could be a problem when calculating the CWT. The problem appears in scab 1 and 14, where the CWT values are bigger than its uncompensated values. When the CWT is calculated over a very irregular defect, the algorithm can encounter a defect within a defect, that is to say, different defect depths on the area, therefore the algorithm could calculate over the deepest defect or another one thinner, which possibly happened with scab 1 and 14. The bigger differences were found in scab 14, where the CWT possibly calculated at the most shallow depth and give approximately 44% of remaining WT, whereas the C-scan possibly calculated at the deepest depth and read and approximate 33% of remaining WT.

Table 3.5: In contact test

Scan Zone	Nominal (mm)	Remaining (%)	CWT (%)	Minimum (%)	Remaining (mm)	CWT (mm)	Minimum (mm)
scab 1	6.4	48.1	52.0	48.1	3.1	3.3	3.1
scab 3	6.4	31.2	29.6	31.2	2.0	1.9	2.0
scab 4	6.4	54.4	28.0	54.4	3.5	1.8	3.5
scab 5 6	6.4	44.4	29.6	44.4	2.8	1.9	2.8
scab 7 8 9 10	6.4	44.1	34.8	40.4	2.8	2.2	2.6
scab 11	6.4	60.1	43.2	60.1	3.8	2.7	3.8
scab 12	6.4	47.6	26.0	47.6	3.0	1.6	3.0
scab 13	6.4	72.3	48.6	71.9	4.6	3.1	4.6
scab 14	6.4	33.5	44.1	33.5	2.1	2.8	2.1

After obtaining all the data from the Lyft system, a statistical analysis was needed to compare the values of the remaining wall thickness from the C-scan and those from the CWT tool, in order to satisfy the aims and objectives of the thesis. To do this, a suitable probability of sizing (POS) was carried out to evaluate the effect of lift-off with and without the

compensation, assuming that the sizing values obtained from the in-contact test were the closest to the real remaining wall thickness.

Table 3.6: Uncompensated values for in contact and CUI test

Scan Zone	Contact Remaining (%)	CUI Remaining (%)	Error
scab 1	48.1	70.3	-22.2
scab 3	31.2	63.0	-31.8
scab 4	54.4	71.9	-17.5
scab 5 6	44.4	70.0	-25.7
scab 7 8 9 10	44.1	63.0	-18.9
scab 11	60.1	73.7	-13.6
scab 12	47.6	63.8	-16.2
scab 13	72.3	78.9	-6.7
scab 14	33.5	67.0	-33.5
Standard deviation			8.6

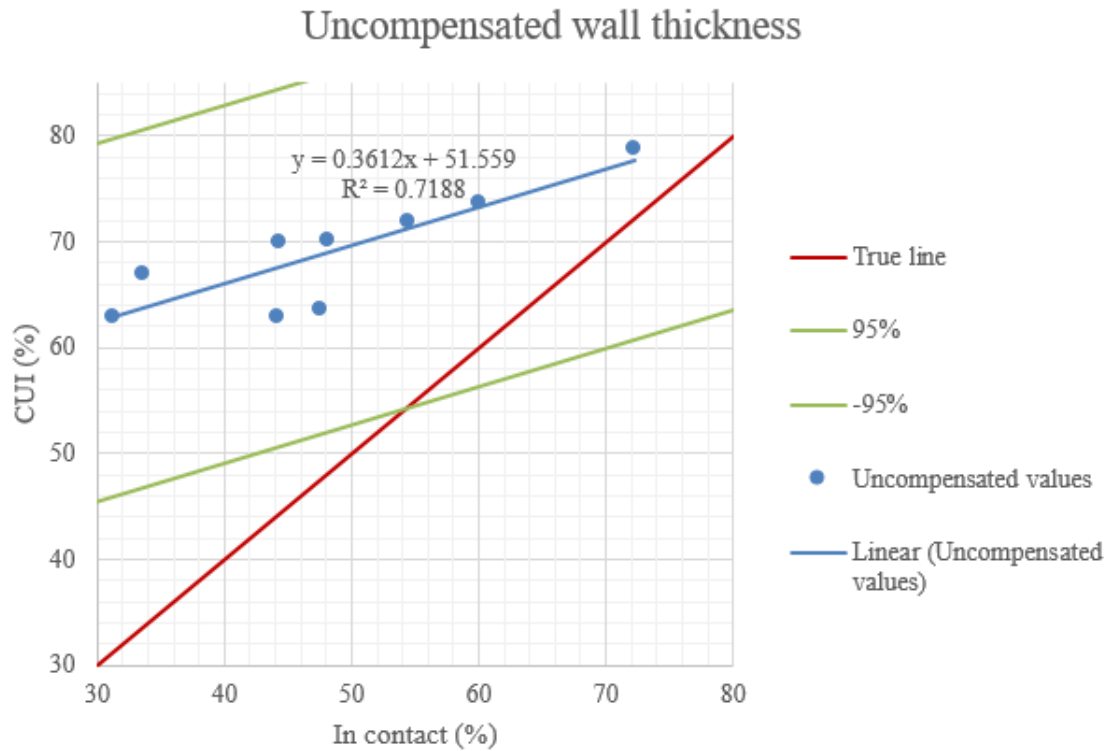


Figure 3.19: CUI vs. In contact test Uncompensated values

Figure 3.19 shows the comparison between the CUI test and the test in contact, using the uncompensated values, to observe how the Lyft system behaves when inspecting through insulation and cladding. Before any analysis is carried out, it is important to mention that only 9 wall thickness measurements of the most affected areas by corrosion were taken.

The figure shows the actual values with the trend line that best fits the set of data. The equation of it has a form of $y=0.3612x+51.559$, with a coefficient of determination of $R^2=0.7188$. The R-squared value gives an acceptable straight-line relationship, where 71.88% of the variation of the uncompensated values from the CUI test is due to the variation of values from the test in contact. The form of the trend line is not very close to the ideal line, this is observed in the low value of the gradient $m=0.3612$, with a high intercept in $y=55.559$. The relationship has a standard deviation of 8.6%, one of the lowest (see table 3.6), this low value narrows the confident limits to obtain an accuracy range of $\pm 16\%$ to 95% confidence. All the values from the CUI test are within those limits.

To observe how well the CWT tool behaves, another comparison was made between the CUI test and the test in contact, but this time using the compensated values.

Table 3.7: Compensated values for in contact and CUI test

Scan Zone	Contact Compensated (%)	CUI Compensated (%)	Error
scab 1	52.0	34.2	17.8
scab 3	29.6	33.9	-4.3
scab 4	28.0	50.8	-22.8
scab 5 6	29.6	39.0	-9.4
scab 7 8 9 10	34.8	34.8	-0.1
scab 11	43.2	69.5	-26.3
scab 12	26.0	34.5	-8.6
scab 13	48.6	75.0	-26.4
scab 14	44.1	29.7	14.4
		Standard deviation	16.3

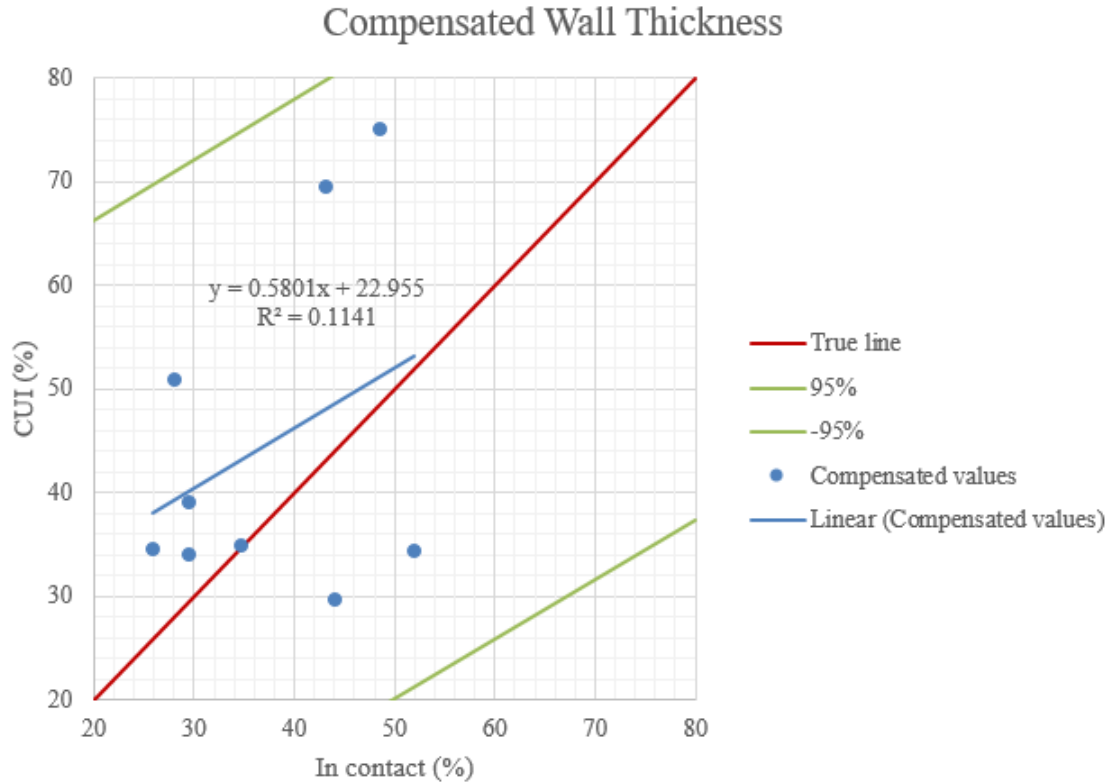


Figure 3.20: CUI vs. In contact testCompensated wall thickness values

Figure 3.20, shows the relationship between the compensated wall thickness values, to see how the CWT tool behaves with the presence of lift-off. If the CWT tool does improve the sizing performance of the PEC signals, a better relationship should be observed in this figure. A very low coefficient of determination is firstly observed, $R^2=0.1141$, which means that only 11.41% of the variation in the compensated values from the CUI test is due to the variation of values from the test in contact. However, the trendline is closer to the ideal line, this is observed in the higher value of the gradient $m=0.5801$ and a lower intercept in $y=22.955$. The relationship gives a high standard deviation of 16.3% (see table 3.7), lowering the accuracy to a range of $\pm 32\%$ to 95% confidence.

Table 3.8: Uncompensated WT for in contact test and CWT for CUI

Scan Zone	Contact Remaining (%)	Compensated (%)	Error
scab 1	48.1	52.0	-3.9
scab 3	31.2	29.6	1.6
scab 4	54.4	28.0	26.4
scab 5 6	44.4	29.6	14.8
scab 7 8 9 10	44.1	34.8	9.3
scab 11	60.1	43.2	16.9
scab 12	47.6	26.0	21.6
scab 13	72.3	48.6	23.6
scab 14	33.5	44.1	-10.6
		Standard deviation	12.9

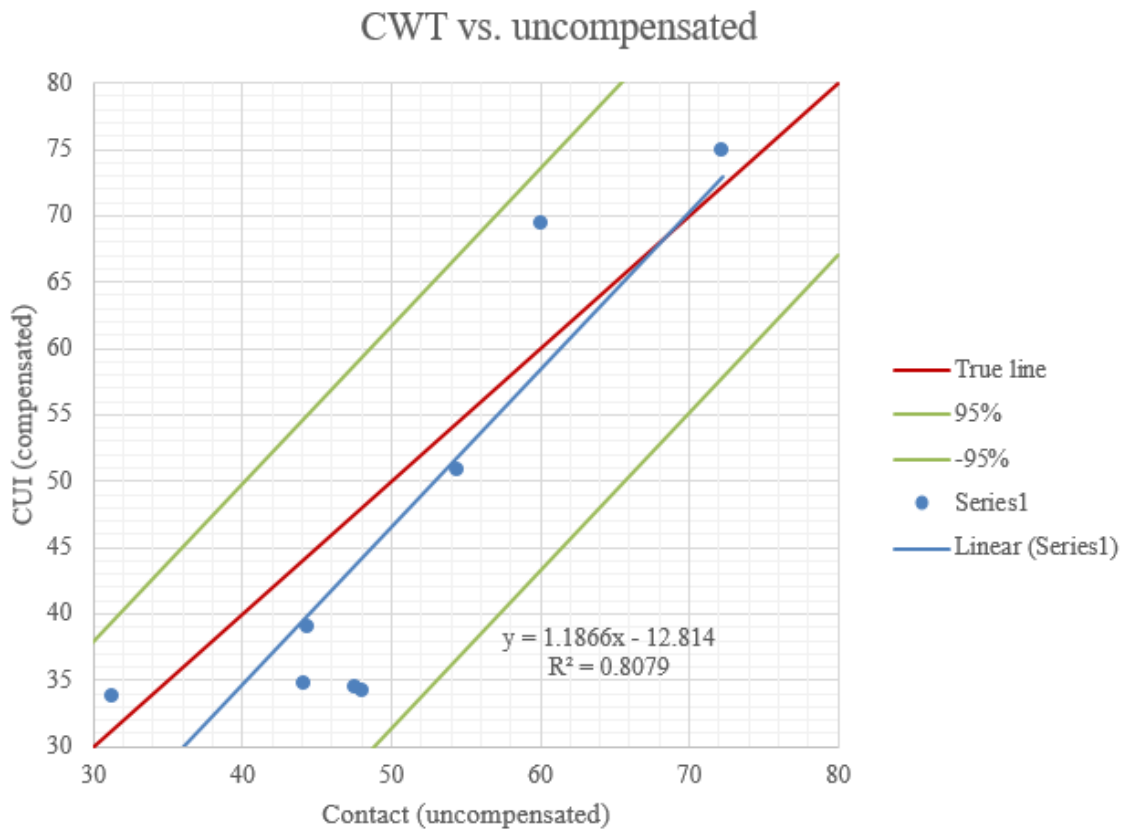


Figure 3.21: CUI test values with CWT vs. in contact test with uncompensated values

By comparing the CWT values for the CUI test with the uncompensated values from the test in contact another improvement is observed. First, the trend line is even closer to the ideal line, this is shown in the value of $m=1.1866$ (when in the ideal case is 1), also in a lower intercept of $y= -12.814$. The compensated values show a better fit to the regression line, by giving an R-squared value of 0.8079, which means that 80.79% of the variation in the compensated values from the CUI test is due to the variation of uncompensated values from the test in contact. The relationship shows the lowest standard deviation, 7.7% (see table 3.8), this narrows the confidence limits gap even more, to a range of $\pm 14\%$ to 95% confidence.

3.3 Comments

This chapter described the capability of the Lyft system. Two tests were performed, the first one was to inspect a carbon-steel pipe (Schedule 20) with several corrosion scabs through insulation and stainless-steel cladding; the second test was to inspect the same pipe after the insulation and cladding was removed. After both inspections were carried out, a C-scan was obtained with the remaining wall thickness measurements, the compensated wall thickness (CWT) was then calculated on each of the corrosion scabs. Experimental results showed that the Lyft system is not only capable of detecting and sizing CUI, it is also useful to detect corrosion scabs under insulation. The idea of carrying out both inspections was to compare and see if there were any improvements on the smaller-than-averaging-area defect sizing when the presence of lift-off. To do this, a statistical analysis was performed through a suitable probability of sizing (POS). No true sizes were known, therefore measurements from the inspection in contact with and without compensation were used as if they were the closest to the real values. Three POS curves were obtained. Results showed that there was an improvement on the sizing when the CWT tool was applied on the values of the inspection through insulation and cladding, A good regression line ($R=0.8079$) and a relatively low

standard deviation of 7.7% was observed in the POS curve. The CWT tool showed an overall accuracy of $\pm 14\%$ to 95% confidence when comparing it with the uncompensated measurements from the Lyft system.

Chapter 4

Simulations

4.1 Simulation in contact

In order to evaluate the behaviour of a PEC system, a simple model was chosen, formed of a carbon steel plate and a send-receive type probe (figure 4.1) to be evaluated using finite element analysis (FEA) through Quickfield software.

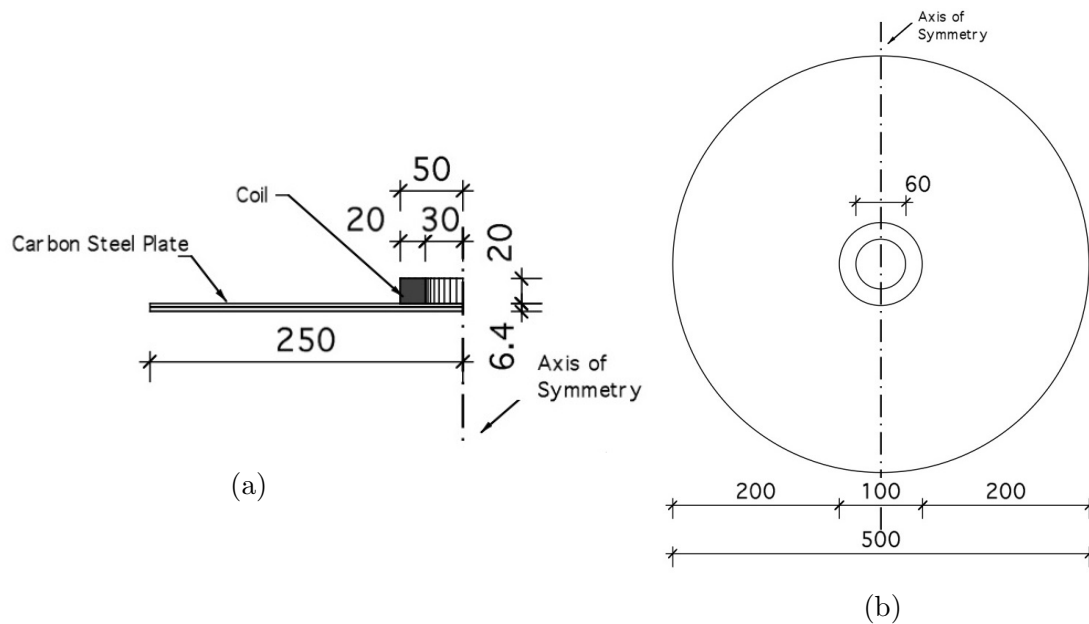


Figure 4.1: Model for simulation in contact a) Front view and b) Top view

The problem properties for this model are shown in table 4.1.

Table 4.1: Problem properties

Problem type	Transient magnetics
Model class	Axisymmetric
Precision	Normal
Coordinates	Millimeters
Coordinates system	Cartesian

The model was then transferred to Quickfield, where the axis of symmetry and rotation were in the vertical and horizontal axis, respectively. Figure 4.2 shows the model created in Quickfield. In order to reduce the simulation time, a fine mesh was selected in the most important blocks (coil and plate) and a coarse mesh in the surroundings. Quickfield created a smooth transition from fine to coarse mesh.

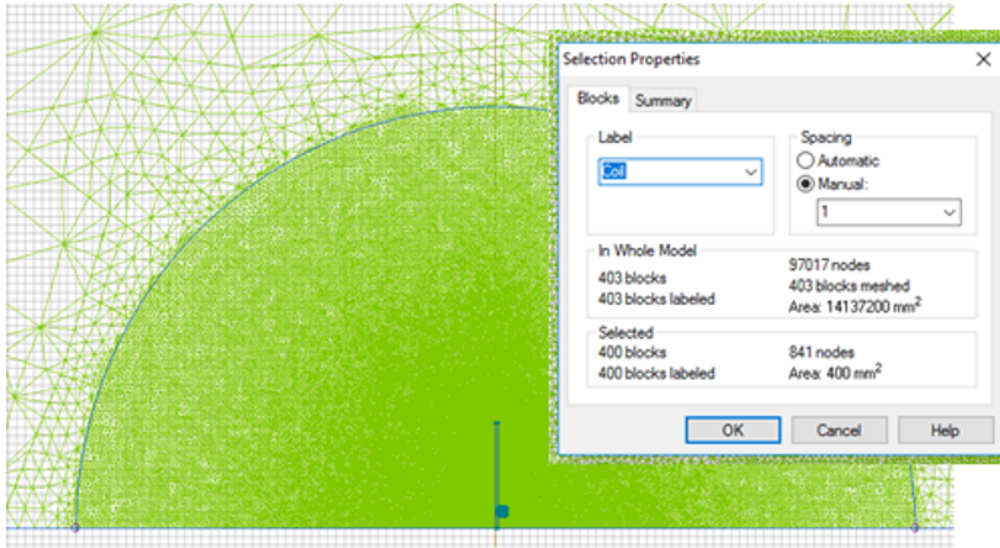


Figure 4.2: Adjustment of spacing between nodes

This model consisted of three parts, the send-receive type coil, the plate and the air for the surroundings (see figure 4.2), the size and the materials of the model in contact are shown in table 4.2.

Table 4.2: Parameters for model in contact

Model	Inside radius (mm)	Outside radius (mm)	Thickness (mm)	Turns	Material	Conductivity (S/m)	Relative permeability (μ_r)
Coil	30	50	20	400	Copper	5.6x107	1
Pipe	-	250	6.4	-	Low-carbon steel	5.9x106	2,000
Air	1,000	3,000	-	-	-	-	1

Table 4.2 also shows the relative permeability of the materials in the model, for non-ferrous materials is assumed as 1 and for low-carbon steel, the relative permeability should change with its B-H curve. Quickfield allows the use of B-H curve data for the material under study, however, an effective μ_r value of 2,000 was used for the pipe to reduce the simulation time.

As explained in the literature review, a typical PEC probe consists of an LR circuit, including the voltage source, an inductor and resistor. Figure 4.3 shows the circuit diagram used to mathematically model the PEC probe. R1 is the resistance of the coil, the coil acting as the inductor and U1 is the input square pulse. The plate was also added as in Quickfield, all conductors in the circuit needed to be included. An impulse function was used to simulate the square pulse, multiplied by a voltage of 10 Volts as most of the PEC probes work in this range. The resistance of the coil was assumed as 10 Ohms.

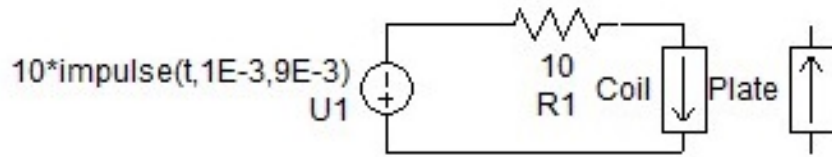


Figure 4.3: Quickfield circuit for model in contact

For the final setup of the Quickfield model, the timing was required to start the simulation. The total time of the integration is the transient time (5τ) of the circuit times two ($5\tau \times 2$) to allow the charge and discharge of the current. To calculate the transient time, Kirchhoffs law can be used, $\tau=L/R$, as explained in section 2.4.2 of the literature review. As resistance

and voltage were assumed and taken from other examples, and the inductance of the coil was unknown, a couple of simulations were carried out to find the most suitable integration timing. See table 4.3 for the obtained simulation timing of the model.

Table 4.3: Simulation timing for model in contact

Calculate up to	0.018
With step of	0.001
Store results every	0.001
Starting at	0

The purpose of this part was to evaluate the PEC signal probe when inspecting a carbon-steel pipe with and without defects. The first simulation was without defect and the results are shown below in table 4.4, where measurements are shown every 1ms up until 18ms, as it was setup. Simulation time took approximately 330s. Quickfield showed the measurements of the current (Amps) and voltage (Volts) for the source, resistor and coil. It is assumed that the PEC signals of the Lyft system are taken from the resistor voltage.

Table 4.4: Circuit results for model in contact with no defect

Time T (s)	Source U1		Resistor R1		Coil	
	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
0	0	0	0	0	0	0
0.001	0.323759	-10	0.323759	3.23759	0.323758	6.76241
0.002	0.516063	-10	0.516063	5.16063	0.516063	4.83937
0.003	0.63724	-10	0.63724	6.3724	0.637239	3.6276
0.004	0.713883	-10	0.713883	7.13883	0.713883	2.86117
0.005	0.762434	-10	0.762434	7.62434	0.762434	2.37566
0.006	0.793232	-10	0.793232	7.93232	0.793232	2.06768
0.007	0.8128	-10	0.8128	8.128	0.8128	1.872
0.008	0.825253	-10	0.825253	8.25253	0.825253	1.74747
0.009	0.509435	0	0.509435	5.09435	0.509436	-5.09435
0.01	0.322208	0	0.322208	3.22208	0.322209	-3.22208
0.011	0.204287	0	0.204287	2.04287	0.204287	-2.04287
0.012	0.129739	0	0.129739	1.29739	0.129739	-1.29739
0.013	0.082542	0	0.082542	0.825416	0.082542	-0.825416
0.014	0.052623	0	0.052623	0.526231	0.052623	-0.526231
0.015	0.033632	0	0.033632	0.336321	0.033632	-0.336321
0.016	0.02156	0	0.02156	0.215597	0.02156	-0.215597
0.017	0.013872	0	0.013872	0.138723	0.013872	-0.138723
0.018	0.008968	0	0.008968	0.0896771	0.008968	-0.089677

Quickfield also showed each curve for the voltage and current of the source, resistor and inductor. Curves are shown in the following figures.

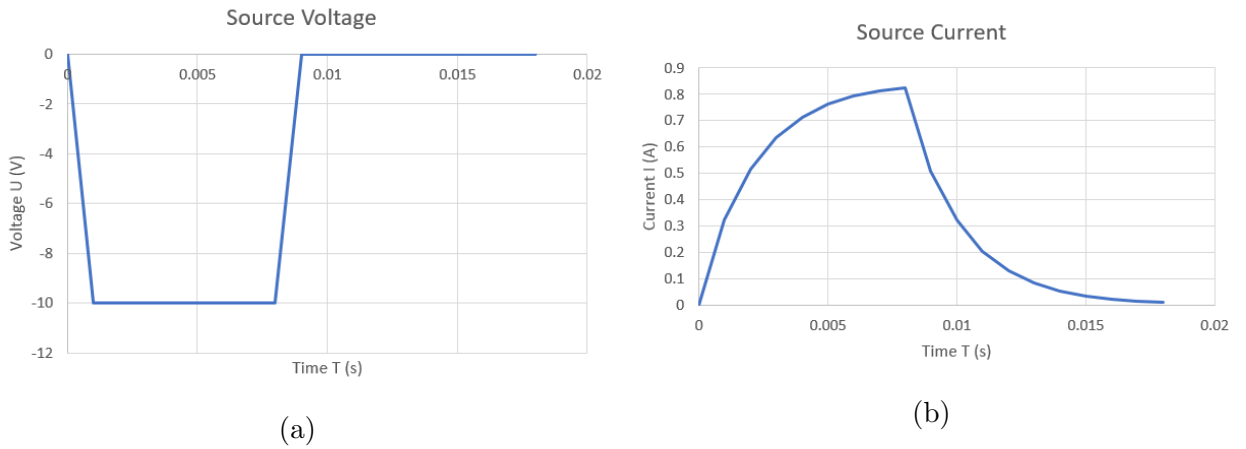


Figure 4.4: a) Source voltage and b) Source current vs. time for model without defect

Figure 4.4a) shows the impulse of the source voltage, starting with a voltage of -10V until the source voltage is turned off in 9 ms. The current had the expected behaviour in each of the circuit components (figure 4.4, 4.5, 4.6b), an exponential growth graph when charging and an exponential decay graph when discharging.

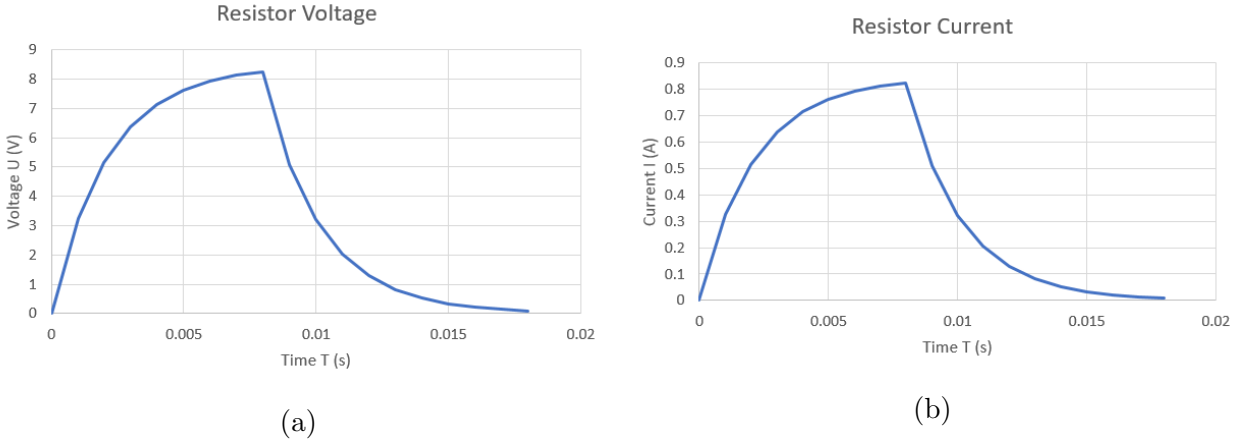


Figure 4.5: a) Resistor voltage and b) Resistor current vs. time for model without defect

Figure 4.5a) shows the resistor voltage behaviour or magnetic response, the curve of interest for the analysis of PEC signals, also growing exponentially when charging and decaying exponentially when discharging. Figure 4.6a) shows the behaviour of the coil voltage, it has the same form as the resistor but when charging it exponentially decays and when discharging it exponentially grows, as the inductor tries to stop the current from changing in the circuit to avoid changes in the magnetic flux.

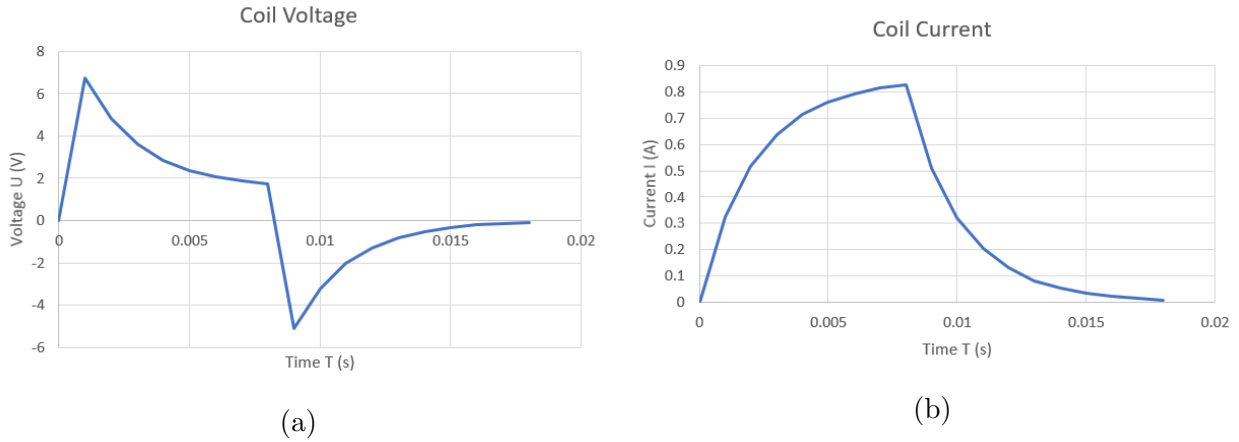


Figure 4.6: a) Coil voltage and b) Coil current vs. time for model with no defect

The literature review showed that new PEC systems like Lyft are focused in the decay of the magnetic response in a Log-Linear scale, which is related to the thickness of the component, therefore, this was done for the magnetic response in figure 4.7 and the rest, where the decay of the curve is shown.

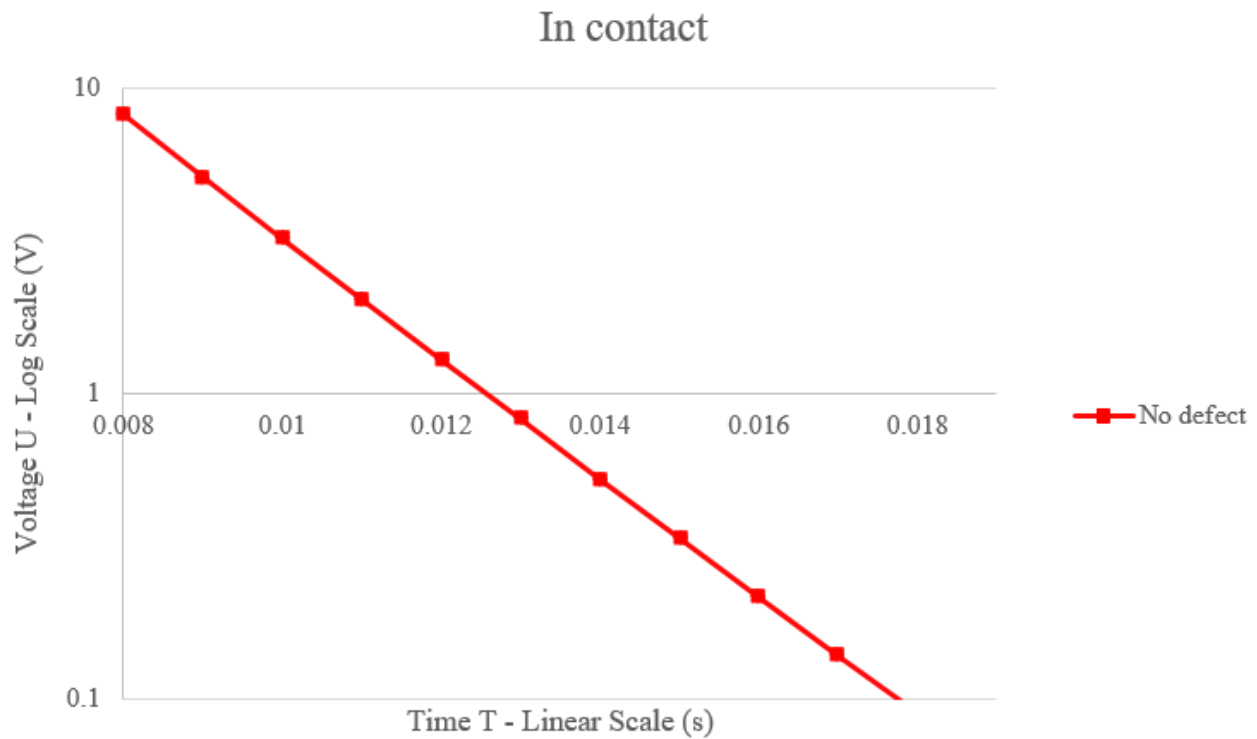


Figure 4.7: Voltage vs. time Log-Lin scale for model in contact without defects

Quickfield is a powerful software, not only does it calculate the voltage and current of

the circuit components, it also shows how the eddy current density changes at each of the steps of the simulation. See following figure 4.8, where the maximum density is shown at 9 ms (figure 4.8a), where the excitation pulse was turned off, then at 13 ms (figure 4.8b), to end with almost no eddy current density at 17 ms (figure 4.8c).

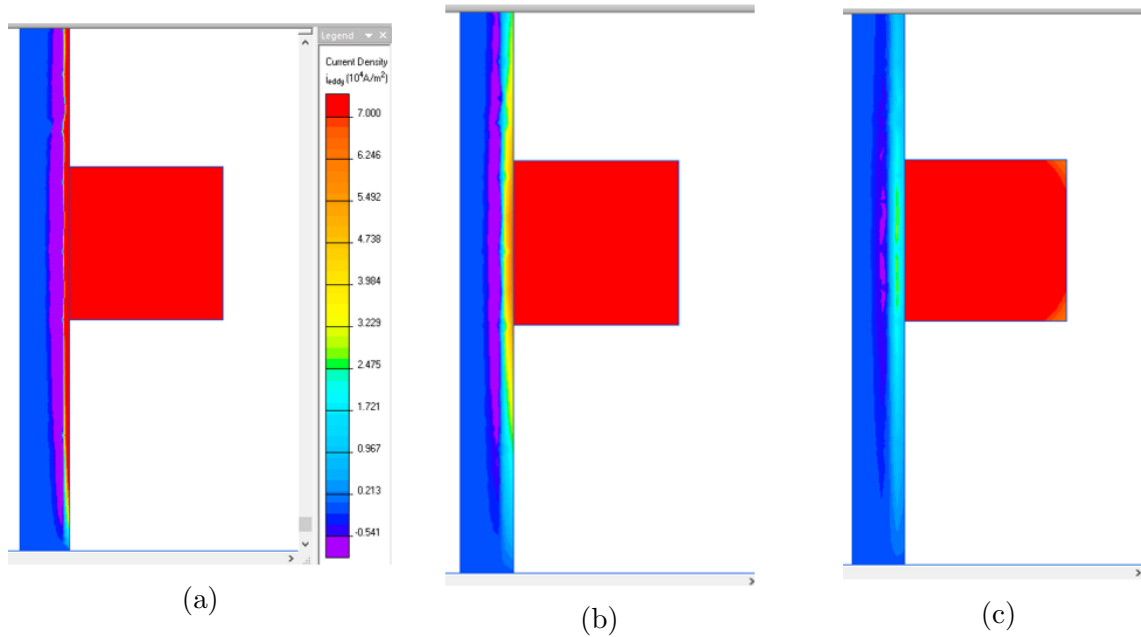


Figure 4.8: Eddy current density at a) 9 ms, b) 13 ms, c) 17 ms

The magnetic flux decay is also shown in figure 4.9 at the same steps. The decay begins at 9 ms (figure 4.9a), then at 13 ms (figure 4.9b), for then to keep on decaying until there is almost none along and outside the plate at 17 ms (figure 4.9c).

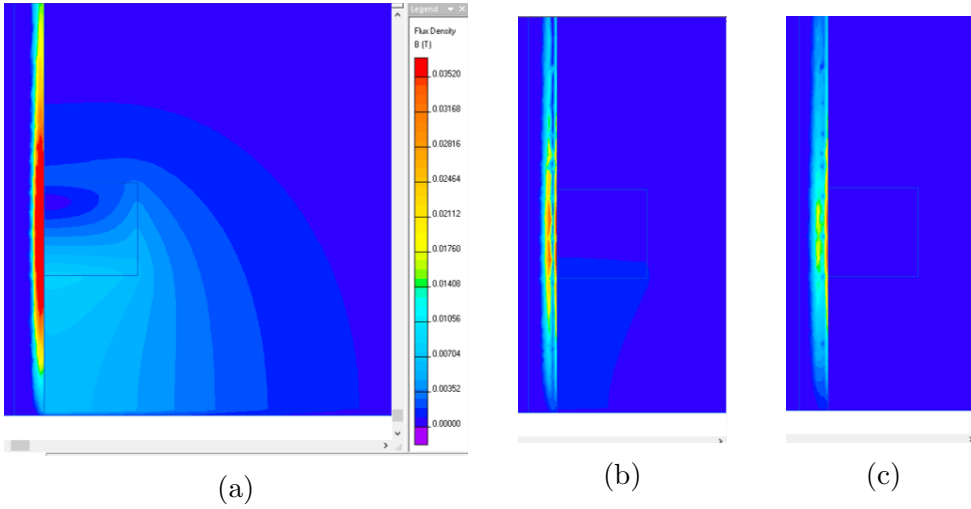


Figure 4.9: Magnetic flux density decay at a) 9 ms, b) 13 ms, c) 17 ms

The next part of the simulation of the model in contact was to introduce some defects on the plate and then compare the results with the simulation without defects. Six defects were modelled, two depths and three lengths. See table 4.5.

Table 4.5: Defect dimensions

Defect	Depth	Length
1	1.6	15
2	1.6	40
3	1.6	65
4	3.2	15
5	3.2	40
6	3.2	65
7	4.48	65

The three first defects had the same depth of 1.6mm, 25% of the plate thickness and three different lengths, 15mm, 40mm and 65mm, named as defect 1, 2 and 3 respectively. See the following figure 4.10.

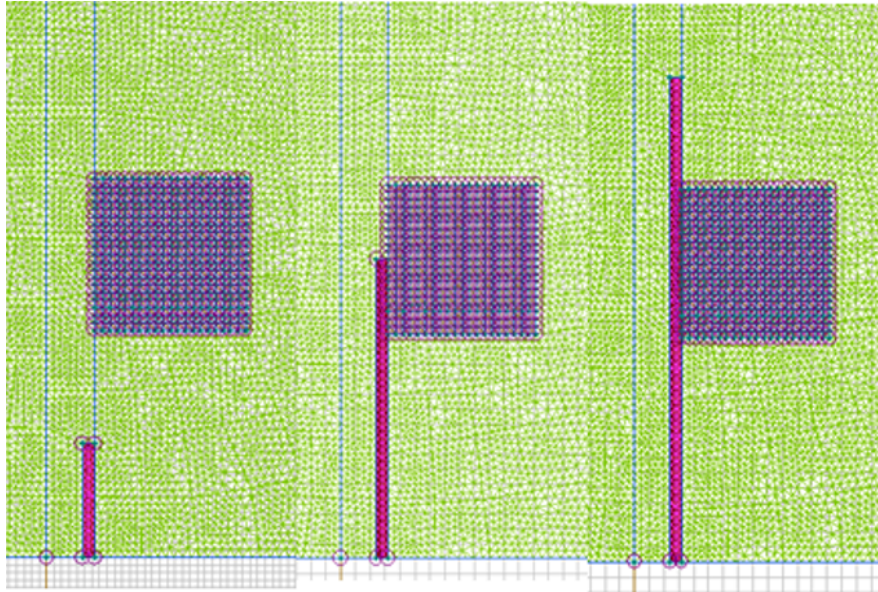


Figure 4.10: Defects 1, 2 and 3 from left to right

The next three defects had a depth of 3.2mm, 50% of the plate thickness and the same three lengths as the first three defects, 15mm, 40mm and 65mm, named as defect 4, 5 and 6 respectively. See figure 4.11.

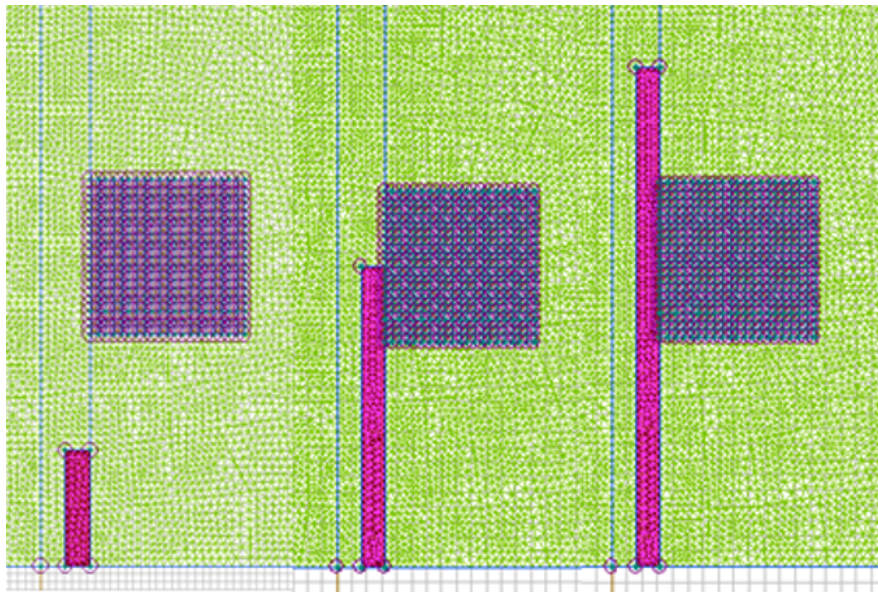


Figure 4.11: Defects 4, 5 and 6 from left to right

The simulation total time for the model with defects was between 330s to 450s, results were then included in the same graph to observe the signal differences. See figure 4.12.

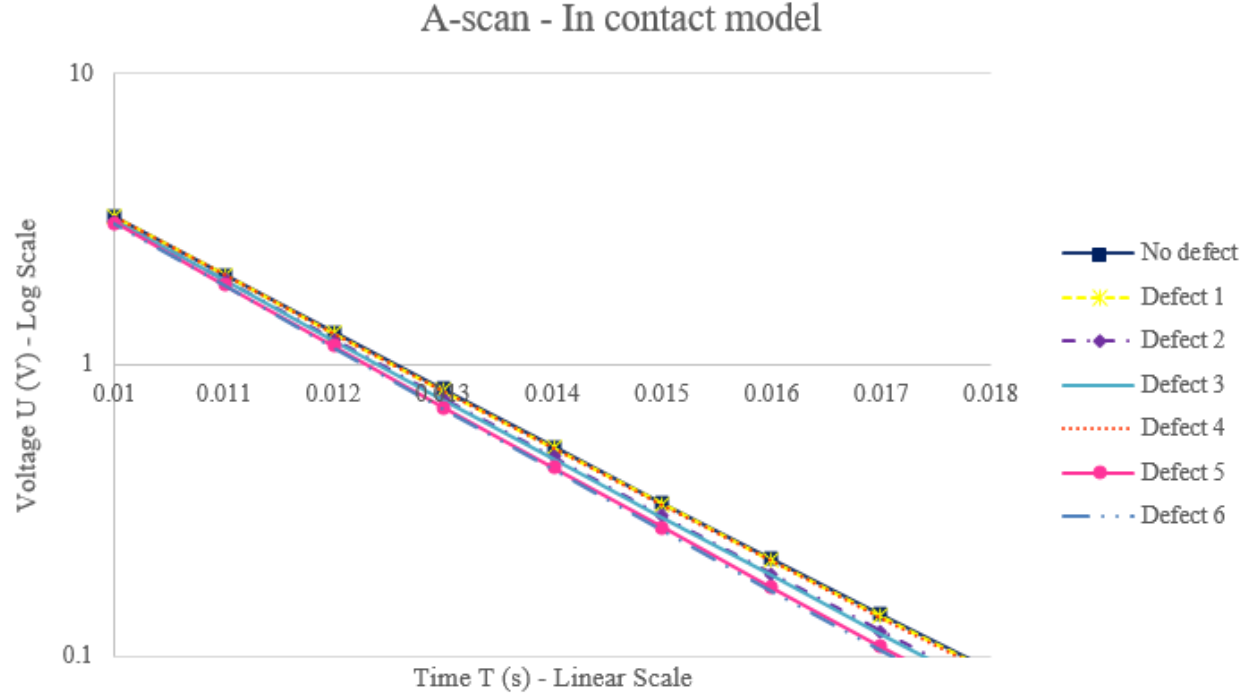


Figure 4.12: Voltage vs. time Log-Linear Scale for model in contact with and without defects

Figure 4.12 shows the changes of the resistor voltage against time in a log-linear scale to show the results as the Lyft system. All signals from each one of the defects are compared with the nominal wall thickness measurement. The latter presented the highest gradient value of -1265.65 (see table 14). When comparing it with the signals from the model with defect 1, 4, where the gradients are -1265.62, -1266 respectively, differences are negligible, defects are too short in length to be detected. When looking at the signals from defect 2 and 3, which have gradient values of -1269.07 and -1269.73 respectively, significant differences are observed because the defects are long enough to be detected. Even more significant differences with respect to the nominal wall thickness are observed from the deepest defects, defect 5 and 6, where the signals have gradient values of -1271.09 and -1273.43 respectively. When carrying out pulsed eddy current inspections with Lyft, signals are observed because of the decay of the eddy currents, those eddy currents should reach the far side of the wall to calculate the remaining wall thickness. The simulations performed showed that the eddy current density did not reach the far side of the wall, so probably this gives small differences

between the defect signals.

One other key point to mention is that the maximum voltage reached by all signals was the approximately 8.2V (see table 4.6), the presence of defects causes small changes on the coil inductance, therefore the different gradients on the signals.

Table 4.6: Maximum voltage and gradient of decay curves from all signals of model in contact

	No defect	1	2	3	4	5	6
Peak	8.25253	8.25534	8.27795	8.2808	8.25699	8.2979	8.30321
Gradient	-1265.6533	-1265.62	-1269.07	-1269.73	-1266	-1271.09	-1273.43

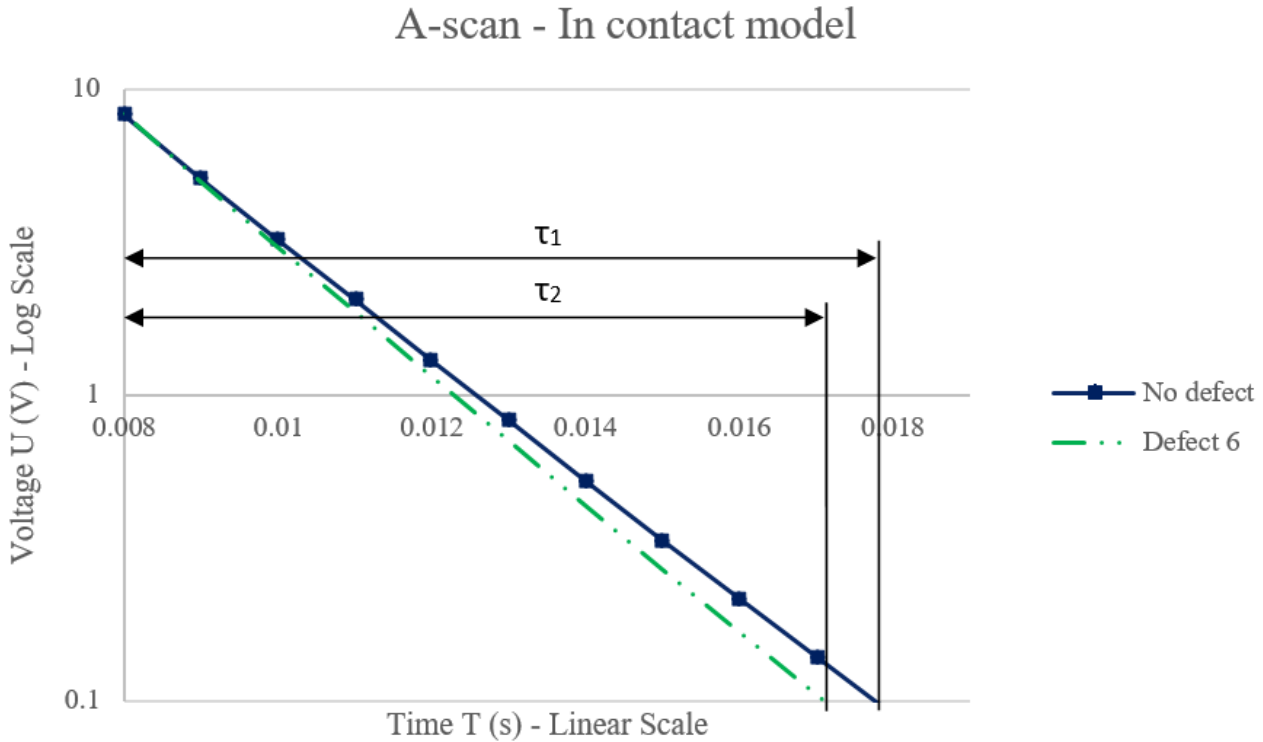


Figure 4.13: Voltage vs. time Log-Linear Scale for model in contact with defect 6 and no defect

Figure 4.13 shows the magnetic response from defect 6, big differences are observed with respect to the nominal thickness signal. One of the rules of thumb of PEC by Lyft is that the time constant is inversely proportional to the decay rate; the thinner the plate, the faster is the decay of the signal, the lower the time constant will be and vice versa. This is confirmed by the performed simulations, where the signal from defect 6 decays more rapidly to zero as

the thickness of the plate on that point is thinner. The faster decay the smaller the time constant (τ), in the figure τ_1 corresponds to the time constant of the nominal decay rate and τ_2 corresponds to the signal from defect 6.

4.2 Simulation through insulation and cladding

In order to fully evaluate the behaviour of a PEC system through finite element analysis (FEA) using Quickfield, a lift-off had to be introduced. According to the reinvented Lyft system, the maximum lift-off through which the component can be inspected is of 305mm. In this model, a lift-off of 80mm was used, with the same dimensions as in the experimental part. See the model in figure 4.14.

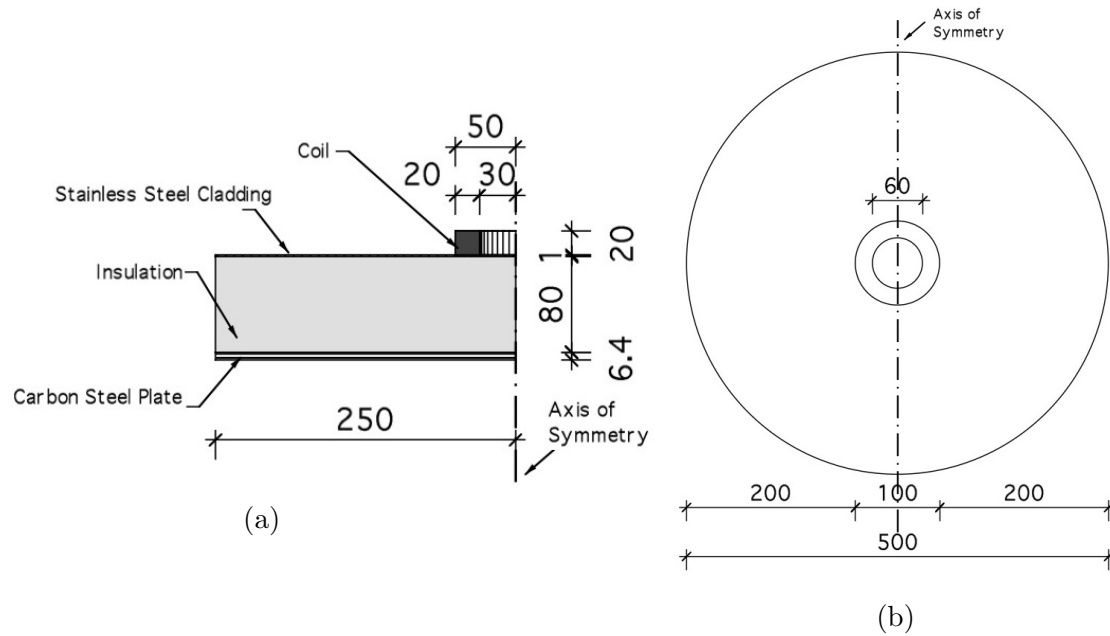


Figure 4.14: Model for simulation with lift-off a) Front view, b) Top view.

The same problem properties as in the previous set of simulations were used, including the timing setup and mesh size. See figure 4.15 for the Quickfield model with 80mm of insulation.

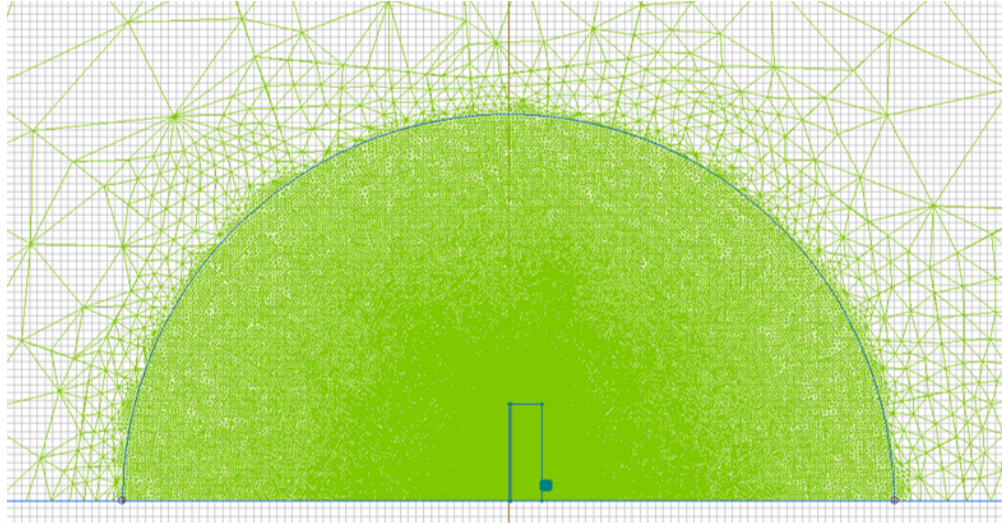


Figure 4.15: Quickfield model with insulation and cladding

This model consisted of five parts, the same send-receive type coil, the plate, the cladding, the insulation (air) and the surroundings. The size and the materials of the model in contact are shown in table 4.7.

Table 4.7: Parameters for model with insulation and cladding

Model	Inside radius (mm)	Outside radius (mm)	Thickness (mm)	Turns	Material	Conductivity (S/m)	Relative permeability (μ_r)
Coil	30	50	20	400	Copper	5.6x10 ⁷	1
Pipe	-	250	6.4	-	Low-carbon steel	5.9x10 ⁶	2,000
Air	1,000	3,000	-	-	-	-	1
Insulation	-	-	0-80	-	Air	-	-
Cladding	-	-	1	-	Stainless steel	1.4 x10 ⁶	1

When all the properties had been entered into the software, the next step was to add the circuit for this model, which was the same as the previous simulation with the only difference that the cladding had to be added as it is also a conductor of electricity, even with its small contribution. See figure 4.16.

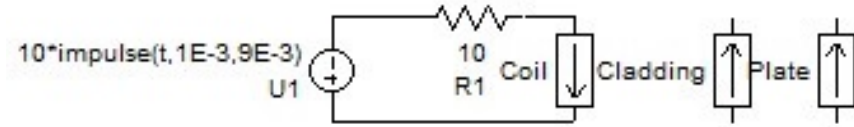


Figure 4.16: Circuit for model with insulation and cladding

The first simulations were carried out with an insulation of 80mm and the same defects on the plate as in the previous part, the signals showed no significant differences from each other, probably because the coil used for this had not enough power to penetrate the magnetic field and form the eddy currents in the plate.

The next set of simulations were carried out to see the behaviour of the send-receive type probe over the plate without defects at different lift-offs. Lyft system behaves in a way that the measurements are not affected by lift-off. When the lift-off is significantly reduced, saturation might happen on the A-scan. This is observed when the lift-off was reduced on the simulations.

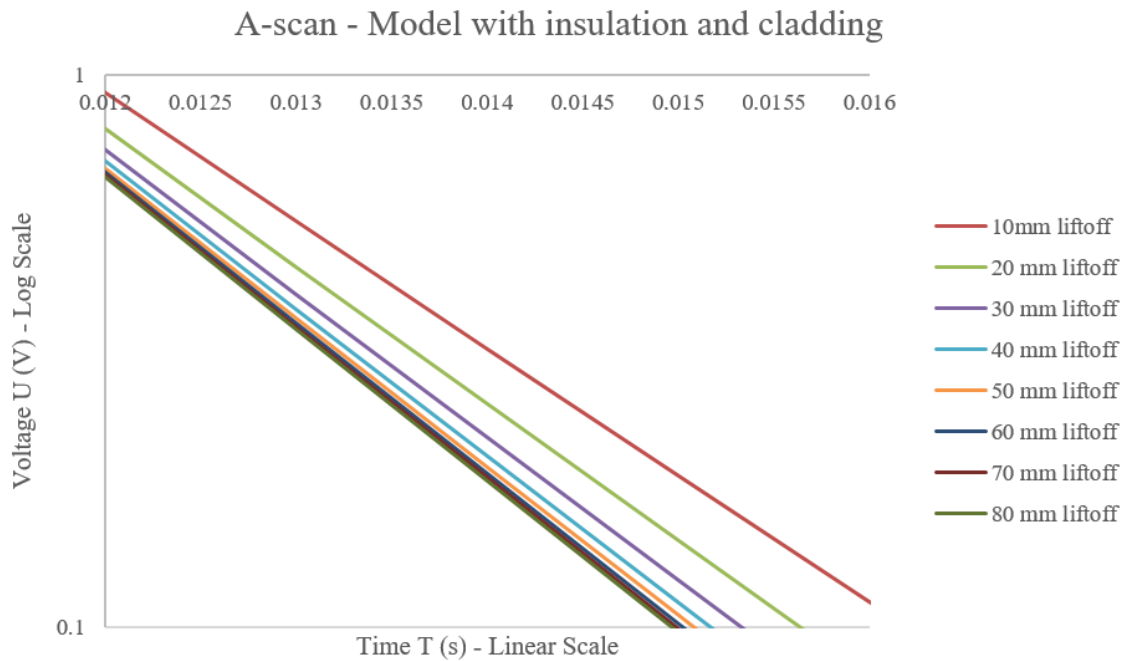


Figure 4.17: Voltage vs. time Log-Linear Scale for model with insulation and cladding

Figure 4.15 shows that the more significant the reduction of lift-off is, the higher the signal over the signal from 80 mm lift-off is. Saturation could happen because of the significant reduction of lift-off. The signals of the lift-off reductions are almost parallel to each other because different voltages were reached during the charging phase, see table 4.8.

Table 4.8: Maximum voltage and gradient of decay curves from signals at different lift-offs of model through insulation and cladding

Liftoff	V (Volts)	Gradient
10	8.35824	-1253.27
20	8.39474	-1251.55
30	8.40981	-1248.71
40	8.4171	-1247.2
50	8.42105	-1246.65
60	8.42335	-1246.4
70	8.42478	-1246.32
80	8.42571	-1246.36

Figure 2.4 shows the changes of the maximum voltage at different lift-offs. Substantial changes in the voltage are observed up until 40mm lift-off, after that, changes are small, probably because of the probe parameters. According to the A-scan in figure 4.17, at the smallest lift-off, a bigger voltage is reached, the opposite is observed in figure 4.18, due to the applied voltage polarity.

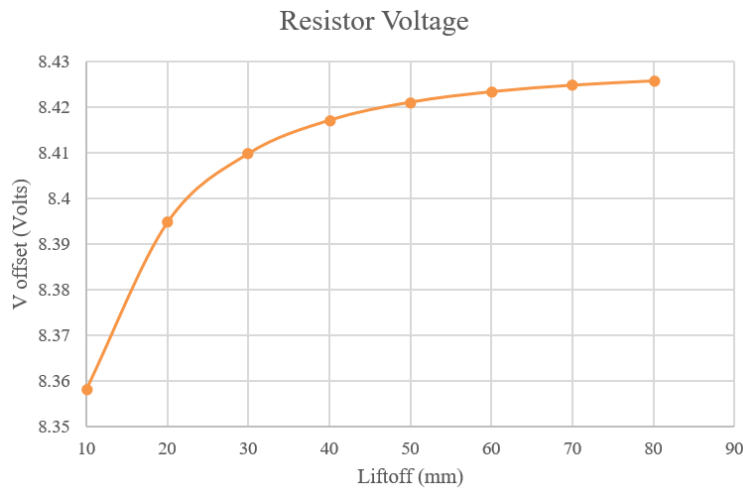


Figure 4.18: Resistor voltage offset vs. lift-off

One final comparison was carried out to confirm that the PEC systems can inspect through

the insulation. At a small lift-off of 10 mm and making the cladding as if it was air, one more simulation was performed, for then to compare it with the results at the same lift-off with the stainless-steel cladding. Results were similar for both cases (See figure 4.19), where the peak voltage was the approximately 8.36V and the gradient of -1253.27 and -1273.18 for the simulation with and without cladding, respectively, confirming another advantage of the PEC systems, especially Lyft by Eddyfi. See appendix for the table of values.

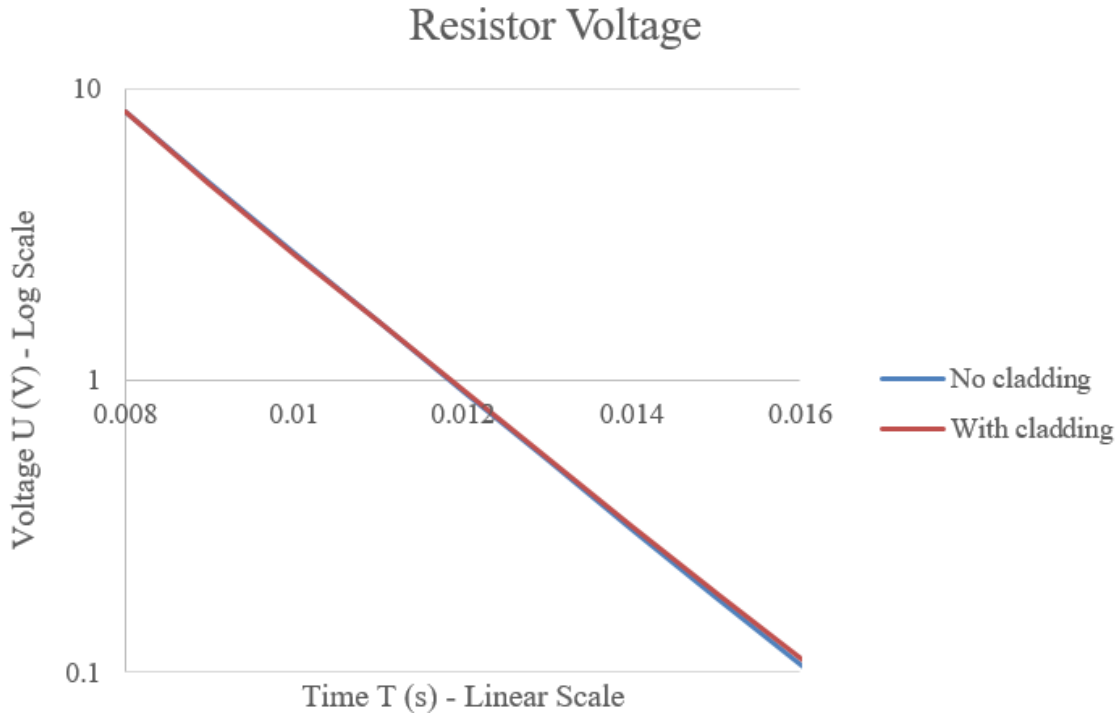


Figure 4.19: Voltage vs. time Log-Linear Scale for model with 10 mm insulation with and without cladding

4.3 Comments

This chapter described the results from the finite element analysis applied to a transient magnetic problem using Quickfield software. One model included a send-receive type probe in contact with a carbon-steel pipe with the presence of defects; the other one included the same probe but in contact with a stainless-steel cladding and insulation to show the effects of lift-off. Both simulations were carried out using the same impulse lenght. An effective

value of relative permeability for the carbon-steel plate was used to reduce the simulation timing. To simulate the signal responses from Lyft, the resistor voltage (log-scale) was plotted against time (linear-scale). Results from the first set of simulations in contact showed that the presence of defects did not cause significant changes in the inductance of the coil, therefore, a similar value of the peak voltage was reached by all signals, thus the different decay rates with different time constants (τ). Defects that were 30mm in length were too small to be detected by the probe, and the deeper the defect, the faster the decay rate, therefore presenting a smaller time constant (τ). The results from the simulation through insulation and cladding showed the effects of lift-off. Different peak voltages were reached by the signals at different lift-offs because changes in the inductance were significant in this case, therefore different peaks and similar gradients. Results also showed that the PEC probe is not significantly affected by the presence of the stainless-steel cladding.

Chapter 5

Conclusions

- Evaluation of the Lyft system, relatively new equipment developed by Eddyfi, was performed to contribute to the validation of its unique CWT post-process tool.
- A good understanding of how the Lyft system works was gained through the performance of the inspections on a carbon steel pipe, both in contact and through the insulating material and stainless-steel cladding.
- It was confirmed that the Lyft system is not only capable of inspecting corrosion under insulation (CUI), it is also capable of testing corrosion scabs, a type of localized corrosion as dangerous as CUI.
- Results from the inspection through the insulation and stainless-steel cladding using PEC-089 G2 probe, showed good quality data with an acceptable level of noise in the A-scan and twelve out of fourteen corrosion areas that were easily observed in the C-scan. The CWT was calculated in each of the corrosion areas, results showed that the CWT tool tried to improve all smaller-than-averaging-area defect sizing, a problem that all PEC systems have. Lyft system showed that with the presence of lift-off, footprint size is increased and defects are undersized, without the compensation there is more undersizing.

- Most of the wall loss and corrosion scabs were located at the six o'clock position (bottom of the pipe), as expected for pipes horizontally installed; corrosion product was probably held by defects on the pipe coating and formed other corrosion layers (scabs) over the pipe.
- The inspection in contact using PEC-025 G2 probe was also carried out in all the corrosion scabs. Results showed that the differences between the remaining wall thickness before and after the compensation were smaller than the first inspection because there was no presence of lift-off, so the footprint size was not affected by this. Results showed two special and not so common cases, where the compensated value was bigger than the uncompensated value, a problem that seemed to happen when testing very irregular areas. When calculating the CWT over very irregular areas (corrosion scabs), the selected box seemed to contain a defect within a defect, in other words, two important defect depths, therefore the CWT might have taken the shallower depth and show a bigger wall thickness than the uncompensated remaining wall thickness.
- A statistical analysis was performed between both inspections to compare the results with and without the compensation. The analysis consisted of carrying out a suitable POS (probability of sizing) technique by making the measurements from the inspection in contact the independent variable as this should have been the measurements closer to the true size.
- The first comparison, between the uncompensated data from the inspection through insulation against in contact, showed an acceptable R-squared value (coefficient of determination) of 0.7188, which made the data points close to the regression line. However, the line was far away from the ideal line, this was observed in the line equation, $y=0.3612x+51.559$. The standard deviation was the second lowest (8.6%). Results showed that when performing inspections through insulations and cladding the sizing accuracy was $\pm 16\%$ to 95% of confidence, an acceptable value but far away from the

true sizes.

- The second comparison was performed to see if there was any improvement on the Lyft sizing when the CWT tool was applied on the data from the inspection through insulation. At first it was noticed that the sizing improved as the regression line was closer to the ideal line, this was confirmed when looking at the line equation ($y=0.5801x+22.955$). However, the low value of R-squared (0.1141) made the standard deviation increase to 16.3%, which made a bigger gap between the confidence limit and result in a higher accuracy of $\pm 32\%$ to 95% of confidence.
- The last comparison was between the compensated data of the inspection through insulation and the uncompensated data of the inspection in contact. The results showed that the CWT tool does make an improvement on the sizing with an accuracy of $\pm 14\%$ to 95% of confidence. The highest R-squared value (0.8079) was observed, resulting in the lowest standard deviation (7.7%) and a regression line that was closer to the ideal line, seen in the line equation ($y=1.1866x+12.814$).
- In order to fully understand how a PEC system works and to compare results with the ones from the Lyft system and with the theory, a transient magnetics analysis through finite element analysis (FEA) was carried out to two models, one with the PEC probe in contact and the other one with a lift-off. Quickfield proved to be a powerful tool that covers everything that is needed for this application and even more.
- The FE model of the PEC system consisted of a component with the same parameters as the experimental part and the send-receive type probe which was represented as a simplified transient circuit. The circuit was formed of the resistor and an inductor (LR circuit) driven by a square pulse. The analysed data was taken from the resistor voltage after the pulse cuts off, which represents the decay of the eddy current as it diffuses in the material thickness. The decay of the resistor voltage against time was shown in a Log-Linear scale. The decay rate was related to the wall thickness of the component

as Lyft does.

- The first model consisted of three parts, the send-receive type coil, the plate and the air for the surroundings. One simulation was carried out with the probe in contact with a defect free carbon-steel pipe, where the signal represented the nominal wall thickness (WT), then defects with different depths and lengths were introduced. Results showed no significant difference between the nominal WT and the signals from the shortest defects (defect 1,4) even when their depths were different. Thus, for defects smaller than half of the internal diameter of the coil, PEC probe could not size properly. Bigger differences were observed in defects 2 and 3, which were at 25% of the nominal WT, and even more in defects 5 and 6, which were at 50% of the nominal WT. Therefore, it was confirmed that the faster the decay of the line, the lower the remaining wall thickness.
- For the simulations in contact, the same voltage was reached by all signals with and without defects because there was no lift-off. Therefore, the different decay rates.
- Quickfield not only showed the data for the circuit analysis, it also showed how the magnetic flux density and the eddy current density changed in the component at each of the recorded steps.
- The second and last model consisted of five parts, the same send-receive type coil, the plate, the cladding, the insulation (air) and the surroundings. Simulations were carried out to see the effect of liftoff and the effects when inspecting through a stainless-steel cladding. Results showed that the PEC signals were not affected by the presence of the cladding, as expected.
- Results also showed that the more significant the reduction of liftoff is, the further away the signal evaluated was over the signal from 80 mm lift-off. Saturation could happen because of the significant reduction of lift-off. The signals of the lift-off reductions are

almost parallel to each other because different voltages were reached by each one of them. The curve of voltage against lift-off showed an exponential growth graph, no significant changes are observed when the lift-off was higher than 40mm due to the probe sensitivity loss.

Chapter 6

Recommendations

- It is recommended that additional tests are carried out with the Lyft system on components with more defects, to obtain more accurate results when performing the statistical analysis through the probability of sizing (POS).
- Regarding the simulations, it is recommended to work with the optimization of the mesh and the PEC probe. Compare results using a coarse and a fine mesh and observe if there are any improvements. Furthermore, include a receive coil to improve the sensitivity of the probe; use other configurations with ferrite cores and/or ferrite shielding.
- Carry out additional work using non-linear permeability data for the carbon-steel plate.

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Appendices

Appendix A

Ampere's law

Ampere's law states that: *'the circulation of H around a closed path is equal to the current enclosed by the path'*. (Ida, 2015)

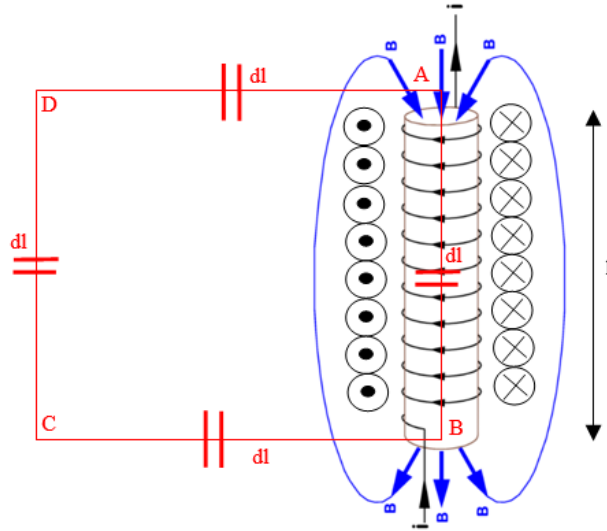


Figure A.1: Ampere's law in the centre of a solenoid

$$\oint H \cdot dl = I_{enclosed}$$

$$\sum I_{loop} = \frac{1}{\mu_0} \oint B \cdot dl$$

$$ni = \frac{1}{\mu_0} \oint B \cdot dl$$

$$ni = \frac{1}{\mu_0} \left[\int_A^B B \cdot dl + \int_B^C B \cdot dl + \int_C^D B \cdot dl + \int_D^A B \cdot dl \right]$$

Path C-D: is far away, path B-C and D-A: are perpendicular to dl, therefore $\theta=90^\circ$ and $\cos 90^\circ=0$, so these three paths are not considered.

$$ni = \frac{1}{\mu_0} \left[\int_A^B B \cdot dl \right]$$

$$B \cdot dl = B dl \cos \theta$$

B is parallel to dl, $\theta=0^\circ$ and $\cos \theta=1$, therefore:

$$ni = \frac{1}{\mu_0} \left[\int_A^B B \cdot dl \right]$$

$$ni = \frac{B}{\mu_0} \left[\int_A^B dl \right] = \frac{Bh}{\mu_0}$$

$$B = \frac{\mu_0 ni}{h} = \mu_0 H$$

Appendix B

RL circuit

Solenoids try to prevent the change of current in a circuit.

- **Charging:** the current when charging the current in the circuit will have a form of growth graph, this can be explained using Kirchoff's current law where:

$$\sum_{k=1}^n I_k = 0$$

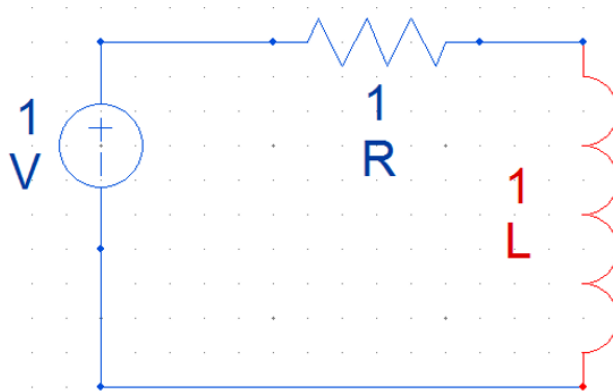


Figure B.1: RL circuit: charging phase

Kirchhoff's loop law states that the voltage across a closed loop is zero:

$$\epsilon m f - i R - L \frac{di}{dt} = 0$$

Where ϵ mf: volts of the battery, iR : volts across the resistor and Ldi/dt : volts across the inductor.

$$\epsilon - iR = L \frac{di}{dt}$$

$$\int_0^t \frac{dt}{L} = \int_0^i \frac{di}{\epsilon - iR}$$

$$\frac{t}{L} = \int_0^i \frac{di}{\epsilon - iR}$$

$$let U = \epsilon - iR, di = \frac{dU}{-R}$$

$$\frac{t}{L} = \int \frac{-\frac{1}{R}dU}{dU}$$

$$-\frac{R}{L}t = \ln U = \ln(\epsilon - iR) \Big|_0^i$$

$$-\frac{R}{L}t = \ln \epsilon - iR - \ln \epsilon$$

$$-\frac{R}{L}t = \ln \frac{\epsilon - iR}{\epsilon}$$

$$e^{-\frac{R}{L}t} = \frac{\epsilon - iR}{\epsilon}$$

$$\epsilon e^{-\frac{R}{L}t} = \epsilon - iR$$

$$iR = \epsilon - \epsilon e^{-\frac{R}{L}t}$$

Therefore, the current on the circuit will be:

$$i = I_f - I_f e^{-\frac{R}{L}t}$$

The time constant is known as the $\tau=L/R$, so when substituing in the previous equation:

$$i_\tau = I_f - I_f e^{-\frac{RL}{LR}}$$

$$i_\tau = I_f - I_f e^{-1}$$

$$i_\tau = I_f \left(1 - \frac{1}{e}\right)$$

$$i_\tau = 0.63 I_f$$

- **Discharging:** By closing to S_1 , the energy will build up until the current is in a steady state as the ϵ mf is 0. When closing to S_2 , the current will start to decrease and L will behave like a battery until the current is 0. The current will have the same form when charging but in this case, will be decreasing until it gets to 0.

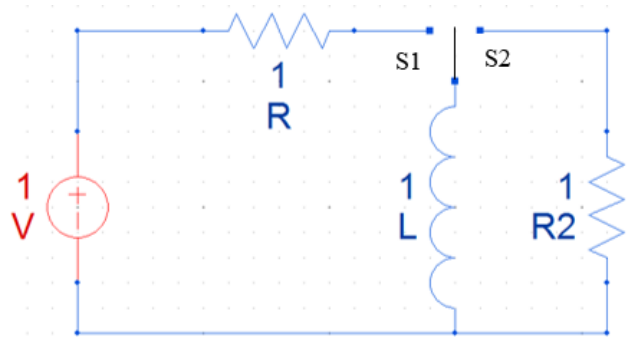


Figure B.2: RL circuit: discharging phase

Using Kirchoff's law:

$$-L \frac{di}{dt} - iR = 0$$

$$-L \frac{di}{dt} = iR$$

$$-L \frac{di}{i} = R dt$$

$$\int_0^i \frac{di}{i} = \int_0^t -\frac{R}{L} dt$$

$$\ln i \Big|_{I_0}^i = -\frac{R}{L} t$$

$$-\frac{R}{L} = \ln i - \ln I_0 = \ln \frac{i}{i_0}$$

$$e^{-\frac{R}{L}t} = \frac{i}{I_0}$$

$$i = I_0 e^{-\frac{R}{L}t}$$

The time constant is known as the $\tau=L/R$, so when substituting in the previous equation:

$$i_\tau = I_0 e^{-\frac{RL}{LR}}$$

$$i_\tau = I_0 e^{-1}$$

$$i_\tau = \frac{I_0}{e} = 0.37 I_0$$

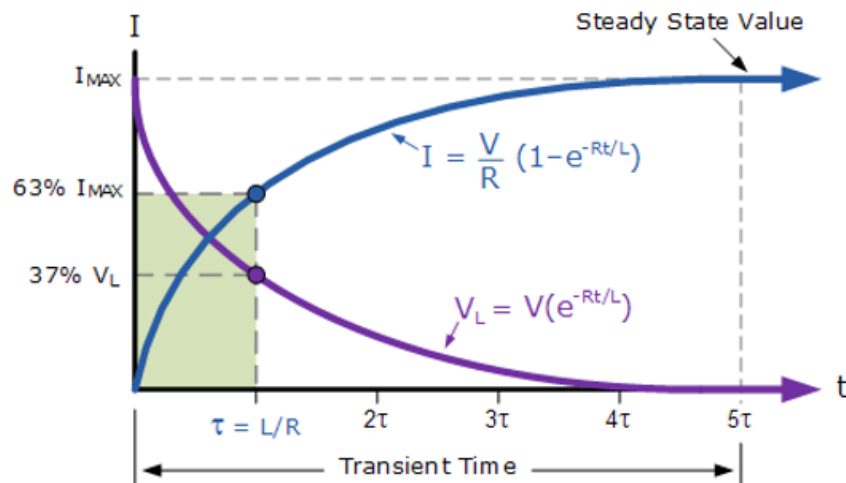


Figure B.3: Transient time

When the current reaches its final steady state value, which is approximate to 5τ (transient time of the circuit) the inductance of the coil is zero AspenCore (2017).

Appendix C

Results

C.1 Inspection of CUI

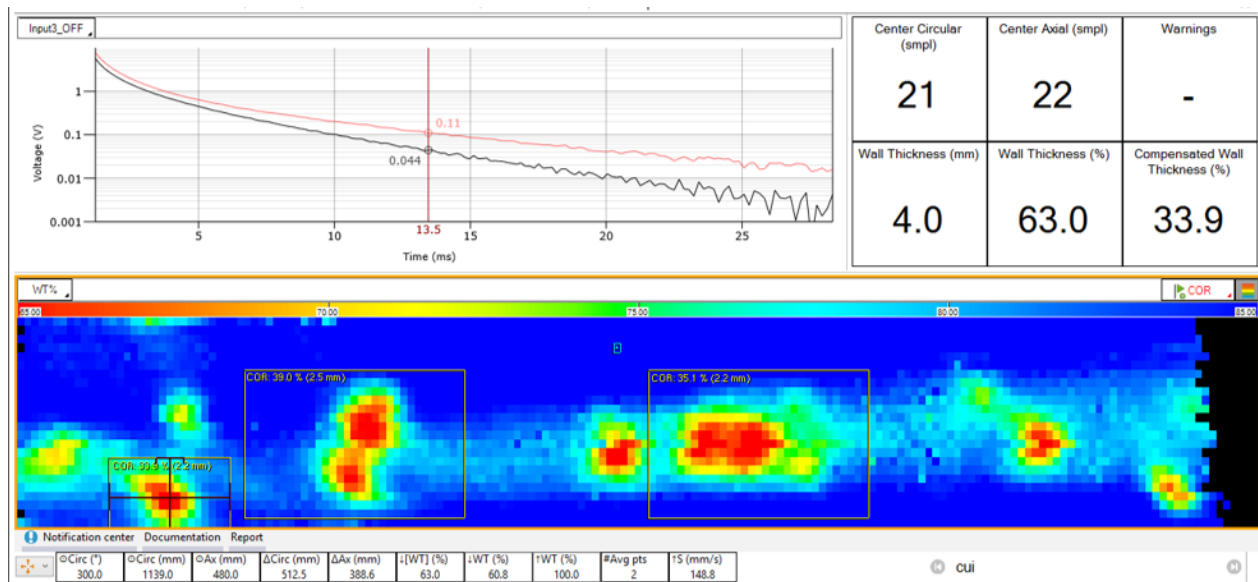


Figure C.1: C-scan Scab 3

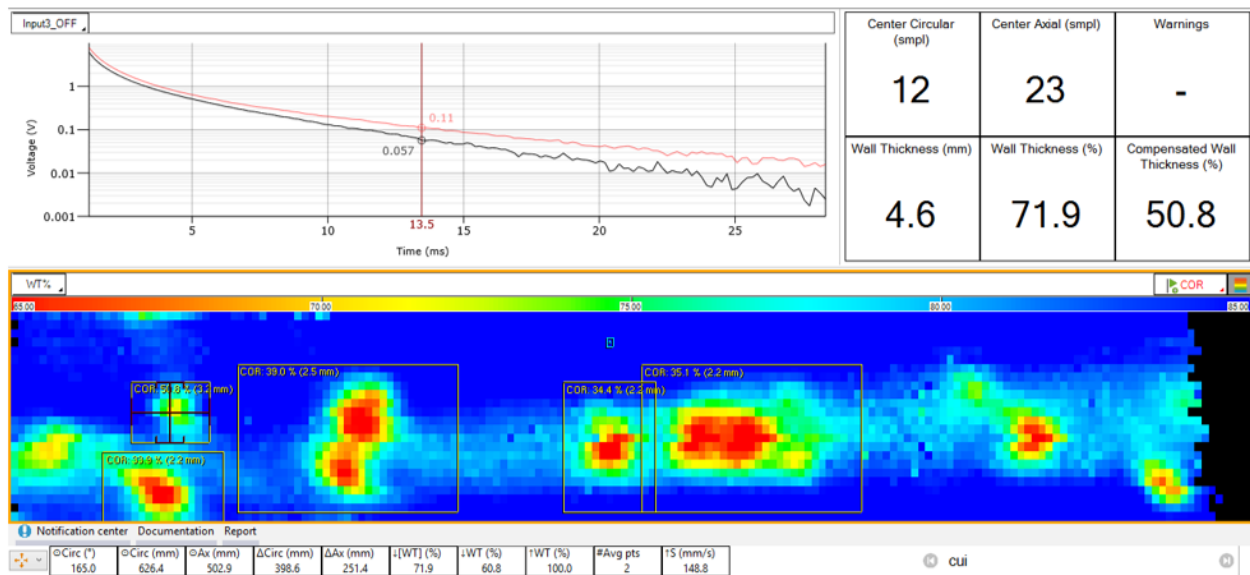


Figure C.2: C-scan Scab 4

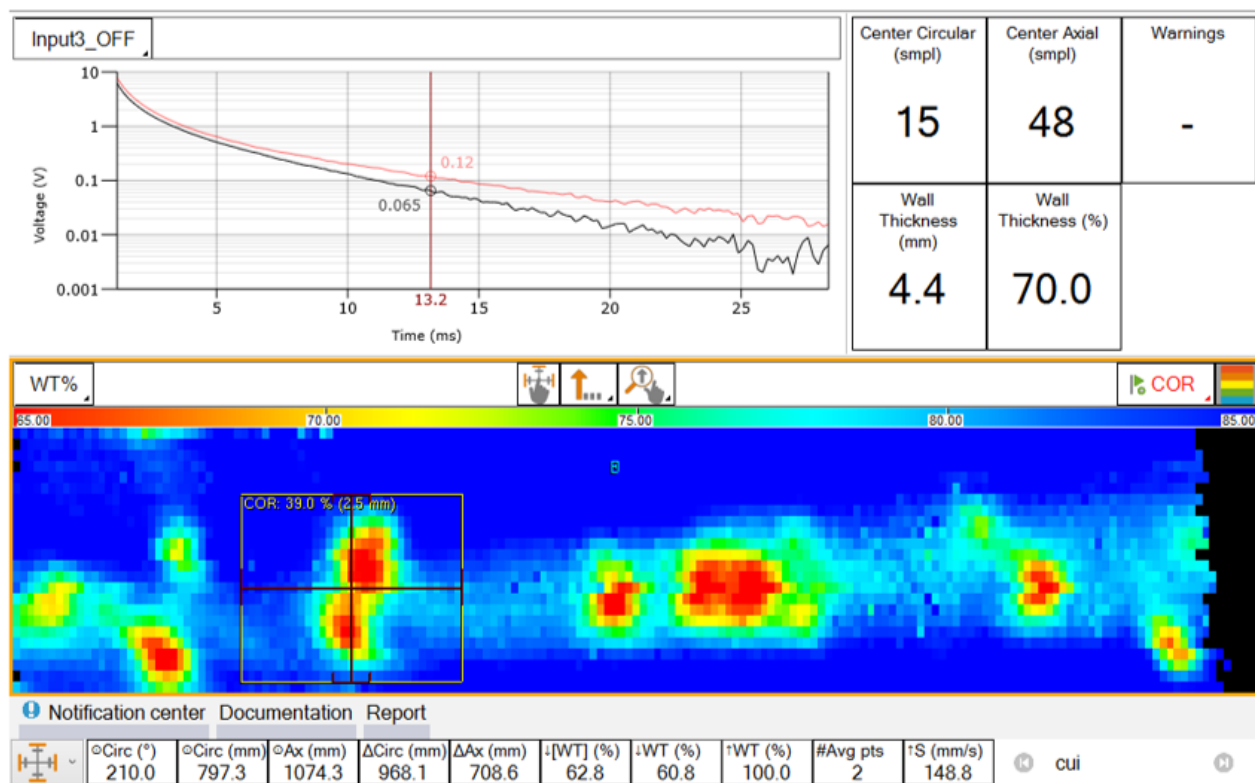


Figure C.3: C-scan Scab 5 & 6

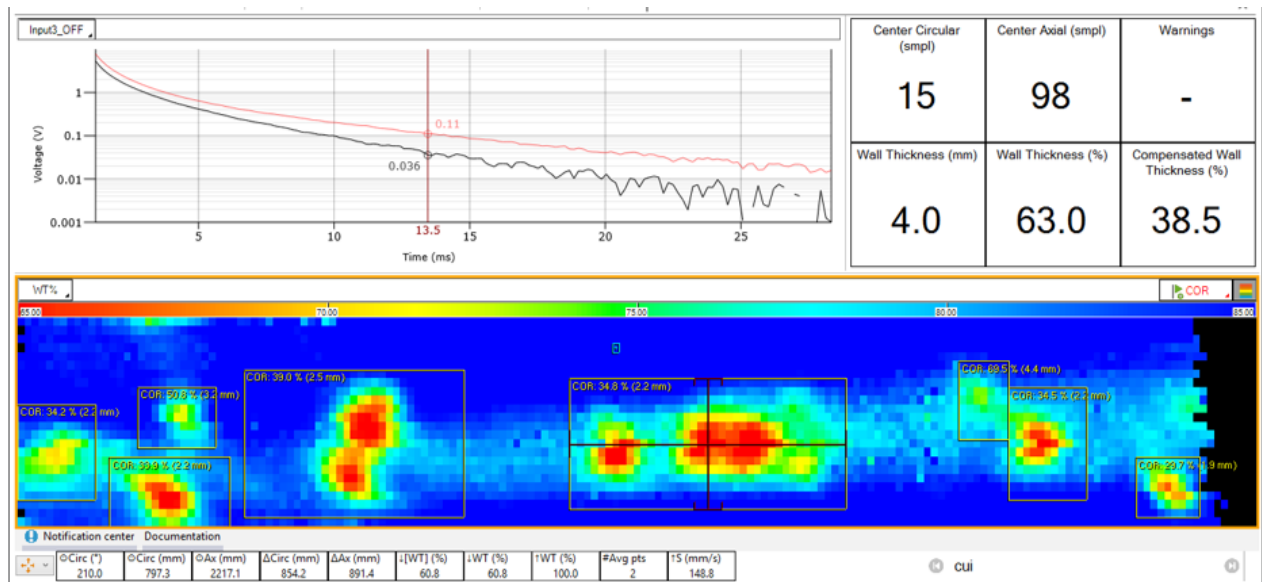


Figure C.4: C-scan Scab 7, 8, 9 & 10

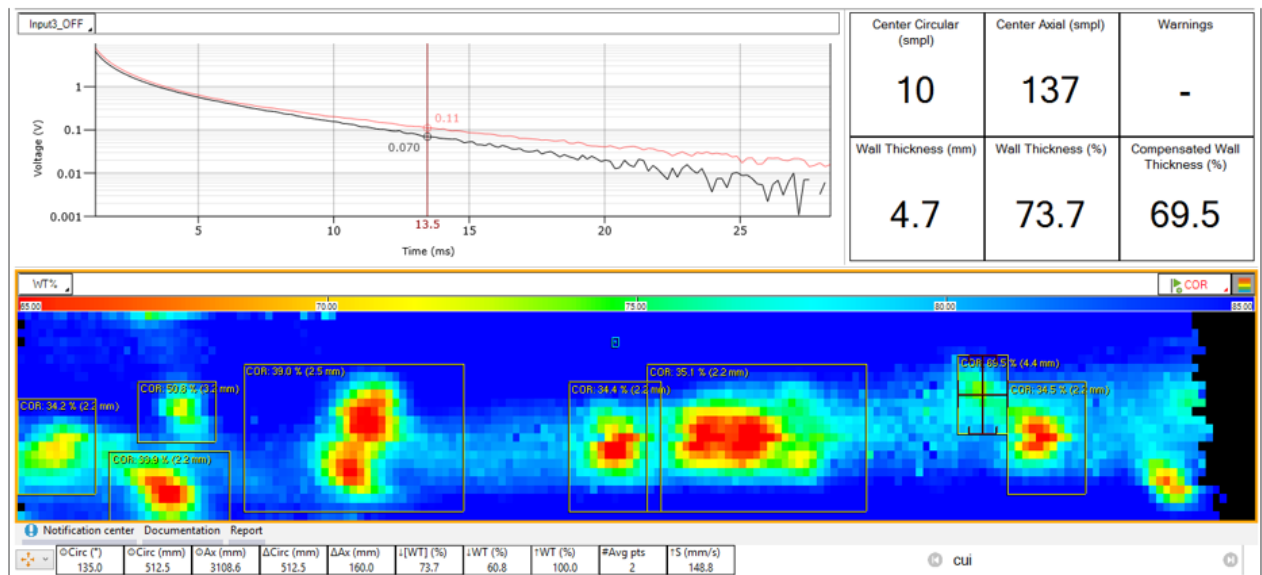


Figure C.5: C-scan Scab 11

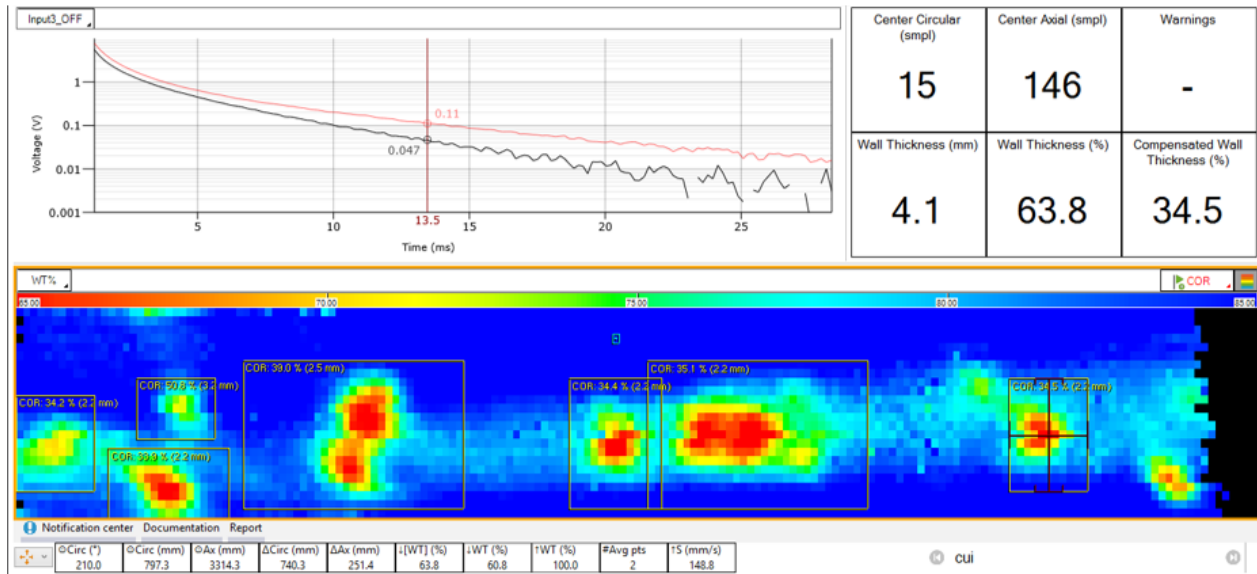


Figure C.6: C-scan Scab 12

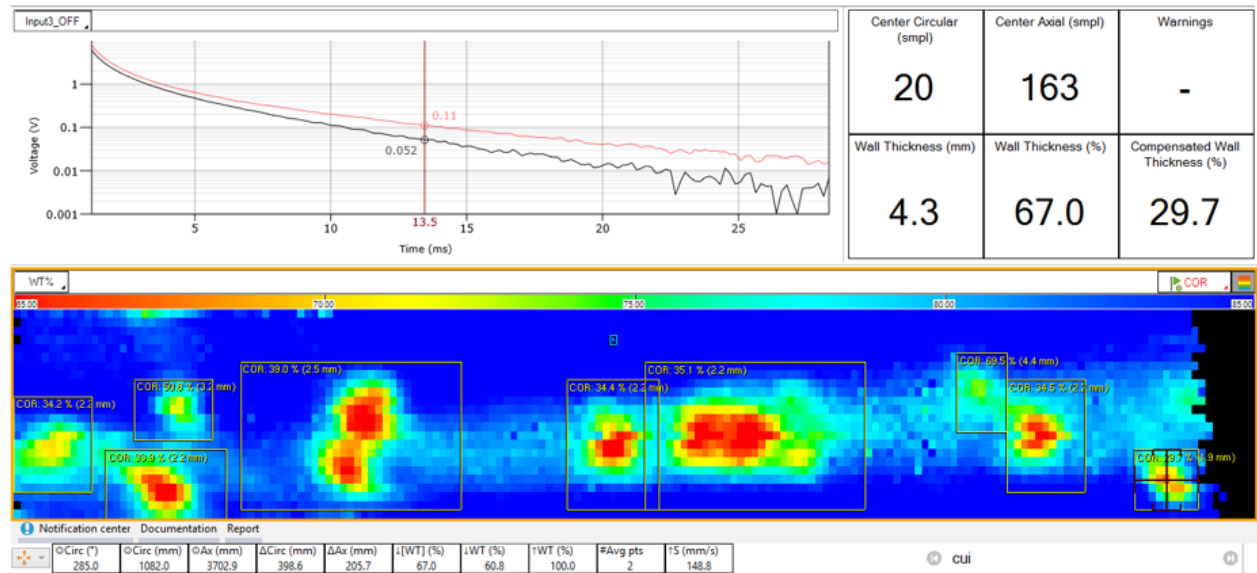


Figure C.7: C-scan Scab 14

C.2 Simulation for model in contact

Table C.1: Defect 1

Time T (s)	Source U1		Resistor R1		Coil	
	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
0	0	0	0	0	0	0
0.001	0.324726	-10	0.324726	3.24726	0.324726	6.75274
0.002	0.517152	-10	0.517152	5.17152	0.517152	4.82848
0.003	0.638233	-10	0.638233	6.38233	0.638233	3.61767
0.004	0.714712	-10	0.714712	7.14712	0.714712	2.85288
0.005	0.763091	-10	0.763091	7.63091	0.763091	2.36909
0.006	0.793737	-10	0.793737	7.93737	0.793738	2.06263
0.007	0.813179	-10	0.813179	8.13179	0.813179	1.86821
0.008	0.825534	-10	0.825534	8.25534	0.825534	1.74466
0.009	0.508674	0	0.508674	5.08674	0.508674	-5.08674
0.01	0.32127	0	0.32127	3.2127	0.321269	-3.2127
0.011	0.203403	0	0.203403	2.03403	0.203402	-2.03403
0.012	0.128989	0	0.128989	1.28989	0.128988	-1.28989
0.013	0.081942	0	0.081942	0.819416	0.081942	-0.819416
0.014	0.05216	0	0.05216	0.521603	0.05216	-0.521603
0.015	0.033284	0	0.033284	0.332839	0.033284	-0.332839
0.016	0.021302	0	0.021302	0.213021	0.021302	-0.213021
0.017	0.013684	0	0.013684	0.136842	0.013684	-0.136842
0.018	0.008831	0	0.008831	0.088314	0.008831	-0.0883135

Table C.2: Defect 2

Time T (s)	Source U1		Resistor R1		Coil	
	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
0	0	0	0	0	0	0
0.001	0.331941	-10	0.331941	3.31941	0.331941	6.68059
0.002	0.526281	-10	0.526281	5.26281	0.52628	4.73719
0.003	0.646831	-10	0.646831	6.46831	0.64683	3.53169
0.004	0.721908	-10	0.721908	7.21908	0.721908	2.78092
0.005	0.768742	-10	0.768742	7.68742	0.768743	2.31258
0.006	0.798003	-10	0.798003	7.98003	0.798003	2.01997
0.007	0.816314	-10	0.816314	8.16314	0.816314	1.83686
0.008	0.827795	-10	0.827795	8.27795	0.827795	1.72205
0.009	0.503069	0	0.503069	5.03069	0.503071	-5.03069
0.01	0.313275	0	0.313275	3.13275	0.313275	-3.13275
0.011	0.1956	0	0.1956	1.956	0.1956	-1.956
0.012	0.122347	0	0.122347	1.22347	0.122347	-1.22347
0.013	0.076678	0	0.076678	0.766778	0.076678	-0.766778
0.014	0.048166	0	0.048166	0.481656	0.048166	-0.481656
0.015	0.030339	0	0.030339	0.303392	0.030339	-0.303392
0.016	0.019176	0	0.019176	0.191755	0.019176	-0.191755
0.017	0.012171	0	0.012171	0.121713	0.012171	-0.121713
0.018	0.007767	0	0.007767	0.07767	0.007767	-0.0776703

Table C.3: Defect 3

Time (s)	T	Source U1		Resistor R1		Coil	
		Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
	0	0	0	0	0	0	0
	0.001	0.332704	-10	0.332704	3.32704	0.332703	6.67296
	0.002	0.527289	-10	0.527289	5.27289	0.527288	4.72711
	0.003	0.647802	-10	0.647802	6.47802	0.647801	3.52198
	0.004	0.722738	-10	0.722738	7.22738	0.722738	2.77262
	0.005	0.769408	-10	0.769408	7.69408	0.769408	2.30592
	0.006	0.798516	-10	0.798516	7.98516	0.798516	2.01484
	0.007	0.8167	-10	0.8167	8.167	0.8167	1.833
	0.008	0.82808	-10	0.82808	8.2808	0.82808	1.7192
	0.009	0.502514	0	0.502514	5.02514	0.502516	-5.02514
	0.01	0.312418	0	0.312418	3.12418	0.312419	-3.12418
	0.011	0.194738	0	0.194738	1.94738	0.194738	-1.94738
	0.012	0.121596	0	0.121596	1.21596	0.121597	-1.21596
	0.013	0.07607	0	0.07607	0.760696	0.07607	-0.760696
	0.014	0.047695	0	0.047695	0.476946	0.047695	-0.476946
	0.015	0.029985	0	0.029985	0.299849	0.029985	-0.299849
	0.016	0.018914	0	0.018914	0.189143	0.018914	-0.189143
	0.017	0.011981	0	0.011981	0.119812	0.011981	-0.119812
	0.018	0.00763	0	0.00763	0.076299	0.00763	-0.0762991

Table C.4: Defect 4

Time (s)	T	Source U1		Resistor R1		Coil	
		Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
	0	0	0	0	0	0	0
	0.001	0.325175	-10	0.325175	3.25175	0.325174	6.74825
	0.002	0.517737	-10	0.517737	5.17737	0.517737	4.82263
	0.003	0.6388	-10	0.6388	6.388	0.6388	3.612
	0.004	0.715198	-10	0.715198	7.15198	0.715198	2.84802
	0.005	0.763481	-10	0.763481	7.63481	0.763481	2.36519
	0.006	0.794038	-10	0.794038	7.94038	0.794038	2.05962
	0.007	0.813404	-10	0.813404	8.13404	0.813404	1.86596
	0.008	0.825699	-10	0.825699	8.25699	0.825699	1.74301
	0.009	0.508345	0	0.508345	5.08345	0.508345	-5.08345
	0.01	0.32077	0	0.32077	3.2077	0.32077	-3.2077
	0.011	0.202896	0	0.202896	2.02896	0.202896	-2.02896
	0.012	0.128546	0	0.128546	1.28546	0.128546	-1.28546
	0.013	0.081583	0	0.081583	0.815826	0.081583	-0.815826
	0.014	0.051882	0	0.051882	0.518823	0.051882	-0.518823
	0.015	0.033075	0	0.033075	0.330751	0.033075	-0.330751
	0.016	0.021149	0	0.021149	0.211487	0.021149	-0.211487
	0.017	0.013573	0	0.013573	0.135731	0.013573	-0.135731
	0.018	0.008752	0	0.008752	0.087519	0.008752	-0.0875187

Table C.5: Defect 5

Time (s)	T	Source U1		Resistor R1		Coil	
		Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
	0	0	0	0	0	0	0
	0.001	0.338816	-10	0.338816	3.38816	0.338816	6.61184
	0.002	0.534776	-10	0.534776	5.34776	0.534776	4.65224
	0.003	0.654733	-10	0.654733	6.54733	0.654732	3.45267
	0.004	0.728458	-10	0.728458	7.28458	0.728458	2.71542
	0.005	0.773841	-10	0.773841	7.73841	0.773841	2.26159
	0.006	0.801821	-10	0.801821	8.01821	0.801821	1.98179
	0.007	0.819099	-10	0.819099	8.19099	0.819099	1.80901
	0.008	0.82979	-10	0.82979	8.2979	0.82979	1.7021
	0.009	0.497605	0	0.497605	4.97605	0.497605	-4.97605
	0.01	0.30577	0	0.30577	3.0577	0.30577	-3.0577
	0.011	0.188388	0	0.188388	1.88388	0.188388	-1.88388
	0.012	0.116278	0	0.116278	1.16278	0.116278	-1.16278
	0.013	0.071913	0	0.071913	0.71913	0.071913	-0.71913
	0.014	0.044581	0	0.044581	0.44581	0.044581	-0.44581
	0.015	0.027718	0	0.027718	0.27718	0.027718	-0.27718
	0.016	0.017297	0	0.017297	0.172966	0.017297	-0.172966
	0.017	0.010844	0	0.010844	0.108435	0.010844	-0.108435
	0.018	0.006838	0	0.006838	0.068384	0.006838	-0.0683838

Table C.6: Defect 6

Time (s)	T	Source U1		Resistor R1		Coil	
		Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
	0	0	0	0	0	0	0
	0.001	0.340114	-10	0.340114	3.40114	0.340113	6.59887
	0.002	0.536888	-10	0.536888	5.36888	0.536888	4.63112
	0.003	0.656812	-10	0.656812	6.56812	0.656812	3.43188
	0.004	0.73021	-10	0.73021	7.3021	0.730209	2.6979
	0.005	0.77521	-10	0.77521	7.7521	0.775209	2.2479
	0.006	0.802844	-10	0.802844	8.02844	0.802843	1.97156
	0.007	0.819843	-10	0.819843	8.19843	0.819842	1.80157
	0.008	0.830321	-10	0.830321	8.30321	0.830321	1.69679
	0.009	0.496683	0	0.496683	4.96683	0.496684	-4.96683
	0.01	0.303921	0	0.303921	3.03921	0.303921	-3.03921
	0.011	0.186492	0	0.186492	1.86492	0.186493	-1.86492
	0.012	0.114655	0	0.114655	1.14655	0.114655	-1.14655
	0.013	0.070636	0	0.070636	0.706357	0.070636	-0.70636
	0.014	0.043623	0	0.043623	0.436232	0.043623	-0.43623
	0.015	0.027021	0	0.027021	0.270214	0.027021	-0.27021
	0.016	0.0168	0	0.0168	0.168003	0.0168	-0.168
	0.017	0.010495	0	0.010495	0.104947	0.010495	-0.10495
	0.018	0.006595	0	0.006595	0.065955	0.006595	-0.06595

C.3 Simulation for model with insulation and cladding at different lift-off

Table C.7: 10 mm lift-off with cladding

Time (s)	T	U1	U1	R1	R1	Cladding	Cladding	Coil	Coil
		Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
0		0	0	0	0	0	0	0	0
0.001		0.372254	-10	0.37225	3.72254	-4.12E-07	4.98E-08	0.372255	6.27746
0.002		0.571655	-10	0.57166	5.71655	-3.47E-07	3.28E-08	0.571655	4.28345
0.003		0.686618	-10	0.68662	6.86618	-3.29E-07	1.98E-08	0.686619	3.13382
0.004		0.753486	-10	0.75349	7.53486	-3.19E-07	1.18E-08	0.753486	2.46514
0.005		0.792477	-10	0.79248	7.92477	-3.13E-07	7.02E-09	0.792477	2.07523
0.006		0.81525	-10	0.81525	8.1525	-3.11E-07	4.19E-09	0.81525	1.8475
0.007		0.82857	-10	0.82857	8.2857	-3.08E-07	2.53E-09	0.82857	1.7143
0.008		0.836376	-10	0.83638	8.36376	-3.08E-07	1.54E-09	0.836376	1.63624
0.009		0.468706	0	0.46871	4.68706	-2.35E-07	-4.89E-08	0.468706	-4.68706
0.01		0.272007	0	0.27201	2.72007	-5.40E-07	-3.22E-08	0.272007	-2.72007
0.011		0.158641	0	0.15864	1.58641	-3.52E-07	-1.95E-08	0.158641	-1.58641
0.012		0.0927236	0	0.09272	0.927236	-2.14E-07	-1.15E-08	0.092724	-0.92724
0.013		0.054301	0	0.0543	0.54301	-1.28E-07	-6.84E-09	0.054301	-0.54301
0.014		0.0318726	0	0.03187	0.318726	1.47E-08	-4.06E-09	0.031873	-0.31873
0.015		0.0187628	0	0.01876	0.187628	9.34E-09	-2.42E-09	0.018763	-0.18763
0.016		0.0110881	0	0.01109	0.110881	5.97E-09	-1.46E-09	0.011088	-0.11088
0.017		0.0065868	0	0.00659	0.065868	3.96E-09	-8.84E-10	0.006587	-0.06587
0.018		0.0039405	0	0.00394	0.039405	2.70E-09	-5.45E-10	0.00394	-0.0394

Table C.8: 10 mm lift-off without cladding

Time T (s)	U1	U1	R1	R1	Cladding	Cladding	Coil	Coil
	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)	Current I (A)	Voltage U (V)
0	0	0	0	0	0	0	0	0
0.001	0.367599	-10	0.367599	3.67599	0	0	0.367599	6.32401
0.002	0.570479	-10	0.570479	5.70479	0	0	0.57048	4.29521
0.003	0.687159	-10	0.687159	6.87159	0	0	0.687159	3.12841
0.004	0.754564	-10	0.754564	7.54564	0	0	0.754565	2.45436
0.005	0.793561	-10	0.793561	7.93561	0	0	0.793561	2.06439
0.006	0.816149	-10	0.816149	8.16149	0	0	0.816149	1.83851
0.007	0.829252	-10	0.829252	8.29252	0	0	0.829252	1.70748
0.008	0.836867	-10	0.836867	8.36867	0	0	0.836867	1.63133
0.009	0.473704	0	0.473704	4.73704	0	0	0.473704	-4.73704
0.01	0.273415	0	0.273415	2.73415	0	0	0.273415	-2.73415
0.011	0.158257	0	0.158257	1.58257	0	0	0.158257	-1.58257
0.012	0.0917488	0	0.091749	0.917488	0	0	0.0917488	-0.917488
0.013	0.0532863	0	0.053286	0.532863	0	0	0.0532863	-0.532863
0.014	0.0310185	0	0.031019	0.310185	0	0	0.0310185	-0.310185
0.015	0.0181105	0	0.018111	0.181105	0	0	0.0181105	-0.181105
0.016	0.0106169	0	0.010617	0.106169	0	0	0.0106169	-0.106169
0.017	0.00625812	0	0.006258	0.0625812	0	0	0.0062581	-0.0625812
0.018	0.00371658	0	0.003717	0.0371659	0	0	0.0037166	-0.0371659