Exploring Pulsed Eddy Current (PEC) Responses in Ferromagnetic Cylindrical Structures

by

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ABSTRACT

Corrosion of carbon steel pipes under insulation has a direct negative impact on the structural integrity of the pipe. Insulation prevents visual inspection of external wall corrosion. Long-time decay, up to 0.1 s, in the transient response of Pulsed Eddy Current (PEC), was examined. The transient response of a coaxial solenoidal drive-receive coil pair, oriented parallel to the longitudinal axis, was analyzed over a range of distances from the pipe (liftoff) and wall thicknesses. The single exponential long-time decay constant was dependent on liftoff, simulating a seemingly thicker pipe wall as liftoff increased. At constant liftoff, an inverse-square power law relationship of the long-time decay slope to wall thickness was observed. Pipe with non-concentric wall thickness variation provided an example of partial-circumference corrosion, which the probe was sensitive to. The decay constant increased with liftoff, except at the thickest part of a non-concentric pipe. The most significant conclusion is derived from comparing long-time decay slope with averaged neighbouring wall thicknesses. Averaging of wall thicknesses ±45° (selected window size) from probe location brings all data sets closer to an expected inverse-square relationship, when compared to the purely beneath-probe thickness. This window increases with liftoff, describing the changes in decay constant as interaction with more and more material, unless at the thickest location of a non-concentric pipe.

Characterization of corroded rebar has important implications for evaluating the integrity of concrete structures. PEC measurements on rebar of varying diameter demonstrated that the long-time decay constant exhibited a power law relationship with rebar radius, in agreement with theory. Intercept of the linearly fitted long-time decay underwent an exponential decay as liftoff increased but showed a separable dependence on rebar diameter. In actual concrete structures, rebar is overlaid orthogonally to provide tensile strength in two mutually orthogonal directions. Altering probe angle with respect to the axis of a single rebar presented an intercept that decreased linearly as sine of the probe angle reached 1 (90°). Response to two orthogonal rebar demonstrated a superposition of independent rebar signals at later times in the transient decay. These observed trends indicate use of PEC to characterize rebar.
Co-Authorship

This thesis was developed by:

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Professor Thomas Krause, Department of Physics and Space Science, Royal Military College of Canada;

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This thesis combines the work of two published journal articles (Chapters 5 and 6) with two additional articles prepared for journal submission (Chapters 4 and 7). All experimental measurements, analysis, and manuscript writing was conducted by the first author unless otherwise stated. The following is a list of the co-authors and contributions for each manuscript.

**Chapter 4**: I. Eddy, J. Morelli, P. R. Underhill, and T.W. Krause, ‘Investigating Pulsed Eddy Current Response to Ferromagnetic Pipes’

- All 6 pipe samples were prepared by Groupe Mequaltech Inc. based in Montréal;
- D. Swanson analyzed the two non-concentric pipe sections in their Master’s thesis and conducted stress-relief baking of the samples. This was conducted at too high of a temperature and resulted in flaking of the outermost layer on these samples;
- T. W. Krause, P. R. Underhill and I. Eddy collaborated on discussions about transient analysis techniques;
- J. Morelli and T.W. Krause supervised and helped review and prepare results for submission.

**Chapters 5, 6, and 7**: I. Eddy, J. Morelli, P. R. Underhill, and T.W. Krause, ‘Investigating Pulsed Eddy Current Response to Rebar’

- All rebar samples were obtained from the Civil Engineering department in the Royal Military College of Canada (RMC)
- T. W. Krause, P. R. Underhill and I. Eddy collaborated on discussions about transient analysis techniques;
- J. Morelli and T.W. Krause supervised and helped review and prepare results for submission.

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LIST OF ABBREVIATIONS & SYMBOLS

\( \alpha \) Diffusion equation constant \((1/\sqrt{\mu \sigma})\)

\( \beta \) Constant in definition of characteristic time constant \((\tau_D)\)

\( \delta m_{fit} \) Error from linear fitting in Matlab

\( \delta m_{system,p,r} \) Error derived from repeat measurements under similar conditions. Subscripts ‘p’ and ‘r’ represent the error for pipe and rebar, respectively.

\( \delta m_{total} \) Combined error from above two values.

\( \eta_o \) Neumann function of zeroth order

\( \theta \) Angle between axis of probe and rebar

\( \lambda \) Solution to differential equation

\( \mu \) Magnetic permeability

\( \xi \) Defined by Wwdensky [1] as exponential term \((t/\tau)\).

\( \pi \) Mathematical constant Pi \((3.14159\ldots)\)

\( \rho \) Density of steel

\( \sigma \) Electric conductivity of a material

\( \omega \) Angular frequency, \( \omega = 2\pi f \) (Fourier transform use).

\( \tau_{D,P} \) Characteristic decay time (subscript ‘D’ denotes long-time decay, subscript ‘P’ denotes probe).

\( \phi \) Angular position in reference to the pipe \((0^\circ\) to \(360^\circ)\).

\( \Phi \) Angle of arc used in voltage drop calculation for pipe conductivity.

\( \Phi_{a,b} \) Sub angles in definition of \( \Phi \)

\( a \) Constant in definition of slope (Chapter 6)

\( A \) Constant in general form voltage response

\( A_d - Q_d \) Solution coefficients in deconvolution (Section 4.2.4)
\( A_{cs,p,r} \) \hspace{1em} \text{Cross-sectional area (subscripts ‘p’ and ‘r’ stand for pipe and rebar).}

\( A_f \) \hspace{1em} \text{Exponential decay constant from fitting}

\( A_\lambda \) \hspace{1em} \text{Constant solution to diffusion equation}

\( b \) \hspace{1em} \text{Intercept in definition of a line}

\( B \) \hspace{1em} \text{Magnetic field}

\( C \) \hspace{1em} \text{General constant used in many equations}

\( C_f \) \hspace{1em} \text{Exponential decay constant from fitting}

\( D_f \) \hspace{1em} \text{Exponential decay constant from fitting}

\( e \) \hspace{1em} \text{Euler’s number (2.7182…)}

\( E \) \hspace{1em} \text{Alternate way of stating scientific notation.}

ECT \hspace{1em} \text{Eddy Current Testing}

Fe \hspace{1em} \text{Iron}

\( h \) \hspace{1em} \text{Height from central axis in pipe conductivity measurement.}

\( I_{VD,p,r} \) \hspace{1em} \text{Current in voltage drop (subscripts ‘p’ and ‘r’ stand for pipe and rebar).}

\( IR_{A-F} \) \hspace{1em} \text{Internal radius pipes A-F}

\( J \) \hspace{1em} \text{Current density}

\( J_{0,1} \) \hspace{1em} \text{Bessel functions of zeroth and first order}

\( \ell \) \hspace{1em} \text{Length variable}

\( \ell_c \) \hspace{1em} \text{Characteristic length}

\( \ell_p \) \hspace{1em} \text{Length of the pipes}

\( \ell_{coil} \) \hspace{1em} \text{Length of probe (~ 100 mm)}

\( \ell_{VD,p,r} \) \hspace{1em} \text{Length from voltage drop calculation (subscripts ‘p’ and ‘r’ stand for pipe and rebar).}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>ln</td>
<td>Natural logarithm</td>
</tr>
<tr>
<td>L</td>
<td>Self-inductances of the coil</td>
</tr>
<tr>
<td>LO</td>
<td>Distance between outer surfaces of metal subject and probe.</td>
</tr>
<tr>
<td>m</td>
<td>Slope of a linear relationship</td>
</tr>
<tr>
<td>n</td>
<td>Iterations of a summation</td>
</tr>
<tr>
<td>N</td>
<td>Number of turns of a coil</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-destructive testing</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PEC</td>
<td>Pulsed-eddy current</td>
</tr>
<tr>
<td>r</td>
<td>Radius variable (used both as general term, then specifically as rebar radius)</td>
</tr>
<tr>
<td>r&lt;sub&gt;chord&lt;/sub&gt;</td>
<td>Center radius of ring used in pipe conductivity calculation</td>
</tr>
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<td>r&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Drive coil radius</td>
</tr>
<tr>
<td>r&lt;sub&gt;f&lt;/sub&gt;</td>
<td>Ferrite core radius</td>
</tr>
<tr>
<td>r&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Receive coil radius</td>
</tr>
<tr>
<td>R&lt;sub&gt;1,2&lt;/sub&gt;</td>
<td>Resistances within drive and receive coils</td>
</tr>
<tr>
<td>R&lt;sub&gt;VD&lt;/sub&gt;</td>
<td>Resistance across the voltage drop</td>
</tr>
<tr>
<td>R&lt;sub&gt;λ(r)&lt;/sub&gt;</td>
<td>Radius function in diffusion equation solution</td>
</tr>
<tr>
<td>RMC</td>
<td>Royal Military College of Canada</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root-mean-square error</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
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<tr>
<td>T&lt;sub&gt;λ(t)&lt;/sub&gt;</td>
<td>Time function in diffusion equation solution</td>
</tr>
<tr>
<td>TMT</td>
<td>Thermo-mechanically treated</td>
</tr>
<tr>
<td>v&lt;sub&gt;sound,A-F&lt;/sub&gt;</td>
<td>Velocity of speed of sound in the pipe material</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
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</tr>
<tr>
<td>( V_{V_D,p,r} )</td>
<td>Voltage measured in a voltage drop resistance measurement. (subscripts ‘p’ and ‘r’ stand for pipe and rebar).</td>
</tr>
<tr>
<td>( WT )</td>
<td>Wall thickness of a pipe</td>
</tr>
<tr>
<td>( z )</td>
<td>Height variable in cylindrical coordinates</td>
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</tbody>
</table>
Chapter 1 – General Introduction

Corrosion of metallic materials in industrial settings is a prevailing issue that is often addressed with non-destructive testing. Ferromagnetic pipes, in particular, are used to transport fluids of a wide range of temperatures and chemical composition. Corrosion may occur both internally and externally over the lifespan of an industrial system requiring replacement to avoid system failure. Scheduling of structural integrity inspections is directly related to industry standards of a given system, while keeping in mind the cost of administering the inspection. Non-destructive evaluation (NDE) methods provide a unique avenue for inspecting without directly damaging materials. The specific method chosen is dependent on how effective the method is in the given application, the expense of procuring the needed inspection tools or inspector, and how often, fast, and confidently inspections can be completed. In this thesis the applications considered are insulation coated pipe-wall thinning and rebar corrosion. Ultrasonic testing (UT) is the leading method for corrosion monitoring and quantification, though direct access to the surface is necessary [2]. Industrial conditions such as insulation covered pipes and concrete embedded rebar introduce barriers between testing probes and the material, and removal of the insulation or concrete is preferably avoided, as replacing the material has an inherently prohibitive cost. NDE may provide a cost-effective approach towards monitoring these structures without the added cost of barrier removal (insulation or concrete, specifically). Pulsed eddy current (PEC) does not require the barrier medium to be removed, since the PEC response depends only on the proximity of conducting and ferromagnetic material, not on electrical insulators such as concrete and insulation. Using a coaxial solenoidal probe aligned along the
longitudinal axis of the pipe/rebar, the ferromagnetic material is detectable at liftoffs up to 70 mm (3 inches) [3][4].

The goal of this work is to show the feasibility of a PEC probe as a fast-scanning tool in detecting corrosion in insulated pipes and rebar. This was achieved by analyzing the transient response of PEC and modeling a linearly fit long-time single exponential decay region to parameters of the experiment, mainly material size and liftoff. Results showed an inverse-square power law dependence of the long-time decay on average wall thicknesses for pipes and on rebar radius. The intercept of the long-time decay reduced exponentially with increased liftoff. The slope of the long-time decay changed somewhat when introducing liftoff for pipes according to an increased sensing range of the field interacting with the pipe circumference. For rebar, however, the slope remained constant with increased liftoff. This thesis means to demonstrate the effectiveness of this PEC inspection as a fast-scanning tool for detecting corrosion in insulated pipes and rebar.

This thesis contains several chapters that examine all pertinent aspects of PEC evaluation. Chapter 2 examines corrosion classifications, relevant PEC theory, and supplemental NDT techniques, specifically highlighting benefits and limitations of each examination method. The goal of this chapter is to explicitly state why PEC is the ideal analysis tool for corrosion inspection for insulation coated pipes and rebar embedded in concrete. Chapter 3 describes the experimental setup, materials used, and characterizes all said materials. This chapter provides an in-depth description of the experimental method not explicitly explored in the manuscripts of Chapters 4 through 7. Chapter 4 is the first of four manuscripts and the only one focusing on the
PEC response from pipes. This manuscript is the main focus of the thesis. Chapter 5, Chapter 6, and Chapter 7 are manuscripts examining PEC to characterize rebar. Chapter 5 examines general response (size variance and liftoff response), Chapter 6 looks at probe limitations at large liftoff, and Chapter 7 examines probe orientation and rebar overlay. Chapter 9 summarizes the findings of all four manuscripts and discusses the similarities and differences of PEC use for pipe and rebar inspection.

1.1 INTRODUCTION – PIPES

Pipes are used in a wide range of industrial settings, from waste transportation to nuclear reactor water transport. The common thread between all industrial uses is that the pipes transport fluids of varying temperature and chemical composition. The electrochemical process of corrosion is dependent on these properties, among other environmental factors. Internal corrosion is generally found in three forms: Full-circumference corrosion or circumferential wall thinning, partial-circumference corrosion or gradual wall thinning circumferentially over 180°, and localized corrosion consisting of pits, cracks, and crevices. Partial-circumference corrosion is defined here by the phenomenon where corrosion occurs markedly more on one side of diametrically opposed pipe wall locations. Condensation can also form on the outer surface of pipes due to the temperature difference between the environment and fluid. Water on the outer surface can initiate corrosion that results in rust (Fe$_3$O$_4$/Fe$_2$O$_3$), and effectively makes the bulk pipe wall material become thinner. Iron oxides are brittle and effectively non-magnetic (with exception of magnetite) and non-conducting [5], and therefore, are non-responsive to PEC testing. This provides the basis for the use of PEC for the evaluation of pipe corrosion explored in this thesis.
Outer-surface corrosion is often mitigated by covering the pipe with insulation, which has the added benefit of lessening the heat lost by the fluid within the pipe. Even when insulation is present, corrosion can still occur either on the inner wall due to the interaction with the fluid, or on the outer surface if water has managed to migrate through the insulation. In both instances, the corrosion (unless severe) is imperceptible to visual inspection due to insulation covering the pipe, which may allow the corrosion to progress until failure occurs.

Many NDT techniques, such as ultrasonics, thermography, or conventional eddy current require the removal of the pipe-covering insulation. Radiography does not require removal of insulation but has other challenges including access to the material and safety considerations. PEC has been proposed as a method of detecting full-circumference corrosion in pipes without requiring insulation removal [6]. Solenoidal PEC probes aligned in a parallel fashion to the longitudinal axis of rebar have been shown to detect the base material at large liftoffs [3], so this research was conducted assuming the same would be true for pipe inspection. The general experimental diagram can be seen in Figure 1.1.
In Chapter 4, insulation will be simulated as experimental liftoff, since the long-time decay is associated with ferromagnetic steel and non-conducting materials (insulation) can be modeled as an air gap between probe and pipe, as both insulation and air gaps equally act as inert barriers between probe and pipe. This paper explores the ways that PEC can detect and characterize full-circumference corrosion (modeled as thinning wall thickness) and the subsequent limitations of this method. This paper specifically investigates the difference in PEC response and characterization between general and partial-circumference corrosion.
1.2 INTRODUCTION – REBAR GENERAL

Rebar, or reinforcing bar, is placed within concrete to provide tensile support to structures. On its own, concrete provides a high degree of compressive support but lacks tensile strength. Typically made from ferromagnetic steels, rebar can be forged into specific lengths and sizes for given applications. Rebar consists of a solid cylindrically shaped inner bulk material with protruding ribs on the surface. These ribs help to mechanically fix the rebar within the concrete and vary in size with relation to the inner cylinder depending on application (larger ribs are required for greater structural integrity [7]).

In the presence of corrosive elements and water ingress within concrete, rebar may undergo corrosion and start to convert to rust. The growth of rust on the ferromagnetic core results in the rod occupying a greater volume [7]. This process may lead to deterioration of the concrete and a loss of structural integrity.

Recent efforts have been taken to quantify the severity of corrosion present through non-destructive testing (NDT) [8]. While rebar can be detected by metal detectors, radiography and microwave technology, ability to determine ferromagnetic wall loss is limited.
Pulsed Eddy Current (PEC) response has demonstrated a sensitivity to ferromagnetic rod radius [9]. PEC uses a square voltage pulse to excite a drive-receive coil pair, in contrast to the continuous sinusoidal excitation in conventional eddy current testing, and thereby, can magnetize ferromagnetic materials resulting in a greater range of detection [10]. Similar to Figure 1.1, Figure 1.2 substitutes the pipe section for a rebar rod. Chapters 5 and 6 look at PEC response to changing rebar radius and to liftoff between probe and rebar sample.
1.3 INTRODUCTION – REBAR JUNCTIONS

Rebar is an important component of modern construction that provides internal support to concrete structures. These ferromagnetic rods are designed to ‘grip’ the concrete through the ribbed architecture on their surface [11], and when fully embedded, provide significant tensile strength to the otherwise substantial compressive strength of concrete. To further increase the support provided by these rods, they are often placed perpendicular to one another forming a cross-hatched lattice structure as shown in Figure 1.3.

![Figure 1.3: Rebar embedded in an interior concrete wall. This rebar is purposefully exposed as an educational display about rebar. Note the horizontal rebar has a smaller diameter than the vertical rods.](image)

PEC has been shown to be a viable tool for detecting corrosion of concrete embedded rebar [3]. Chapter 5 examines how rebar radius and liftoff affect PEC response for a solenoidal driver-pickup coil configuration oriented parallel with the rebar axis. Chapter 6 examines the effect of liftoff (depth of rebar embedded in concrete) on limits of detectability as a function of rebar diameter, with detectability limits for 19 mm diameter rebar out to 84 mm liftoff [4]. PEC signals, obtained using a normally oriented coil with AMR (anisotropic magneto-resistive) sensor and analyzed using principle component analysis, have also been used to effectively detect rebar
up to 55 mm liftoff [12]. In this particular study [12], the authors have also induced corrosion in 20 mm diameter rebar samples to take data with actual corroded rebar.

In all the above cases, data was collected on isolated rods. Under field inspection conditions, the lattice-like structure of rebar within concrete likely does not provide an isolated rod (see Figure 7.5). Therefore, examining how adjacent rebar affects the transient response becomes necessary. This novel work examines the dependence of the PEC signal response on the angle between the solenoid axis of the probe and the longitudinal axis of the rebar. It is observed that the signal decreases with angle in a manner similar to that of liftoff, but a remnant signal remains for the orthogonal orientation. For the case of the junction of two perpendicular rebars, the resulting signal is the direct superposition of the individual signals obtained from the parallel and perpendicular oriented rebar in the long-time transient decay. This novel observation permits the potential evaluation of rebar condition even if nearby ferromagnetic structures are present.
Chapter 2 – Literature Review

This thesis proposes the application of PEC for the detection of corrosion by employing a quantitative experimental approach. Before the experiment is laid out in full, it is important to examine the corrosion classifications explored in the thesis along with the NDT techniques that are used throughout. The goal of this chapter is to define the expected corrosion that may occur on both pipes and rebar and to discuss how different NDT techniques may possess benefits and limitations for its detection. More specifically, this chapter will highlight the need for PEC development for detection of corrosion under insulation.

2.1 Corrosion

Learning how corrosion occurs, propagates, and is mitigated provides the necessary foundation to effectively inspect pipes and rebar for corrosion damage. Under field inspection conditions, instances of corrosion occur due to the environment surrounding the metallic structure. While production of corrosion is achievable in a laboratory, the time and precise environmental control it takes to reach the expected types and severity of corrosion adds significant complexity to an experiment. To circumvent this difficulty, the expected corrosion damage of pipes and rebar is represented by machined defects or changing wall thicknesses. While these representations are explicitly described within the respective manuscripts of this thesis, they are also mentioned after defining the types of corrosion below.

2.1.1 Types of Corrosion

Corrosion is an electrochemical process where metal atoms within a metal surface interact/react with the surrounding environment. This process results in a metallic oxide forming on the surface, which is converted from the base material. Any corrosion reaction can be broken
down into anodic and cathodic halves. Cathodes are identified as the material gaining electrons, whereas the anode is losing electrons and visually experiencing corrosion. The corrosion rate and corroding metal is dependent on environmental conditions such as material selection, temperature, geometry, solute concentration, and external mitigating factors. The resulting corrosion can be grouped into three classifications, which change the localization of the damage: a) full-circumference corrosion, b) localized corrosion, and c) partial-circumference corrosion, all three of which are represented schematically on the outer surface of a pipe in Figure 2.1 below. Note that partial-circumference corrosion is characterized as occurring over approximately one half of the pipe circumference and not the other. It should also be noted that both full-circumference and partial-circumference corrosions are a form of general corrosion, just with differing circumferential footprints due to the corrosive environment. The creation of each type is described within its respective sub-section.

![Figure 2.1: Corrosion classifications used throughout this thesis. As shown in the legend, grey material represents the unaffected material, with the brown/orange colour representing the corroded location. The three classifications are as follows, a) full-circumference corrosion, b) localized corrosion, and c) partial-circumference corrosion.](image-url)
2.1.2 Corrosion Types: Full-Circumference Corrosion

Full-circumference corrosion is the most common form of corrosion with metallic surfaces [13]. This process occurs naturally when iron alloys interact with air or water and results in what is commonly referred to as rust (Fe$_2$O$_3$/Fe$_3$O$_4$) [3][4]. Rust is known as a naturally occurring oxide, where it is the natural oxidation state of the element. Oxide layers may be passive, in the case where a thin film is formed on the outer layer, which is stable and limits oxygen/water ingress through to the base material. Other oxides are brittle and can flake off, exposing the previously un-corroded material below. While alloy composition largely determines the passivity of an oxide film, environmental factors can also contribute to corrosion progression/oxide failure [14]. Passive oxides that are strongly resistant to water ingress may provide poor barriers against aggressive chlorine anions (among other anions), so the composition of the affecting solution is important to determine in order to choose the most corrosion resistant alloys.

Assuming that full-circumference corrosion can occur in the field due to aggressive environmental factors causing isotropic wall loss [13], this corrosion progression in the target materials must be simulated in the experimental process. Here, this is achieved with several pipes by taking a single long pipe section and cutting it into four sections of equal length, and then using a lathe to progressively thin the wall of each subsequent section. This thinning of the base material is meant to represent the aggressive progression of full-circumference corrosion, effectively converting the base metal into a non-conducting oxide layer (this process was performed by Groupe Mequaltech Inc.). These four sections represent outer-wall full-circumference corrosion progressing in the direction of structural failure.
2.1.3 Corrosion Types: Localized Corrosion

Localized corrosion is a pervasive and dangerous type of corrosion that can result in component failure without notable visual clues. Localized corrosion is an umbrella term that envelops many phenomena, but this section will just discuss the last type of corrosion that is simulated through this thesis’ experiments, specifically pitting corrosion.

Pitting corrosion is fairly well described as a corrosion process that once initiated may be difficult to subside [2]. Pitting corrosion occurs when aggressive anions (i.e., Cl⁻) interact with the metallic surface creating a small and pinpoint potential difference (catalyst for corrosion) [17]. This potential difference starts the corrosion process and results in ‘pits’ forming on surface of the metal. Within the pit the local chemistry of the solution progresses this corrosion onward. Half-cell reactions (cathodic and anodic) are the basis of corrosion and a small change in solution chemistry due to a pit or crevice (sometimes known as an occluded tip [5][6]) creates a potential drop between the pit and the surrounding unaffected material. If left unattended, pits can corrode away the base material quickly, thus becoming a worrisome type of corrosion. Pitting can be considered a localized volumetric loss of base metal material that progresses at a rapid rate. Pitting often occurs as a large collection of pits on a metallic surface (many anion interaction locations), though this thesis considers just the case of a few pits having aggressively corroded over half of the pipe wall thickness. Specifically, one of the pipe sections had a localized grouping of four machined ball-milled defects to a depth over half of the immediate pipe wall thickness. These were meant to represent pits that had progressed significantly. Localized corrosion was not considered in the rebar analysis, even though pitting can also occur in rebar [18].
2.1.4 Corrosion Types: Semi – Localized Corrosion

The remaining corrosion classification is the thesis-defined term of partial-circumference corrosion. Partial-circumference corrosion is effectively the process of full-circumference corrosion in a more localized region. Specifically, due to water ingress (condensation) on the pipe surface or other corrosive reactions occurring on one side of a pipe more than on the diametrically opposed side. This is likely due to gravity and might be expected on the lower pipe wall. Depending on pipe geometry or fluid transported, however, inner wall corrosion may occur and not necessarily on the lowest pipe wall. These pipes have a non-concentric wall thickness, which is achieved in-lab by machining a concentric pipe to have a gradient wall thickness from thick to thin over 180°. This is shown on the right (label c) of Figure 2.1.

2.2 NDE Techniques

Non-destructive evaluation (NDE) is an umbrella term than encapsulates all inspection methods that are non-destructive in nature. Pulsed eddy current (PEC), conventional eddy current testing (ECT), thermography, radiography, and ultrasonic testing (UT) are all NDE methods that characterize materials without directly altering the subject. Regarding defect inspection, PEC, radiography, and thermography are generally considered the macro techniques with ECT and UT being more effective for localized defect detection. PEC is the focus of this thesis, with some use of UT and even less of ECT. The following sub-sections explore the five NDE methods mentioned above.

2.2.1 Pulsed Eddy Current (PEC)

Pulsed eddy-current (PEC) is dependent on a magnetic field generated by a pulsed square voltage applied across a drive coil. The magnetic fields interact with the metallic conducting
structures according to Faraday’s law [19], inducing eddy currents that in turn create a secondary magnetic field, which is then detected and analyzed. This can be visualized in Figure 2.2 where the red lines represent the initial magnetic field, the green line is the resulting induced magnetic field, with \( I_d \) and \( I_e \) representing the direction of the drive and eddy currents, respectively.

![Figure 2.2: Schematic of initial (red) and resulting (green) magnetic field lines from a PEC probe. Drive coil is the outer black circle on the probe with the receive coil being the smaller black circle lodged within. Eddy-currents shown travel into the depth of the material.](image)

Understanding how these magnetic fields interact with the specific geometry of the structure to be inspected provides the groundwork for further analysis.

Solutions to PEC responses in a pickup coil often start from a parabolic differential equation, the diffusion equation (Equation (2.1)) for the magnetic field, and apply it to the target geometry [7][19][20].
Ohanian [20] examined the shortcomings of common textbook solutions. Ohanian [20] pointed out that these initial attempts did not consider the transient phenomena occurring within the conductor. Specifically, ignoring the dynamics of the magnetic and electric fields. The relaxation of free charges within a conductor volume will reach equilibrium very quickly, but the transient currents relax at a much slower rate [20]. Maxwell’s equations provide the groundwork for determining the electromagnetic field solutions [19]:

\[
\nabla^2 \mathbf{B} = \mu \sigma \frac{\partial \mathbf{B}}{\partial t},
\]

(2.1)

where \( \mathbf{B} \) is the magnetic field, \( \mu \) is the magnetic permeability, \( \sigma \) is the conductivity, \( \partial \mathbf{B}/\partial t \) is the time derivative of the magnetic field, \( \nabla \) is the gradient operator, and \( \nabla \cdot \mathbf{E} = \rho/\varepsilon \), \( \nabla \cdot \mathbf{B} = 0 \), \( \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \), \( \frac{1}{\mu} \nabla \times \mathbf{B} = \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} \)

(2.2)

(2.3)

(2.4)

where \( \mathbf{E} \) is the electric field, \( \rho \) is the resistivity, \( \varepsilon \) is the permittivity, \( \mathbf{B} \) is the magnetic field, \( t \) is the time, \( \mu \) is the magnetic permeability, and \( \mathbf{J} \) is the current density. These equations use \( \varepsilon \) and \( \mu \), as opposed to \( \varepsilon_0 \) and \( \mu_0 \), because these equations will be applied within matter, assuming the materials are linear (which is approximately correct due to weak fields generated by PEC). Often, Equations (2.2), (2.3), and (2.4), are referred to as Gauss’ laws (for electricity and magnetism), Faraday’s law, and Ampere’s law with Maxwell’s correction, respectively [10][11]. In order to simplify Equation (2.4) into Equation (2.1) defining the current density, \( \mathbf{J} \), as a function of the electric fields is necessary. To obtain an expression for \( \mathbf{J} \), consider Ohm’s law and subsequent definitions [19]:

\[
\nabla \cdot \mathbf{E} = \rho/\varepsilon, \quad \nabla \cdot \mathbf{B} = 0,
\]

(2.2)

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]

(2.3)

\[
\frac{1}{\mu} \nabla \times \mathbf{B} = \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J}
\]

(2.4)
\[ J = \sigma E, \]  
\[ R = \frac{l}{\sigma A_{cs}}, \]  

(2.5)  
(2.6)

where \( \sigma \) is the conductivity, \( I \) is the current, \( R \) is the resistance, \( l \) is the unit length, and \( A_{cs} \) is the cross-sectional area of whatever the current is passing through. Also noting that the current density, \( j \), is defined as the current, \( I \), per unit area and a uniform field, \( E \), is defined by the voltage drop, \( \Delta V \), over a length[20]:

\[ J = \frac{I}{A_{cs}}, \quad E = \frac{\Delta V}{l}, \]  
\[ \frac{l}{A_{cs}} = \sigma \left( \frac{\Delta V}{l} \right) \rightarrow \Delta V = l \left( \frac{l}{\sigma A_{cs}} \right) = IR. \]  

(2.7)  
(2.8)

Taking the curl of Equation (2.4) and substituting into Equation (2.2), (2.3), and (2.5):

\[ \frac{\partial^2 B}{\partial t^2} + \frac{\sigma}{\varepsilon} \frac{\partial B}{\partial t} = \frac{1}{\mu \varepsilon} \nabla^2 B, \]  

(2.9)

and noting that in a good conductor, \( \sigma \) is very large compared with \( \varepsilon \), and at frequencies less than \( 10^9 \) Hz the first term can be ignored, leading to the parabolic differential equation shown as Equation (2.1).

Knowing that, in general, solutions to differential equations of this form are exponential decays \( (B \sim B_0 e^{-t/\tau}) \) allows for an estimate of the transient voltage response following from Faraday’s law [10][11],

\[ V(t) = -N \frac{dB(r,t)}{dt}. \]  

(2.10)
where $N$ is the number of turns of the receive coil. Here, the voltage response will also be a series of exponential decays as there are a series of exponential decaying magnetic fields as detected by the pick-up coil. The generalized format for the voltage solution is [20][22][23]:

$$
V(t) \cong \sum_{i=1}^{\infty} A_i e^{-(\frac{t}{\tau_i})},
$$

where $A_i$ is a lumped coefficient and $\tau_i$ is the $i^{\text{th}}$ exponential decay constant. In general, there are two sets of exponential decays considered throughout this research (there are many others in the early times that are not considered) [24]: that of the drive coil interaction with the receive coil and the sample (imagine the initial pulse being detected by the receive coil) and the material dependent interaction with just the receive coil. In this thesis, the latter (material dependent) exponential decay is more important to analyze as the exponential decay constant is dependent on the thickness of the given material, along with electrical conductivity and magnetic permeability [20],

$$
\tau_2 = \tau_D \sim \mu \sigma (\ell_C)^2,
$$

where $\mu$ and $\sigma$ are the magnetic permeability and conductivity, respectively, of the target material, and $\ell_C$ is the geometric dependent characteristic length. Considering only the long-term exponential decay, substituting (2.12) into (2.11), and taking the natural logarithm gives the relationship:

$$
\ln(V) = -\left(\frac{1}{C\mu\sigma\ell_C^2}\right) t + \ln (A),
$$

where $C$ is a constant. Using this relationship and noting that graphically one can fit a linear relationship to $\ln(V)$ and $t$, gives a slope value inversely dependent on thickness squared. In this
regard, this method can be used to measure the reduced bulk material due to the presence of corrosion. In the two proposed materials (pipes and rebar), this characteristic length is defined by two separate terms. For rebar it is defined as the radius of the cylinder, \( r \), whereas for pipes it is assumed to be defined as the wall thickness, \( WT \). The pipe definition is made because PEC inspection of flat plates (or the limiting pipe example of an infinitely large radius), the characteristic length is indeed the wall thickness \([24][25]\). This research work assumed only the simplest dependence with an \( \ell_c \) considering only the wall thickness for pipes, ignoring contributions from pipe radius.

2.2.2 PEC: MAGNETIC FIELD DIFFUSION THROUGH A CYLINDER (REBAR)

Pulsing current through a coil creates a finite magnetic field that interacts with a ferromagnetic rod. The diffusion of this magnetic field into the cylinder can be described through the following derivation. Wwdensky [1] follows a similar derivation as seen below, but neglects to consider the back-emf of the magnetic field on the drive coil. Considering the coordinate system shown below in Figure 2.3:

![Coordinate system of the cylinder/rebar in question.](image)
Where \( b \) is the radius, \( B_z \) is the magnetic field in only the z-direction, and the z-direction is oriented along the longitudinal axis of the rod. The general solution to Equation (2.1), the magnetic field diffusion equation, in cylindrical coordinates, with only considerations from the z-direction (i.e., \( B_z = B \)) is:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial B}{\partial r} \right) = \mu \sigma \frac{\partial B}{\partial t} \tag{2.14}
\]

This equation is subject to the boundary conditions of \( J(b, t) = J_1 \), and \( J(r, 0) = 0 \). Performing a separation of variables into terms \( R(r) \) and \( T(t) \), where the solution to Equation (2.14) is in the general format is obtained:

\[
B(r, t) = R(r)T(t) \tag{2.15}
\]

Substituting Equation (2.15) into (2.14) results in the following two equations:

\[
\frac{d}{dr} \left( r \frac{dR}{dr} \right) + \lambda r R = 0, \tag{2.16}
\]

\[
\frac{dT}{dt} = -a^2 \lambda T, \tag{2.17}
\]

where \( a^2 = \frac{1}{\mu \sigma} \) and \( \lambda \) is the differential equation solution. There is also a solution following the Dirichlet boundary condition, or \( B_1 = \text{constant} \), where:

\[
B(r, t) = B_1 + \sum_{\lambda} A_\lambda R_\lambda(r)T_\lambda(t). \tag{2.18}
\]
Equation (2.18) also requires the two boundary conditions to be satisfied: \( R_4 (r) \to 0 \) as \( r \to b \) & \( B(b,t) = B_1 \). Setting \( \lambda = k^2, x = kr \), the radial function is reduced to a Bessel differential equation of order zero:

\[
\frac{d^2 Y}{dx^2} + \frac{1}{x} \frac{d Y}{dx} + Y = 0
\]  
(2.19)

where \( Y(x) = R(r) \). As stated, this solution is of the form of \( J_0(x) \), the zeroth order Bessel function, since the Neumann function, \( \eta_o(x) \), is not finite at \( r=0 \) and the eigenvalues follow the Dirichlet condition. It is important to note:

\[
J_0(kb) = 0
\]  
(2.20)

yields the eigenvalues:

\[
\lambda_n = \frac{\alpha_{0n}^2}{b^2}
\]  
(2.21)

where \( n=1,2,3 \) and \( \alpha_{0n} \) are the zeros of \( J_0 \). The time domain function as expressed in Equation (2.17) has the general solution:

\[
T(t) = C_1 e^{-a^2 \lambda_n t}.
\]  
(2.22)

Substituting Equations (2.21) and (2.22) into Equation (2.18) gives:

\[
B(r,t) = B_1 + \sum_{n=1}^{\infty} A_n J_0 \left( \alpha_{0n} \frac{r}{b} \right) e^{-\frac{a^2 \alpha_{0n}^2 a^2}{b^2} t}.
\]  
(2.23)
This satisfies the boundary condition $B(r,0)=0$, which requires:

$$B_1 = - \sum_{n=1}^{\infty} A_n J_0 \left( \alpha_{on} \frac{r}{b} \right). \quad (2.24)$$

This is a Fourier Bessel series of order zero for the function $f(r) = -u$. Using a formula from Marion and Heald Chapter 13 [26] one can determine the solution of $A_n$.

$$A_n = \frac{-2B_1 \int_0^b J_0 \left( \alpha_{on} \frac{r}{b} \right) r \, dr}{b^2 [J_1(\alpha_{on})]^2} \to -\frac{2B_1}{\alpha_{on} J_1(\alpha_{on})} \quad (2.25)$$

Substituting Equation (2.25) into (2.23) and factoring the $B_1$ term, gives the diffusion of the magnetic field:

$$B(r, t) = B_1 (1 - 2 \sum_{n=1}^{\infty} J_0 \left( \alpha_{on} \frac{r}{b} \right) \frac{\alpha_{on} r}{b} e^{-\frac{\alpha_{on}^2 a^2}{b^2 t}}) \quad (2.26)$$

As stated, this response is very similar to the solution given in Wwdensky’s paper [1]. Upon changing the names of variables, $r = \rho$, $b = r$, and $B_1 = B_o$, the second term is found to be the same. The main difference between the two solutions, is that Wwdensky’s derived the response assuming a step function in the magnetic field saturation, where Equation (2.26) exponentially decays up to a constant, $B_1$. Wwdensky also assumes a constant field. These assumptions seem
to be effective in modelling the long-time decay, however, as the characteristic time constant, \( \tau_D \), would remain unaffected by these early-time assumptions.

### 2.2.3 PEC: Superposition From Two Perpendicular Rods (Rebar Junctions)

Rebar are often not isolated within structures, and most commonly placed in a perpendicular grid-like pattern. These intersections, where perpendicular rebar overlap, are referred to as junctions throughout this thesis. PEC transient response is described, in prior sections, as a summation of multiple exponential decays with the proposed response containing the individual two long-time decays summing together in superposition.

At later times, only the dependence on the material properties remains as expressed by Equation (2.12). In the case of rebar, the characteristic length in Equation (2.12) corresponds to the radius, \( r_{1,2} \), where the subscripts denote the two respective rebar samples at a given junction (consider Figure 1.3 and the four junctions present). In this instance, the numbering subscripts are a placeholder for actual naming conventions to be considered later. Considering strictly the long-time decay region, the transient voltage response is represented by the following equation:

\[
V_{1,2} = A_{D1,2} e^{-\frac{t}{\tau_{D1,2}}} 
\]

\[
\tau_{D1} \sim \mu_1 \sigma_1 r_1^2, \quad \tau_{D2} \sim \mu_2 \sigma_2 r_2^2, \quad (2.27)
\]

where \( \tau_D \) is the longest time decay constant of the interaction with the respective rebar sample \([1]\).

The long-time transient field decay outside the rod will also be a function of \( \mu, \sigma, r, \) and of a constant \( C \) (shown in Equation (2.29) below), which can be considered a generalized constant that is dependent on the transient changes in the external field that is coupled to an external
pickup coil. Combining Equations (2.34) and (2.35) and taking the natural log gives a linearized expression for the long-time decay (identical to Equation (2.13) of the respective voltage response outside the rebar as:

$$\ln(V_{1,2}) = -\left(\frac{1}{C\mu_1,2\sigma_1,2n_{1,2}^2}\right)t + \ln(A_{D1,2}),$$

(2.29)

where the term in brackets, $m$, is the slope of the line given as,

$$m_{1,2} = \frac{1}{\tau_{D1,2}} = \frac{1}{C\mu_1,2\sigma_1,2n_{1,2}^2}.$$  

(2.30)

Now considering that the two rebar samples are in close proximity to one another and directly overlap orthogonally, an examination of superposition shows the expected addition in the long-time region of the response signal.

Superposition can be explained by considering that the voltage of a coil within a magnetic field is described by Faraday’s Law [19]:

$$V = -N \frac{d\Phi}{dt},$$

(2.31)

where $N$ is the number of loops (or turns) in the coil and $\Phi$ is the flux of the magnetic field passing through the loops. Considering just one rebar, the transient magnetic field produced by the eddy currents will pass through the coil, inducing a voltage. By adding a secondary rebar to the same configuration, a second magnetic field is created by a different set of eddy current interactions, which will increase the net flux passing through the coil. As long as individual responses are strong enough to be detected this relationship should hold true independent of the number of rebar
added. Taking the measured voltage response to be the superposition of the two individual variations in Equation (2.27) gives the final superposition in the long-time decay:

\[
\ln(V_{\text{superposition}}) = \ln (V_1 + V_2)
\]

\[
\ln(V_{\text{superposition}}) = \ln \left( A_{D1} e^{-t/\tau_{D1}} + A_{D2} e^{-t/\tau_{D2}} \right),
\]

where if \( V_1 \gg V_2 \) then the total response is approximately equivalent to the subscript 1 version of Equation (2.29). The opposite of this is also true.

In a semi-logarithmic plot, analyzing the linear long-time decay for single rebar inspections (material characteristic dependent) results in a power-law relationship between radius and slope for a single rebar, as well as an exponential decay between intercept of that line and liftoff [3].

2.2.4 PEC: MAGNETIC FIELD DIFFUSION THROUGH A HOLLOW CYLINDER (PIPE)

A pulsed magnetic field generated by a solenoidal field coil and interacting with a hollow cylinder provides a significantly more complex system of equations than previously derived. For this case, Swanson [27] derives and models the expected transient PEC response from a pipe. A complete definition of the probe coils, electromagnetic interactions (mutual and lossy), with derivation of expected voltage and current responses is present throughout the work [27]. To solve the boundary value problem Swanson [27] applies the second order vector potential (SOVP), \( W \) [28], to derive the inductance terms:

\[
B = \nabla \times \nabla \times W,
\]

which helps model the probe response to the eddy currents within a pipe. It should be noted that the modeled probe is an air core solenoid, whereas the probe used throughout this thesis has a
ferrite core. Ferrite cores create additional complexity to an already complex modelling system [29]. COMSOL modelling has been done to simulate the eddy current distribution throughout a pipe under different coil configurations and orientations [30]. This work shows that under a system where the probe and pipe longitudinal axes are parallel, the eddy currents are localized on the surface of the pipe near the probe in early times and disperse circumferentially over time (even travelling the full circumference) [30]. Of the three probe orientations (longitudinal, radial, and tangential), longitudinal shows that while eddy currents may travel the entire circumference, this probe also localizes the eddy currents the most [30]. These simulations were conducted over a perfectly even wall thickness distribution. Any variations in pipe radius and changes of circumferential wall thickness would also affect the eddy current dispersion, and thus the resulting magnetic field detected by the receive coil.

No discrete analytical magnetic field equation was derived for interactions with pipes in this thesis (see Ref. [27]), although it is assumed here that it can be described by a series of exponential decays with coefficients far more complex than that seen in Equation (2.26).

2.2.5 PEC: Applicable Research

Research into changing the radius and the liftoff between a PEC probe and rebar has been conducted [3] and the long time decays have been analyzed. The electrical sensing system will reach a noise floor, where transient changes in log(voltage) are no longer discernable from electronic noise, and as liftoff increases, the voltage response shifts downwards closer to the noise floor. Another important factor in the response is probe orientation (in this thesis, probe axis parallel to material axis is generally used, but most published literature uses a perpendicular
to surface probe orientation [24]), with different orientations having distinct limitations and benefits.

Ulapane, et al. [31] examines PEC for inspection of flat plates. Looking at the long-time decay section of the transient response allowed the authors to relate plate thickness to slope and show a power law relationship as expected from Equation (2.13). It was also noted that with the introduction of liftoff (14 mm) slope magnitude does not change significantly. Instead, the voltage where the long-time decay occurs is vertically shifted downwards in a semi-logarithmic space as mentioned earlier, and as corroborated in Section 4.2.6. Up until a liftoff limit where the noise floor encompasses the transient response, the power law relationship remains valid. Investigations into material properties like conductivity and permeability were also conducted and it was experimentally shown to affect the long-time decay slope [31]. It stands to reason that conductivity and permeability either need to be held constant or directly measured to relate responses from different plate materials. The authors [31] also attempted to determine the thickness of the pipe walls, but results were found to vary by up to 5 mm from the actual thickness, which is large [31]. This is likely due to the geometric changes between pipes and flat plates, as the flat plate results were used to calibrate findings from the pipes.

Silva, et al. [32] uses PEC to examine flat plates at large liftoffs due to the effects of cladding. The paper [32], which is more qualitative than quantitative, sheds light on important benefits and potential limitations of PEC inspection of materials undergoing corrosion under insulation (CUI). Using a probe with pole axis perpendicular to the plate face, response to liftoffs at 30 mm were recorded and qualitatively described [32]. The effect of the presence of cladding
was also investigated and with cladding (aluminum plate) 1 mm thick, a notable difference in diffusion time was observed. Ultimately the authors were able to detect drilled holes of 2 mm, 4 mm, and 6 mm depth in carbon steel with liftoff of 30 mm under the presence of 1 mm thick cladding (simulated by an acrylic tile and aluminum sheet)[32]. This report is thorough and mentions the effect of cladding, though the material thickness is never specifically stated. Silva, et al. [32] also only analyze the response in a non-semi-logarithmic (regular) plot and show a distinct change when cladding is present, but this may be non-existent when analyzed in a similar method in the semi-logarithmic space.

Most significant to the research done in this thesis, Fu et al. [30] used COMSOL modelling to inspect the behaviour of eddy currents dispersing through a pipe wall as time increased. Three probe orientations were considered: longitudinal, tangential, and radial, each with a unique dispersal of eddy currents. A probe aligned along the longitudinal axis of the pipe has eddy currents that are localized near the probe in early times, but can spread the circumference of the pipe as time nears the long-time region [30]. While this circumferential travel may limit the angular resolution (explored in-depth in Chapter 4), the eddy currents are the most localized longitudinally, when compared to the other two probe orientations where eddy currents may travel many probe lengths down the pipe before returning [30]. Knowing how the eddy currents are expected to disperse with the given probe orientation was crucial in developing and understanding the collected data in Chapter 4.

In conclusion, PEC is an emerging method for the inspection of materials potentially experiencing corrosion, but is continually being adapted for application to more and more
complex geometries [7][8][25][21][22]. The largest limitation is in detecting localized corrosion (pits, cracks, etc.) as even for a perpendicular probe orientation with a smaller magnetic footprint, still lacks localized resolution. PEC shows the most promise, as a quick way to detect full-circumference corrosion in objects at large liftoffs (generally up to 100 mm for rebar of 1” (25.4 mm) diameter [35] and up to 70 mm for pipes [36]), namely rebar under concrete or pipes under insulation, but may also be used as a tool to characterize the conductivity of cylinders [22]. The effectiveness of PEC as an inspection tool for full-circumference corrosion and not localized corrosion is a product of PEC’s footprint in regards to both the size of the region, which the magnetic fields interact with (much larger than pits), and how eddy currents dissipate within a pipe (in the longitudinal probe orientation, circumferentially).

2.2.6 **Supplemental NDE Techniques**

PEC is not the only NDE technique that is well developed for characterizing steel structures. Ultrasonic testing (UT), eddy-current testing (ECT), radiography, and thermography all have the ability, dependent on the application to inspect metallic structures. This section briefly explores each of the listed techniques (with a focus on the few NDT technique applications used in this research), while highlighting the capabilities and limitations of each method.

2.2.7 **NDE: Ultrasonic Testing (UT)**

Ultrasonics is the study of pulsing an ultrasonic wave through a medium and analyzing the reflected signals. Ultrasonic probes are placed on the surface, with the ultrasound beam either perpendicular or at an angle to the surface, where it is then partially refracted into the material [2]. The simplest measurement of wall thickness, for a normal beam orientation, is based on a series of internal reflections of diminishing intensity.
Figure 2.4: Example of perpendicular probe with diminishing full wall reflections. The lower graph is a sample output [2] where times, \( t_2 \) and \( t_4 \), denote the times of the detected reflections.

Using a gating function on the instrument screen, the times of return peaks are recorded. Assuming the speed of the wave is constant and knowing the time it takes for a series of reflections, one can determine the distance travelled by the wave. Equation (2.35) states that the wall thickness is simply the distance travelled by the wave divided by the number of reflections. The ultimate initial goal is to determine the velocity of a wave travelling through the base material, as described in Equation (2.37).

\[
WT = \frac{d}{N_r} \quad (2.35)
\]
\[
\Delta t = t_4 - t_2 \quad (2.36)
\]
\[
v_{wave} = \frac{d}{t_4 - t_2} \Rightarrow v_{wave} = \frac{N_r WT}{\Delta t} \quad (2.37)
\]
where \( d \) is the distance the wave travelled, \( WT \) is the wall thickness, \( N_r \) is the number of internal reflections, and \( \Delta t \) is the specific time interval between the considered reflections. More internal reflections can be spanned (\( t_6 \) or \( t_8 \) reflection was detected), which will reduce relative error (same measurement error with larger magnitude base value), causing both \( \Delta t \) and \( N_r \) to increase. Taking a calibrating thickness measurement with calipers on a free end of the pipe and then measuring the time between reflections at that location results in a known medium velocity, \( v_{\text{wave}} \), for that given material. Knowing the material wave velocity, \( v_{\text{wave}} \), subsequent measurements in the central region of the pipe (inaccessible to mechanical instruments) can have thickness determined by applying Equation (2.37). This method is used in Section 3.2.2 to map all six pipe sections under study.

UT inspection is dependent on being able to bring the probe into direct contact with the material surface, coupled by an ultrasonic impedance matching lubricant. Most analysis techniques assume and prefer a single medium for simplified modelling, since at interfaces between media waves will both reflect and transmit through (with those transmissions reflecting at the far wall [2]). Materials where direct contact is not an option or that have a coating between the probe and the test material make this inspection less effective, as the ultrasonic waves attenuate through the intermediary media. An array of probes can be sent down the inside of a pipe and can determine the presence of cracks in the pipe wall [37]. Work has also studied the UT response from imperfect surfaces [38]. T-joints, rough surfaces, coatings, and sharp defects are all considered by Khalili et al., [38] with recommended waveforms and frequencies stated for each scenario. Ultrasonics is one of the most well-developed NDT techniques, with the main
limitation being the need for surface access of the material. Used as a complimentary inspection method, the limiting access barrier may be removed after PEC fast-scans and locates a flagged region, with UT then used to measure remaining material thicknesses.

2.2.8 NDE: **Eddy Current Testing (ECT)**

Eddy current testing (ECT) uses the process of inducing eddy currents in conductors by Faraday’s law by driving a time-harmonic field through a series of coils, or solenoids. The response to the source magnetic field is in opposition to this changing magnetic field (Lenz’s Law [19]) and is picked up by a receive coil and analyzed. This thesis uses ECT response to compare magnetic permeabilities on an impedance plane output, with the process described after Equations (2.38) and (2.39). Ampere’s Law can be applied to obtain the current densities induced by time varying magnetic fields as [23]:

\[
J = J_0 e^{-\frac{z}{\delta}} e^{i(\frac{z}{\delta} - \omega t)},
\]  

(2.38)

where \(J_0\) is the initial volume current density, \(J\) is the current density, \(z\) is the depth into the medium, \(\delta\) is the skin depth and \(\omega\) is the angular frequency of the alternating current. The signal of the voltage response can be analyzed on an impedance plane display due to the real and imaginary components, corresponding to in-phase or quadrature-phase components. The largest limiting factor for inspection of ferromagnetic pipes is the skin depth, defined as [23]:

\[
\delta = \sqrt{\frac{2}{\mu \sigma \omega}}
\]  

(2.39)
where $\mu$ is the magnetic permeability and $\sigma$ is the electrical conductivity, both of the studied material. Larger frequencies, while not penetrating as deeply, have a higher resolution near the surface due to the small skin depth, which increases as the frequency decreases [39]. Changes in the magnetic permeability between samples, as defined within the skin depth equation, will alter the output reading on the impedance plane. Without needing to directly quantify the characteristic property, this variable can be compared qualitatively. This is the methodology used to compare the magnetic permeabilities of all rebar samples in Chapters 5, 6, and 7.

ECT is a useful tool for scanning the surface of a metal and is sensitive to surface-breaking cracks, changing permeabilities (which can signify stress changes) or surface pits [23]. This technique is limited by the necessity to have direct or near contact with the surface because the signal is exponentially attenuated by liftoff (distance of pick-up and/or transmit coil to target sample surface). The combination of ECT and ultrasonics can provide a very detailed set of information about thickness, and surface structure [23]. ECT is not nearly as effective in determining thickness, especially if the thickness is larger than $3\delta$ [39].

2.2.9 NDE: THERMOGRAPHY TECHNIQUE

Thermography is the study of observing how heat dissipates within a specific material [40]. Different materials and geometries hold and diffuse heat through the bulk media at different rates [40]. Thermography utilizes a material’s thermodynamic properties to show that a sharp contrast in a thermal image signifies a change in material characteristics (general thickness, large defects [41][42]). Specifically, most thermographic inspection methods utilize a heat lamp to evenly heat a surface to a desired temperature (lock-in heating), and then apply a thermal camera to take a time-lapse series of images or video to see how the heat dissipates over
time [40]. Other heating methods, step heating, and pulsed, are also often utilized with respective applications summarized by Dosvarpassand, et al.[42]. All methods can be extremely useful in detecting large pits and crevices [41][42], although they often lack resolution in estimating the thickness and describing the corroded surface topology due to changing emissivity for different materials. A novel thermodynamic inspection method notes that many pipes already have hot liquids flowing through them and under field inspection conditions can be observed how the heat dissipates without need of a heat lamp [41]. Thermography also has inherent error as most infrared cameras have a ±2% accuracy when reading temperature [43]. Most models of these corroded regions assume perfectly flat cylindrical defects [42], which is not an accurate depiction of the corroded surface, which tends to be rough and non-uniform [44]. Specifically, surface corrosion often occurs as an exfoliation, or flaking, of the base material [44]. In any case, this method can often estimate both width and depth of the corroded region [42]. As with UT and ECT, thermography is dependent on surface exposure in order to facilitate imaging of heat transfer through the surface. So the presence of any insulation or cladding would directly impede thermography inspection.

2.2.10 NDE: RADIOGRAPHY TECHNIQUE

Radiography is an NDT technique that uses radioactive sources (emitting X-rays) and images the diffusion of these rays through a material, similar to X-rays performed in the medical field [45]. Radiography is useful in corrosion inspection for being able to view metallic structures through other materials (rebar mapping, pipe imaging through insulation). One limitation of this method is that not all inspection regions have access to the far side for proper imaging by film or sensor (such as some concrete embedded rebar). An important factor to consider is the necessary
exposure time required to collect a complete image, while also limiting the potential of creating interstitials and vacancies through knock-on atoms (displacement of atoms within a lattice structure), which change structural properties like ductility and loss of structural integrity (more severe at significant exposure times) [46]. While X-rays have less energy than radiated protons or gamma rays, they still can damage materials at long exposure times. Radiography is limited by the general safety aspects that need to be met when conducting tests in the field. There must be significant shielding around the radioactive source, inspector and pedestrian health must be considered when setting up the device (does the far side of the wall contain a working office or pedestrian walkway, etc.). These considerations are often cumbersome and expensive to overcome.

Tangential radiography is the process of imaging the two tangential sides of a pipe. This is a useful process as it images the cross-section of a defect (given that it is located at the tangential location), thus characterizing the flaw [36][37][38], as illustrated in Figure 2.5. This method is only applicable, however, if the radiation direction axis is not aligned with the defect depth, as then only the location but not the depth can be ascertained [49].
Figure 2.5: Tangential radiation diagram. Radiation source interacts with entire pipe and diffuses through the material at different rates (shown by change in shades of grey). Locations where X-rays tangentially intersect with pipe has the best resolution as the leftmost band of lighter grey acts as a cross-section/depth of the defect. This is unlike the central very light band that shows a defect is present but gives no other classifications.

Similar to medical X-rays, a full 3-D image is only possible by collecting the 2-D image along a minimum of 180° rotation. Think of the radiation source rotating circumferentially around the pipe and imaging along the way. At a certain rotation, the defect that is currently making that very light grey band in the center of the image will be located tangentially and a cross-section will be imaged. Needing a 3-D image limits the situations where this method can be used under field inspection conditions where a 2-D image isn’t sufficient.

Radiography provides a useful tool in non-destructively assessing materials and their respective defects. With enough exposure time and access to a full 360° rotation, 3-D imaging is an effective analysis tool. Radiographic imaging devices are not only expensive to procure but meeting field inspection safety considerations with access at difficult-to-reach areas make radiography difficult to administer, often requiring samples to be transported to a lab.
Chapter 3 – Experimental Procedure

The measurements reported in all manuscripts of this thesis were acquired with the same probe and excitation unit (Nexum Pulser) system. This excitation unit is paired electronically with a LabView PEC program, which allowed for customization of pulse variables. For use in the experiments described within this paper, the duration of the pulse time was set to 0.4 s and was held at this length throughout all measurements with an equal amount of off-time between pulses (50% duty cycle). Long pulse times would be beneficial with very thick materials due to a longer required diffusion time, with the converse also being true. The 0.4 s pulse time was sufficient to capture the transient probe response across all samples examined and thus was not changed. The LabView program also provided the option to average over a number of pulses so as to reduce noise in the signal response. For each measurement, ten pulses were averaged, resulting in an entire data collection time of approximately 8 s per raw data set.

3.1 General Methodology

Pulsed eddy current measurements were performed using a Nexum Pulser that excited a coaxial solenoidal probe (solenoidal pickup coil within a 100 mm long solenoidal drive coil). The coaxial pair of coils are often illustrated as two neighbouring coils with an inductance between them. While these circuits are described in much greater detail by both Desjardins [29][30] and Swanson [27], Figure 1.1 is just meant to illustrate the voltage pulse shape, $v_d$, driven through the drive coil (left) and the resulting voltage signal detected, $v_r$, in the receive coil (right).
The rising edge of the square voltage pulse acts as an almost immediate change in state, which nature abhors, as described by Lenz’s Law. The falling edge acts in a similar manner, however this change from a high voltage to none allows all transient currents and fields to diffuse through the conducting material to be detected by the receive coil in the air. The relaxation period from the excited voltage pulse to a steady state allows the transient response seen in the receive coil to have separate regions of voltage response dependency. Namely, at earlier times the voltage response is dominated by an exponential decay which is largely dependent on probe parameters (resistance and inductance as well as initial field interactions within the sample) and decays rather quickly, while later time exponential decays are dependent on material properties as described in Equation (2.12).
The probe used throughout all experiments within this thesis has the drive coil with a larger diameter than the receive coil, with the receive coil lodged within the inner radius of the drive coil, thus the defining term of a coaxial solenoidal probe. Other PEC probes may use a transmit-receive orientation where the drive and receive coils are not physically touching each other, with some distance between them. The coaxial nature of the probe used makes for a simpler theoretical derivation for the expected response. Specifically, since the received magnetic fields (which drive a current that is recorded) are being detected at the same location the initial magnetic fields are created (i.e., the central axis of the hollow coil). Probe parameters like the radii of both coils, number of turns, gauge of wire, and length of the coil all affect the signal created and received [19][26][29], where this probe’s receive coil has many more turns relative to the drive coil to increase the gain on the resulting magnetic fields (which is significantly reduced in magnitude compared to the initial field). The commercially available probe ended up being ideal for the uses examined within this thesis as the diameter of the drive coil is similar in scale to the diameters of the rebar studied and most of the pipe wall thicknesses. The length (approximately 100 mm), while creating a larger probe footprint (thus reducing resolution), significantly increases the liftoff that the probe is effective at, which is an essential constraint for both the pipe and rebar analyses.

Figure 3.2 shows the sample transient response of the falling edge in a semi-logarithmic plot with different regions highlighted. The initial exponential decay (before $t=0.1$ s) is the probe dependent decay, with the ‘knee’ acting as the transition between the short and long-time decays. The linear region found after the knee (until the signal decays to the noise floor) is the
region under study. In this region the response of the receive coil is only due to changes of the electromagnetic field diffusing into the rebar sample [1]. The electronic noise from the probe and Nexum Pulser system is at 1E-5 V. This lower bound impedes the ability to collect data at greater liftoffs. For the remainder of this work, all data sets will have the lower bound 1E-5 V for the Y axis.

![Graph](image)

Figure 3.2: Sample of data response. The long-time decay starts at ~0.025 s and the noise floor is reached at 1E-5 V. The region left of the knee is the early-time decay.

There are three main orientations of the probe with respect to the pipe or rebar to consider. Each orientation has advantages and limitations. Longitudinal orientation occurs when the longitudinal axes of the probe and pipe or rebar are parallel. Tangential orientation occurs when the longitudinal axes of the probe and pipe or rebar are perpendicular. Transverse orientation occurs when the probe axis is perpendicular to the pipe or rebar surface. Consider the radial coordinates of a cylinder, \((r, \phi, z)\), where \(r\) is the radial axis, \(\phi\) is the angular rotation, and \(z\) is the height or length of the cylinder. The three stated orientations are the longitudinal axis of the probe being aligned with the radial axes, respectively. Many PEC analyses use a transverse orientation as it has a reduced probe footprint with a greater depth of penetration.
into the material [19][26]. For pipes, the transverse orientation was modeled through COMSOL as having eddy currents travelling multiple probe-lengths down the length of the pipe, while not travelling fully circumferentially [30]. Transverse orientation is also significantly limited by liftoff, as any introduced liftoff significantly reduces the signal response from this orientation. This automatically negates this orientation as an option for inspection of pipes or rebar when significant liftoff (insulation or concrete) greater than 50 mm is present. Tangential orientation (explored in Chapter 7 for rebar) was shown by finite element modelling to travel not only probe-lengths down the pipe but in a spiral pattern circumferentially, producing the largest probe footprint of the possible orientations [30]. Longitudinal orientation was modelled to travel less than a half a probe-length down the length of the pipe on either side of the probe while travelling the full pipe circumference [30]. Longitudinal orientation is able to effectively take data at large liftoffs [5][7]. Longitudinal orientation has some inherent liftoff occurring even when the probe is in contact with the material, as the magnetic field is being generated at a coil radius distance away from the material, however this liftoff will not affect the signal response in the way it would for the transverse orientation. As it was the most effective for taking measurements at liftoff and produced the shortest longitudinal footprint (compared to the other orientations) a longitudinal orientation between probe and material was used unless explicitly stated otherwise.

3.2 PIPES—EXPERIMENTAL METHOD

This laboratory investigation used six different pipe sections, provided by industrial partner Groupe Mequaltech Inc. The pipe section samples can be split into two categories: uniform and non-concentric. The first four pipes, labeled A-D (as denoted throughout this paper), are ‘relatively uniform’ in wall thickness with respectively, decreasing wall thickness. These pipes
have the same inner radius and were machined from the same ‘parent’ pipe. Therefore, the
electrical conductivity was assumed to be the same for each of these four pipe sections. The
electrical conductivity of these pipes was measured, as explained in Section 3.2.1 to further
characterize the material properties relevant to PEC measurements. Reference angle, 0°, was
arbitrarily taken to be at a rotary position 1 cm from one end of each pipe section, as discussed
in Section 3.2.3. Specifically, Section 3.2.3 describes the process of translating the pipe’s
coordinates such that the reference location is in the same position relative to the arbitrarily
chosen location of Pipe A.

Pipes E and F are non-concentric, with the 0° marker conventionally chosen as the thinnest
circumferential location (consistent down the length of the pipe). Pipe E has a larger inner radius
and increases in wall thickness by approximately 90% to the far side, 180°, whereas Pipe F has a
smaller inner radius and increases by approximately 50% to its thickest point.

Each pipe section has the same length, within each of the two pipe classifications. All
dimensional information is summarized in Table 3.1 with Figure 3.3 and Figure 3.4 showing the
important characteristic dimensions.

Table 3.1: Summary of pipe dimensions. Note the two sections representing the common types of corrosion. Thickness ranges (A-D) were provided by manufacturer Groupe Mequaltech Inc. and minimum and maximum measurements of Pipes E and F were initially obtained using calipers on a free end of the pipe (E and F).

<table>
<thead>
<tr>
<th>Pipe Identifier</th>
<th>Length, ( \ell_p ) (mm)</th>
<th>Inner Radius, ( IR ) (mm)</th>
<th>Nominal Thickness Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>570 ± 1</td>
<td>61 ± 1</td>
<td>8.8 ± 0.3</td>
</tr>
<tr>
<td>B</td>
<td>570 ± 1</td>
<td>61 ± 1</td>
<td>8.3 ± 0.3</td>
</tr>
<tr>
<td>C</td>
<td>570 ± 1</td>
<td>61 ± 1</td>
<td>7.7 ± 0.3</td>
</tr>
<tr>
<td>D</td>
<td>570 ± 1</td>
<td>61 ± 1</td>
<td>7.0 ± 0.4</td>
</tr>
<tr>
<td>E</td>
<td>370 ± 1</td>
<td>77 ± 1</td>
<td>(4.1 -&gt; 7.9) ± 0.1</td>
</tr>
<tr>
<td>F</td>
<td>370 ± 1</td>
<td>61 ± 1</td>
<td>(6.1 -&gt; 9.2) ± 0.1</td>
</tr>
</tbody>
</table>
Figure 3.3: Diagram showing the variables: length of pipe, $\ell_p$, inner radius, IR, and wall thickness, WT.

Figure 3.4: Visual representation of non-concentric pipes E (left) and F (right) showing minimum and maximum wall thicknesses.

Pipe E also contains four ball-mill machined circular defects in close proximity to each other and located at the center of the pipe, simulating localized corrosion (specifically, aggressive pits). These defects are on the thickest section, aligned circumferentially at the same axial position on the outer wall as shown in Figure 3.5. The defects were drilled with a ball mill having a diameter of 13.4 mm. They span a circumferential extent of 51.3 mm (there is overlap of some drilled diameters). Figure 3.5 is an image taken of the defect area on the pipe, highlighted to show its relative position. Figure 3.6 shows a zoomed in version alongside a straight ruler to provide a scale. The patchy colouring on this sample (also present on Pipe F) is a byproduct of
previous heat treatment performed by Swanson [27]. These pipes were heat-treated so as to remove residual stresses within the surface to produce a uniform permeability, but were overheated to 700°C resulting in the flaking oxide [27]. Unlike Pipes A-D, the conductivity was not measured for these two samples, and instead these samples were used to explore general PEC response without comparing the two pipes directly to one another.

Figure 3.5: Picture of the large non-concentric pipe (Pipe E) with the drilled defects highlighted in the red box. Defects have depths between 4.5 and 6.1 mm at maximum in the 8 mm thick wall at this location. Heavy oxidation is expected to not heavily effect PEC transient response.

Figure 3.6: Zoomed-in image of drilled defects. Circumferential extent is 51.3 mm (doesn’t line up with image exactly as ruler is not bent tight to the circumference in this image). Diameter is 13.4 mm, with the respective depths shown on each drilled defect.
### 3.2.1 Pipes – Conductivity Measurements

Electrical conductivity, $\sigma$, is a characteristic property that determines how well a material can conduct electricity. Conductivity can help characterize the PEC response obtained from different samples (explored later in Section 5.2.1). As previously stated, it is assumed that the conductivity is expected to be identical across the four full-circumference corrosion pipe sections.

A thin ring from the ‘parent’ pipe section was machined off and a slit was removed to ensure a known current path, as shown in Figure 3.7. A current source sent 100 mA through the ring and a voltmeter was attached at locations inward from the slit (see Figure 3.7) in parallel, to determine the voltage drop across a calculable distance. Current was reversed to -100 mA, to remove potential drift, and the voltage was recorded again. To calculate the conductivity, four variables are required: voltage, current, length between positive and negative voltage probe locations, and cross-sectional area. The thickness of the sectioned pipe ring was measured with calipers as (3.2 +/- 0.1) mm. The cross-sectional area was had square dimensions along the entire circumference (was measured at multiple locations), so this thickness was squared to determine the area. Halving the thickness and adding it to the measured inner radius gave the chord radius, $r_{chord}$ (64.9 +/- 0.2) mm. Referring to Figure 3.7, the following equations define the process used to calculate the length traveled between the voltage probes on the pipe ring, $\ell_{VD,p}$:

\[
\ell_{VD,p} = r_{chord} \cdot \Phi, \quad (3.1)
\]

\[
\Phi = \pi - (2\Phi_a), \quad (3.2)
\]

\[
\Phi_a = \Phi_b = \sin^{-1}\left(\frac{h}{r_{chord}}\right). \quad (3.3)
\]
In these equations, ‘\(h\)’ represents the height above the horizontal axis, measured to be (10.0 +/- 0.1) mm using grid paper and a sketch of the ring in a 1:1 scale. Voltage drop was measured in accordance with Equation (3.3).

![Diagram of pipe ring used in calculation of Pipe A-D conductivity. The variables presented are used in Equations (3.1) – (3.5).](image)

With the above variables calculated/measured, the conductivity was calculated and all variables with their errors are summarized in Table 3.1. Error propagation equation is given in Equation (3.5).

\[
\sigma = \frac{l_{VD,p}}{V_{VD,p}} * \frac{\ell_{VD,p}}{A_{cs,p}} \tag{3.4}
\]

\[
\delta \sigma = \sigma \sqrt{\left(\frac{\delta l_{VD,p}}{l_{VD,p}}\right)^2 + \left(\frac{\delta V_{VD,p}}{V_{VD,p}}\right)^2 + \left(\frac{\delta \ell_{VD,p}}{\ell_{VD,p}}\right)^2 + \left(\frac{\delta A_{cs,p}}{A_{cs,p}}\right)^2} \tag{3.5}
\]

46
Table 3.2: List of values with errors used to calculate the conductivity of Pipes A-D.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{VD,p} ) (A)</td>
<td>0.100</td>
<td>0.001</td>
</tr>
<tr>
<td>( V_{VD,p} ) (V)</td>
<td>0.000310</td>
<td>0.000006</td>
</tr>
<tr>
<td>( \ell_{VD,p} ) (m)</td>
<td>0.1838</td>
<td>0.0008</td>
</tr>
<tr>
<td>( A_{cs,p} ) (m²)</td>
<td>1.02E-5</td>
<td>0.06E-5</td>
</tr>
<tr>
<td>( \sigma ) (S/m)</td>
<td>5.8E+6</td>
<td>0.4E+6</td>
</tr>
</tbody>
</table>

Comparing the values in Table 3.2 with literature, the conductivity agrees within error of cast steel material (6.2E+6 S/m) [50] and carbon steel (5.9E+6 S/m) [51], although it lies closer to the carbon steel value.

### 3.2.2 Pipe Thickness Mapping/Translation

Seamless pipes are generally manufactured through the extrusion of molten iron cross-rolled to the desired dimensions. In the extrusion process, the base material reaches the target dimensions by passing over a series of angled rollers creating a three-lobe wall thickness distribution along the circumference meeting or exceeding the industry standard of a maximum 12.5% wall thickness variation [52]. This percentage is specifically the maximum allowed difference between the stated nominal thickness and the minimum thickness on the pipe (there is no maximum thickness specification) [52]. Before the relation between thickness and PEC response can be evaluated, the thickness needs to be directly measured.

Ultrasonic testing (UT) provided the ideal method for mapping the wall thickness distribution of each pipe section. In order to determine the thickness, a value of the speed of sound in each pipe needed to be determined. This was achieved by measuring the thickness 1 cm from a free end of each pipe section every 22.5° with a set of calipers. An ultrasonic probe was placed flush against the surface (to produce a normal beam) and the time it took for the
ultrasonic wave to travel the distance of the wall thickness and return was measured on the A-
scan display. The ultrasonic interface allows one to change the gain, scaling and frequency of the
ultrasonic response. By setting the two voltage gates to occur at peaks and determining the
number of internal back-wall reflections occurring between these peaks, \( N_r \), the speed of sound,
v_{sound,A-F}, may be calculated as:

\[
v_{sound,A-F} = \frac{N_r WT}{\Delta t},
\]

where ‘\( WT \)’ is the measured wall thickness at the given point and \( \Delta t \) is the time interval between
these given peaks. The sixteen calculated velocities were averaged for each pipe with respective
standard deviation representing the error incurred by measuring with calipers (for example due
to potentially uneven surface). Across Pipes A-D, the calculated velocities averaged to
approximately \((5950 \pm 50) \text{ m/s}\), which is in agreement with the expected speed of sound (within
error) for a mild steel [53]. The pool of data allowed for ultrasonic mapping of the pipe sections.

Pipes A-D have a length, \( \ell_{A-D} \) (subscript ‘p’ removed from here due to all lengths in
Chapter 4 being of a pipe), of 57 cm, and as mentioned above, the initial ultrasonic measurements
were performed 1 cm from one of the free ends and circumferentially every 22.5°. The
subsequent ‘ring’ of UT measurements was performed every 5 cm down the length of the pipe.
This was repeated until reaching a 1 cm distance from the opposite end. In each case, the wall
thickness was a function of the length, \( \ell_{A-D} \), and angular position, \( \phi_{A-D} \). A similar process was
followed with Pipes E and F with the exception that they have a length, \( \ell_{E,F} \), of 37 cm. A visual
depiction of this segmenting and mapping of the pipe can be seen in Figure 3.8.
Figure 3.8: Diagram showing ultrasonic wall thickness mapping locations for each pipe. Note Pipes A-D have the same characteristic length parameters, just different WT values. Pipes A-D have 192 UT measurements per pipe. There are 128 UT measurements for each of Pipe E and F. $0^\circ$ for Pipes E and F are at the thinnest pipe wall location.

With the pipes adequately mapped and UT measurements taken, three styles of plots were produced to characterize the natural WT variation: full mapping, circumferential variation, and $\ell_{A-F}$ thickness variation, which are described in the following two sections.

3.2.3 MAPPING AND TRANSLATION: PIPECES A – D

A full mapping plot represents the wall thickness of the pipe displayed as though the pipe is cut longitudinally along the $0^\circ$ position. Figure 3.9 shows an example of the UT determined thickness values of Pipe A plotted through Excel. The graph contains a series of scatter plots with X and Y axes representing the angle, $\phi$, and wall thickness, $WT$, respectively. Combining these plots through a Z axis, $\ell_A$, a visual representation of changing thickness for Pipe A can be seen. The remaining two plot styles represent the averaging of every data point at the same $\phi$ position (circumferential) and at every ring ($\ell_A$ thickness variation). Comparing those two styles highlights
how Pipes A-D needed to be translated such that the origin, \((\phi, \ell_{A-D})=(0,0)\), of each pipe had the same circumferential distribution of peaks and valleys, but with a different average wall thickness.

Figure 3.9: Full picture mapping of Pipe A. Nominal given thickness was 8.8 +/- 0.3 mm. Patterns of peaks and valleys are visible with thickness gradually increasing down the length of the pipe.

Pipe A is used as the reference that every subsequent pipe section (excluding E and F) will be translated to, so the base reference angle can be established. Figure 3.10 and Figure 3.11 show the trends seen in Pipe A thickness. Maxima are present at 45°, 180°, and 292.5° with minima at 22.5°, 90°, and 270° and it is important to note the thickness increases as the length down the pipe, \(\ell_A\), increases. The collection of minima, maxima and \(\ell\) trends are combined in Table A1.1 with the necessary translation given. This translation eliminates the arbitrary location of the (0,0,0) point when comparing the segments. Figure 3.12 also describes the collection of this information to help clarify the process. The vertical flip needed on two translations is done
on the $90^\circ$-$180^\circ$ axis. Figure 3.12 also has positive and negative symbols next to the respective titles and this denotes the trends seen in Figure 3.11.

Figure 3.10: Average wall thickness as a function of angle. Green coloured data points represent the valleys, and red data points represent the peaks.

Figure 3.11: Average WT as a function of position. It is noted that as the distance from the origin increases, the average thickness increases. This is likely a product of the machining process.

The same collection of three Figures for Pipes B, C, and D are found in the Appendix, specifically as Figures A1.1-A1.3, A1.4-A1.6, and A1.7-A1.9, respectively.
Figure 3.12: Distribution of peaks and valleys for Pipes A – D given in Table A1.1. Green ‘x’s represent the minima with the red ‘o’s representing the maxima. The length down the pipe thickness trends are shown next to the respective titles.

Though ultimately unsuccessful, these translations were initially conducted as a critical step in solving a sixteen-equation deconvolution (explored in Section 4.2.1). Regarding PEC measurements, the center of the 100 mm long probe is held at a $\ell_{A-D}$ of 30 cm such that the two ends of the PEC probe also have associated UT wall thickness measurements. When considering the thickness under the probe, five UT measurements were averaged with even weighting (3 encompassed by probe, 1 above, and 1 below). The translations allow for comparisons between the four pipes, not only at similar wall thicknesses (as some of the ‘extreme’ thicknesses of consecutive pipes overlap) but now at the identical circumferential position (due to similar distribution of minima and maxima). Examining all four pipe sections’ wall thickness distribution on the same plot (Figure 3.13), Pipe A and Pipe B seem to follow a similar distribution intensity and Pipe C and Pipe D demonstrate a similar pattern with one another as well. Examined further
below, these pairings also seem to affect PEC response in a similar manner, showing a grouped
distribution of slope values on these pipes.

![Diagram](image)

Figure 3.13: Wall thickness distribution for each translated pipe section at the center pipe location. Pipes A and B show similar distribution. Pipes C and D share a distribution as well.

### 3.2.4 Mapping: Pipe E and F

Unlike Pipes A – D, the remaining two pipe sections did not need to be translated as the 0° position was taken at the thinnest section. It is still important to know the specific $WT$ values as to generally relate them to trends in PEC response. Due to the oxide formed on the outer edges, these measurements have more uncertainty as the surface is uneven when compared to the four concentric pipes (though large flakes were removed with sandpaper). Through a similar process to that described above, a statistically determined $v_{soun}$ for each pipe was calculated. This value, along with UT measured back wall reflection was used to measure the $WT$. Figure 3.14 and Figure 3.16 are the respective full mapping plots for Pipes E and F with Figure 3.15 and Figure 3.17 showing the circumferential distribution along the central 5 data points used in WT averaging (recall 0° is the thinnest section, 180° is the thickest).
Figure 3.14: Full mapping of WT values of Pipe E (large non-concentric). Thickest region seems relatively flat.

Figure 3.15: Pipe E circumferential distribution of WT around the central 5 UT measurements (region under consideration in PEC response). Blue data set ignores the machined defects, where the orange is the estimated wall thickness due to drilled defects as described in Section 3.2.4.

For Pipe E, as shown in Figure 3.14 and Figure 3.15, full WT is reached within 90° of the origin. The thickest point of this pipe covers half of the circumference. Pipe F, however, has a distinct peak at 180° when compared to Pipe E (Figure 3.17), and a gradual increase to that thickness.
Figure 3.16: Full mapping of Pipe F (small non-concentric) UT measurements.

Figure 3.17: Circumferential distribution about the central 5 UT wall thickness measurements on Pipe F.

With all six pipe sections fully mapped, translated, and characterized, analysis of PEC experimental data can begin (see Chapter 4).
3.3 Rebar Samples—General Experimental Method

The rebar experiments presented in this thesis employed six rebar samples of different diameter as shown in Figure 3.18, with properties listed in Table 3.3. Four of them were original (off the shelf) rods, while one was machined from a 25 mm (1” Sample) diameter rod to produce a reduced 22.2 mm (7/8” Sample) diameter and the last was a smooth 57 mm diameter rod. Classification of the rebar samples with subsequent naming conventions [54] is summarized in Table 3.3. The nominal diameters closest to those measured were used. Nominal diameters were taken as the smallest diameter, as the ridges that surrounded the rebar increased the local radius by up to 1 mm (~0.04”).

Figure 3.18: (A) Rebar samples used with nominal closest fractional inch [left to right]: 1”, ¾”, 5/8”, 2/5”. (B) 7/8” diameter [left] (lathed rebar, originally 1” diameter sample), 1 1/2” diameter smooth rod [right].
Table 3.3: Measured diameters, inner and outer, with closest nominal values [54] stated as sample fraction identifier, all agree within 0.5 mm (0.02”) with standard rebar size.

<table>
<thead>
<tr>
<th>Smallest Diameter (mm)</th>
<th>Largest Diameter (mm)</th>
<th>Diameter Range (inches)</th>
<th>Sample Fraction Identifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.1</td>
<td>38.1</td>
<td>1.500</td>
<td>1 ½”</td>
</tr>
<tr>
<td>24.9</td>
<td>26.3</td>
<td>0.971-1.027</td>
<td>1”</td>
</tr>
<tr>
<td>22.2</td>
<td>22.2</td>
<td>0.872</td>
<td>7/8”</td>
</tr>
<tr>
<td>18.6</td>
<td>20.4</td>
<td>0.725-0.795</td>
<td>3/4”</td>
</tr>
<tr>
<td>15.0</td>
<td>15.8</td>
<td>0.583-0.617</td>
<td>5/8”</td>
</tr>
<tr>
<td>10.2</td>
<td>11.2</td>
<td>0.398-0.438</td>
<td>2/5”</td>
</tr>
</tbody>
</table>

Since the 5 uppermost data rows agree with the nominal values (<0.02”), the associated fractional values will be used in naming conventions: 1”, 7/8”, 3/4”, and 5/8”, respectively. The smallest of the rebar samples did not have a listed nominal size closest to it. So instead, the naming convention used the closest fraction (2/5”).

3.3.1 Permeability and Conductivity Measurements

The expected transient response and longest decay time of the PEC system with a solid rod is defined by Equations (2.11) - (2.13). From these equations, in order to accurately compare the long-time decay response to the inverse critical length squared, the remaining characteristic properties, magnetic permeabilities, μ, and electrical conductivities, σ, are either assumed to be homogenous across all samples or directly measured and isolated from the relationship. Under field measurement conditions, it is assumed that all conductivities and permeabilities are similar as the materials are likely ordered in bulk from one company. In this thesis, that assumption wasn’t made, as the rebar samples came from the Civil Engineering department in Royal Military College (RMC), and ultimately from different production batches. First, the relative permeability
was compared between rebar samples. Using a Nortec pencil probe operated by a Nortec II® eddy current instrument the sample permeabilities were compared on the complex impedance plane display using the method outlined in [39]. Upon further inspection, the outer edge of the 1” Sample was shown to have a much stronger signal, which was taken to be a by-product of carburizing or thermo-mechanically treating (TMT) process commonly employed for larger rebar samples to resist corrosion effects by changing the outer surface electrical conductivity. This process improves strength and durability in the field but creates a heterogeneous permeability within the sample. Since the PEC is expected to interact with the bulk material and not just the surface, the heterogeneous permeability of the 1” Sample was taken to be equivalent to that of the inner homogeneous core material (or the end). Therefore, all sample permeabilities were taken as being qualitatively the same and were not quantitatively determined.

Conductivity measurements were performed on each of the rebar samples in order to compensate for possible variations in this parameter, which is a component of the characteristic diffusion time \( \tau_D \) as expressed in Equation (2.12). The 4-point method was used to collect the data [55]. A current of 100 mA DC was driven between the rod ends using a Keithley: 6221 current-source. Voltage was measured over a fixed length on the rod, at a minimum distance of two rod diameters from either of the ends. The acquisition software collected ten voltage samples and found the average and standard deviation of the readings. The voltage, current and cross-sectional area (found using mass measurements and the known constant density, 7840 kg/m\(^3\) [56]) were used to calculate the conductivity, which is further discussed in the following and Table 3.4.
The conductivity of each sample was determined using a 4-point resistance measurement [55]. By applying a current through the samples and measuring the voltage over a known distance, \( \ell_{VD} \), and using a measured cross-section, \( A \), the conductivity can be determined using the following equation [57]:

\[
R = \frac{V_{VD,r}}{I_{VD,r}} = \frac{\ell_{VD,r}}{\sigma_r A_{cs,r}}
\]

(3.7)

The cross-section of the rod was measured in order to calculate the conductivity, and this was done by using the density of the metal (carbon steel has a density of 7840 kg/m\(^3\)[56]) and measuring the mass and length of each rod. It should be noted that these calculations did not account for the carburized outer surface present in the 1” Sample, which has a different electrical conductivity, making it less reactive with its environment.

Using a current of 100 mA and a voltage reading across a probe that was 139.54±0.07 mm in length, the conductivities were calculated and compared. Table 3.4 below shows the measured rod parameters. It should be noted that conductivities are similar in value with the exception of the 5/8” Sample. There are no length or mass measurements for the 1 ½” Sample as the cross-sectional area was very easily determined due to its constant diameter.
Table 3.4: Rod properties with estimated errors used for conductivity measurements.

<table>
<thead>
<tr>
<th>Label</th>
<th>Length (m)</th>
<th>Error (m)</th>
<th>Mass (kg)</th>
<th>Error (kg)</th>
<th>Conductivity (S/m)</th>
<th>Error (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1/2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>6.90E+06</td>
<td>0.03E+06</td>
</tr>
<tr>
<td>1</td>
<td>0.941</td>
<td>0.004</td>
<td>3.7271</td>
<td>0.0006</td>
<td>6.84E+06</td>
<td>0.02E+06</td>
</tr>
<tr>
<td>7/8</td>
<td>0.3000</td>
<td>0.0008</td>
<td>1.0917</td>
<td>0.0006</td>
<td>6.7E+06</td>
<td>0.2E+06</td>
</tr>
<tr>
<td>3/4</td>
<td>0.6064</td>
<td>0.0008</td>
<td>1.3804</td>
<td>0.0006</td>
<td>5.9E+06</td>
<td>0.4E+06</td>
</tr>
<tr>
<td>5/8</td>
<td>1.0001</td>
<td>0.0008</td>
<td>1.5121</td>
<td>0.0006</td>
<td>6.7E+06</td>
<td>0.3E+06</td>
</tr>
<tr>
<td>2/5</td>
<td>0.7620</td>
<td>0.0008</td>
<td>0.5835</td>
<td>0.0006</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Upon inspection of this data, the conductivity of the 5/8” Sample varies noticeably from the rest of the rebar samples. The 5/8” Sample has the same conductivity as a carbon steel alloy (5.9E+06 S/m [50]), while all other samples seem to be within the range of pure iron (7.0E+06 S/m [50]) and the carbon steel. Due to the varying conductivity across the samples, these values are grouped with the slope values to discretely relate radius with the signal (explored further in Section 5.2.1). It can also be shown that the cross-sectional area as obtained from density, volume, and length measurements result in an accurate reading of radius when compared to the measured radius range presented earlier in Table 3.4. The cross-sectional area radii all fall within the stated ranges as expected as presented in Table 3.5.

Table 3.5: Comparison of cross-sectional areas compared to measured ranges. Note the 7/8” and 1 ½” Samples were taken to be near exact radius because they are smooth cylinders with the measurement error of 0.001 mm.

<table>
<thead>
<tr>
<th>Cross-Sectional Radius [mm]</th>
<th>Measured Radius [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.05</td>
<td>19.05</td>
</tr>
<tr>
<td>12.68</td>
<td>12.45-13.17</td>
</tr>
<tr>
<td>11.08</td>
<td>11.08</td>
</tr>
<tr>
<td>9.62</td>
<td>9.30-10.19</td>
</tr>
<tr>
<td>7.84</td>
<td>7.43-7.91</td>
</tr>
<tr>
<td>5.58</td>
<td>5.10-5.62</td>
</tr>
</tbody>
</table>
The rod being examined was fixed laterally for all measurements. The effect of variation of experimental parameters was then investigated including varying radius, liftoff, and angle of the probe axis relative to the rebar axis. Varying the radius affects the transient response as an inverse square power law between long-time decay slope and radius (Section 5.2.1), as expected [1], and an increasing liftoff resulting in stable slope but diminishing voltage response (effectively a changing intercept) as shown in Section 5.2.2. Probe angle variations from parallel to perpendicular with respect to the rebar had similar results to liftoff. A simple geometric conversion may be applied that relates the probe angle to the closest distance from rebar to probe tip and produces a useful linear dependence (Section 7.2.1). All experimental results from rebar samples mentioned above can be found in Chapters 5 and 6.

3.4 **Rebar Samples – Junction Specific Experimental Method**

Two separate studies performed for the case of rebar junctions (main focus of Chapter 7): variation of signal with angle, \( \theta \) (as illustrated in Figure 3.19), between the probe and longitudinal axis of the rebar, and the effect of two mutually orthogonal rebar as shown in Figure 3.20. Three rebar samples were used throughout both studies, the 1” (V1), 1” (V2), and 3/4” Samples were chosen (Table 3.6 has characteristics of the 1” V1 and 3/4” Samples, with similar conductivities and qualitative permeabilities when comparing V1 to V2).
Table 3.6: Rebar minimum and maximum (including ridge) diameter, and conductivity labeled by standard designations [54] in fractions of an inch. This table is an excerpt from Table 3.4.

<table>
<thead>
<tr>
<th>Sample Fraction Identifier</th>
<th>Minimum Diameter (mm)</th>
<th>Maximum Diameter (mm)</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1”</td>
<td>24.9</td>
<td>26.3</td>
<td>6.8E+6</td>
</tr>
<tr>
<td>7/8”</td>
<td>22.2</td>
<td>22.2</td>
<td>6.8E+6</td>
</tr>
</tbody>
</table>

The 1” Sample provided the strongest signal response in early stages of this research; thus, it was used in both studies. The 3/4” Sample was used as the sample in the angle experiment. A secondary rebar sample of a 1” diameter was acquired and used in the junction analysis. The three rebar samples are used in two pairing combinations to examine junctions of similar and dissimilar diameters.

![Diagram of experimental setup with the enlarged protractor and definition of angle between longitudinal axes, θ.](image)

Figure 3.19: Diagram of experimental setup with the enlarged protractor and definition of angle between longitudinal axes, θ.
Figure 3.20: Definition of junctions A and B. In-field, both rebar may be the same diameter, so two 1” rebar from separate sources were used. Note that V1 indicates the 1” Sample used in Chapters 5, 6, and in the coupling angle analysis. V2 denotes the secondary 1” Sample used in this A) shows the solenoid aligned to closer 1” rebar, B) shows solenoid aligned with the 1” rebar further away.

Figure 3.21: Four possible geometrical variations for two rebar with different diameters. C) shows the solenoid aligned with closer 1” rebar with 3/4” rebar behind. D) shows the solenoid aligned with the 3/4” rebar which is behind the 1” rebar. E) shows the solenoid aligned with the 3/4” rebar, which is closest to the probe, with the 1” behind it. F) shows the solenoid aligned with the 1” rebar which is behind the 3/4” rebar.

Junctions A and B are the study of a same-sized rebar junction, whereas Junctions C through F examine PEC response to differing rebar sizes (representing corrosion presence or different size rebar). While Junctions A and B are the main focus of this analysis, Junctions C-F provide
supplemental agreement of superposition of individual signal response observed in Junctions A and B.

Concerning the experimental setup to measure angle, a protractor is drawn and enlarged on a clear sheet of paper and labelled. This paper is placed beneath the rebar with the rebar longitudinal axis placed along the 0° line. A line indicating the middle length (50 mm from one end) is put on the probe. For each angle increment (15°), this marker is placed at the central point of the compass to ensure that the mid point of the probe is aligned with the central axis of the rebar.

Regarding the junction analysis, utilizing the same compass from the angle variation measurements, the perpendicular rebar samples were held fixed and angular dependent measurements were made on all rebar illustrated in Figure 3.20 and Figure 3.21.

3.5 Systematic Error/Repeatability

The electronic circuit pairing of driver and probe has an inherent error with regards to the eddy current response. This section aims to determine the base error in the data analysis. This process consisted of taking bi-weekly measurements over a 3-month period, while recording the room temperature each time and comparing the linear response in semi-logarithmic space of the long-time decay. The subjects were chosen as Pipe A and the 1” Sample. These were the thickest samples available and provided the strongest signal (largest response above the noise floor). The probe was oriented parallel to longitudinal pipe and rebar axes and held at the same surface position without liftoff, as deviations from either of those parameters would reduce signal strength (explored in Sections 4.2.6 and 5.2.2, respectively). The collection of pipe and rebar
repeat-trial data are shown in Table 3.7, with the subsequent averages and standard errors stated.

Table 3.7: Slope and intercept values of Pipe A at 0° and the 1” Rebar Sample, without liftoff. Temperature was noted as constant across every measurement at 19°C. Measurements were taken bi-weekly over 3-month period.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Pipe - Pipe A</th>
<th></th>
<th>Rebar - 1” Sample</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope (log(V)/s)</td>
<td>Intercept (log(V))</td>
<td>Slope (log(V)/s)</td>
<td>Intercept (log(V))</td>
</tr>
<tr>
<td>1</td>
<td>-28.04</td>
<td>-2.55</td>
<td>-33.97</td>
<td>-1.68</td>
</tr>
<tr>
<td>2</td>
<td>-28.01</td>
<td>-2.55</td>
<td>-33.61</td>
<td>-1.69</td>
</tr>
<tr>
<td>3</td>
<td>-27.81</td>
<td>-2.53</td>
<td>-33.56</td>
<td>-1.71</td>
</tr>
<tr>
<td>4</td>
<td>-27.51</td>
<td>-2.57</td>
<td>-33.68</td>
<td>-1.69</td>
</tr>
<tr>
<td>5</td>
<td>-27.67</td>
<td>-2.55</td>
<td>-34.05</td>
<td>-1.64</td>
</tr>
<tr>
<td>6</td>
<td>-27.98</td>
<td>-2.55</td>
<td>-33.81</td>
<td>-1.69</td>
</tr>
<tr>
<td>Average</td>
<td>-27.8</td>
<td>-2.55</td>
<td>-33.78</td>
<td>-1.68</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.2</td>
<td>0.01</td>
<td>0.08</td>
<td>0.01</td>
</tr>
</tbody>
</table>

These results show that there is a good repeatability when the signal is above the noise level with a standard error of ±0.08 log(V)/s or ±0.24% (derived through the standard deviation of a mean equation [58]) for slope and ±0.01 log(V) for intercept, with rebar. It should be noted that pipe slopes seem to show more variance, ±0.72%, although are still relatively small. Differences in probe location on the rebar could have been a source of this variance, as the effective diameter can change by up to 2 mm depending on how much of the ribbed material is present. Variation in the pipe results is likely due to the more complex nature of eddy currents within a pipe that cause these fluctuations [30]. These variations will be added to the uncertainty of the fit when determining overall uncertainty. Equation (3.8) below shows a summation of systematic error of the pipe or rebar, \( \delta m_{\text{system}, p.r} \), and fitting errors, \( \delta m_{\text{fit}} \), used in calculating slope:
\[ \delta m_{\text{total}} = \delta m_{\text{fit}} + \delta m_{\text{system,pr.}} \]

(3.8)

It is important to note that other sources of variation are present in the characteristic properties of the samples examined within the manuscripts. Within the respective manuscripts of this thesis, these sources of variation are highlighted in the experimental procedure section, and include radii, thickness, and conductivity.
Chapter 4 – PULSED EDDY CURRENT GENERAL RESPONSE TO PIPES UNDER INSULATION (PIPE EVALUATION)

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4.1 ABSTRACT

Pipes are often made from metal and used in a wide range of industries. Nuclear, oil and gas, and the industrial sectors all use a system of pipes to transport fluids or gas. Industrial pipes often have a layer of insulation surrounding the outermost surface. Insulation prevents the environment from affecting the temperature of the transported liquid (when not desired) and often limits oxidation of the outer surface. This insulation may experience water ingress (or ingress of other corrosive solutions), resulting in corrosion occurring on the interface between the insulation and pipe wall. Ultrasonic testing can be used to determine the thickness of pipe wall but becomes ineffective when insulation is present. This paper highlights the efficacy of using pulsed eddy current (PEC) to determine the wall thickness of a pipe. The effect of changing values of wall thickness on PEC response is modeled to characterize extent of pipe wall corrosion. A loose-fitting inverse squared relationship is shown to arise when comparing long-time decay slope with thickness under the probe across a number of pipe samples. Considering an averaging window of ± 45° from the probe projected onto the pipe tightens the data to the model. It is expected that very small contributions come from the remaining pipe circumference, but the
majority of transient response is dependent on the quarter pipe closest to the probe. PEC response due to the introduction of liftoff is also explored to address varying insulation thickness under field inspection conditions. When comparing to the in-contact (zero liftoff) response, the long-time decay slope gets shallower with increased liftoff, simulating response to increasing wall thickness. The exception to this trend is only present at the thickest region of a non-concentric pipe where the slope steepens. The derived series of slope to thickness equations must be further developed for a specific liftoff as the slope values will change. Reported results demonstrate the potential for PEC to be used in the inspection of industrial piping.

4.2 RESULTS

The experiments performed on the six pipe sections can be separated into two categories: wall thickness variation and liftoff response. Ultimately, the goal of this research was to determine how effective a tool PEC is in detecting changes in wall thickness, which corresponds to onset of corrosion, at a distance away from the pipe surface (simulating insulation). Chapter 5 highlights the steps in determining the patterns in PEC response for changing liftoff and critical length, namely, isolating the two important parameters so the conclusions based on those patterns are attributed to that parameter. Analyzing the PEC response to changes in wall thickness (without liftoff present) is an integral first step to understanding the limitations of PEC in this application.

---

1 Introduction, theory, and experimental materials/methods can be found in Chapters 1.1, 2.2.3, and 3.2.
4.2.1 VARYING WALL THICKNESS RESPONSE

PEC response is often modeled as a series of exponential decays [20]. This thesis focuses on examining the long-time decay (material interaction) region and correlating changes in the log-linear region to variation in experimental parameters including wall thickness and liftoff. A square wave voltage is pulsed across the solenoidal drive coil, which produces a magnetic field. This magnetic field interacts with a magnetic material and eddy currents occur on the surface, diffusing into the bulk material, opposing the change in the magnetic field. Due to Lenz’s law [19], these eddy currents produce a magnetic field in opposition to the changes of the primary field and this subsequently interacts with the receive coil. To generalize the equations, the voltage response of the receive coil can be stated as [20]:

\[ V(t) = \sum A_n e^{-\frac{t}{\tau_n}}, \]  

(4.1)

where the subscript \( n \) denotes the different exponential decays and regions where (in general) later time decays can be examined experimentally. Note here that all long-time decay regions will be represented visually in raw data images by a red triangular region. When specifically examining the material dominant decay, the decay constant has the general form of [20]:

\[ \tau_D \sim \mu \sigma \ell_c^2, \]

(4.2)

where \( \ell_c \) represents a characteristic system length, \( \mu \) is the magnetic permeability and \( \sigma \) is the electrical conductivity of the material. If one were to consider a solid ferromagnetic rod this characteristic length would be the radius of the rod, as predicted by the model [1], where it is assumed that for hollow cylinders, the characteristic length is the wall thickness, \( W/T \), [59]. This presumed model is derived by following that for flat plate PEC response and analysis has the wall
thickness defined as the characteristic length[60]. As postulated in Section 2.2.4 this model may be lacking in complexity that properly describes the response. Specifically, there should be a dependence on pipe radius that this proposed model is without, not to mention that any circumferential variation in wall thickness will cause a change in spatial diffusion of eddy currents within the pipe. For the purposes of examining transient PEC responses to a simple model, the approximation of wall thickness being the characteristic length is assumed here. Considering only the long-time decay region in a semi-logarithmic plot formatting the equation to resemble that of a linear one (i.e., $y=mx+b$):

$$\log(V) = -\left(\frac{1}{C\mu\sigma W T^2}\right) t + \log(A).$$  \hspace{1cm} (4.3)

Research using a similarly structured model and experimental procedure of rebar showed that changing the characteristic length changed the slope (as per the definition), but altering the liftoff affected only the intercept (Section 5.2.2). Fitting a line to (4.3), a definition of the slope was isolated as:

$$m = -\left(\frac{1}{C\mu\sigma}\right) W T^{-2}$$  \hspace{1cm} (4.4)

The following two sections will examine if a direct relationship between slope magnitude and inverse wall thickness squared is accurate.
4.2.2 Wall Thickness: Pipes A – D

Initial steps in checking Equations (4.3) and (4.4) consisted of taking PEC measurements at each of the UT measured angular positions. The probe was moved to each angular location (every 22.5° around the circumference) at the middle of the pipe and a set of data was collected. After the data set is collected and saved, the probe is moved to the next angular location on the outer wall and held still while the subsequent data set is collected. The midway of the pipe is located at an \( \ell_{A-D} \) of 31 cm, and the probe is centered on this ring. Five UT thicknesses (two above, two below, and one central as seen in Figure 4.1) are averaged together to simulate the thickness of that one angular location. The thicknesses chosen in this average were selected as COMSOL models showed that in this orientation eddy currents will not travel very far longitudinally and thus the average of these 5 UT measured thicknesses represent the thickness directly beneath the probe.

Figure 4.1: Diagram of the averaging ring on Pipes A-D. Central point of probe is aligned with middle of the five UT measurement locations.
A sample set of data from Pipe A is shown below in Figure 4.2 and Figure 4.3 where the probe was in-contact with the surface of the pipe, at 0° to 158° and 180° to 338°, respectively. Recall that long-time decay is dictated visually by a red triangular region on the raw data sets below.

![Figure 4.2: Pipe A data from 0° to 158°. There is no liftoff present between probe and pipe. The red lines show the region that will be fit with a linear relationship. Note the tightly packed group of data sets.](image)

![Figure 4.3: Pipe A data from 180° to 338°. 2nd plot is used to help see more of the individual data sets. No liftoff present between probe and pipe.](image)
The remaining three pipe sections (B-D) also had the same sets of data collected, though not shown here. Using a Matlab curve fitting tool [61], a straight line was fit to the data along the region between the red lines. The collection of all slope magnitudes with angular position is shown in Figure 4.4 below.

![Figure 4.4: Slope values for each pipe at the given angular position. General trend of slope variation with WT can be seen. Nominal thicknesses for Pipes A-D are (8.8±0.3), (8.3±0.3), (7.7±0.3), and (7.0±0.4) mm, respectively.](image)

Locations of the maxima and minima in Figure 3.13 show the pairing of Pipes A/B and C/D regarding the intensity and transition between them. Figure 4.4 shows this same pairing of pipes but the variation of slope with angle is much smoother, as though averaging effects of wall thickness over a finite circumferential extent is taking place, which will be explored in greater detail later. The proposed PEC model, Equation (4.4) specifically, dictates that a large thickness results in a smaller slope (higher on the Y-axis in Figure 4.4), which can be understood from Equation (4.3). Patterns in increasing slope are similar between Pipes A and B, and Pipes C and D, which is attributed to similar intensity of semi-localized peaks as seen in the collection of
thicknesses over the same Y-axis (Figure 3.13). Specifically, the pairings of wall thickness variations in Pipes A and B, and Pipes C and D, are also shared in PEC distributions.

These two plots provide an example of how PEC response on pipes reflect a semi-localized sensitivity. This sensitivity is explored further in the next section and is effectively the most significant result of this entire thesis. Fitting the slope values as an inverse squared function of relative thickness shows a general fitting trend but with increased scatter. The inverse squared model, Equation (4.5), is likely too basic, as varying wall thickness in the presence of curvature likely affects the relationship.

![Graph showing slope values vs. wall thickness with fitting trend and error lines.](image)

Figure 4.5: Collection of slope values when compared to the averaged (5 under probe UT locations, pictured in Figure 4.1) wall thickness. Follows general inverse square relationship. The error line represent 2σ of the fitting error. Pipes A-D are data sets going from right to left.

\[
m = -906 \times WT^{-2} - 15.9 \tag{4.5}
\]

Finally, using this same relationship, it might be beneficial to look at the same plot but from a set of four averaged thicknesses and slope values (one data point for each pipe section).
The thinking here is that although it is evident that the PEC response is affected by circumferential variations in the wall thickness, better agreement may be obtained if all UT and slope values, separately, are averaged together. It is evident that this PEC probe is sensitive to both general and partial-circumference corrosion (wall thicknesses changing circumferentially), as Figure 4.5 shows that PEC response can detect changes in overall circumferential wall thickness in a given pipe section and Figure 4.6 shows that PEC can detect large changes in the overall wall thickness across the pipe sections.

![Graph](image)

Figure 4.6: Average slope as a function of wall thickness averaged over 16 measurements. Standard deviation is represented by error bars. WT averaging over 20 cm length by 360° circumference. Pipes A-D can be identified from right to left.

4.2.3 WALL THICKNESS: PIPES E AND F

The previous section began to explore PEC sensitivity to semi-localized wall thickness variation and this section will expand on this investigation. Pipes E and F provide an exaggerated variation of wall thicknesses, whereas the distribution seen on Pipes A through D fall within the industry standards [52]. As previously mentioned, Pipes E and F are non-concentric pipes, with the thinnest location denoting the starting angular position, 0°. This gradual changing of wall
thickness simulates material loss on one side of a pipe (generally the lower side for horizontal pipes) and the subsequent PEC trends present a more pronounced effect of PEC response to semi-localized pipe corrosion. Recall that Pipe E is the radially larger pipe section with machined defects at the thickest section. Following a similar process as above, examining the long-time decay, the semi-logarithmic slope can be fit with and compared to an averaged thickness for Pipes E and F. Figure 4.7 and Figure 4.8 show the raw data collected, split into two plots, to show the symmetry in response around the circumference of the pipe.

Figure 4.7: Pipe E raw data from 0° to just before the thickest point and 158°. Thinner material results in steeper slopes. Region between red lines indicates where the slopes were fit.
Figure 4.8: Pipe E PEC response of the angular positions $180^\circ$ to $338^\circ$. Similar distribution seen here when compared to Figure 4.7 due to symmetry.

Distribution of lines are symmetric between the two paths from thin to thick pipe wall, which agrees with the expected result when considering Figure 3.15, as the thickness (and distribution of nearby thicknesses) at each location is almost mirrored about $180^\circ$. Looking at how the slopes change at each position highlights the difference between localized pits and partial-circumference corrosion response. If PEC is very sensitive to large, localized pits, then the slope values at $158^\circ$, $180^\circ$, and $203^\circ$ will be reduced, showing a similar trend as the estimated orange data set in Figure 3.15.
Figure 4.9: Distribution of slope values on Pipe E with probe in contact with surface. Secondary axis represents the averaged thickness directly under the probe (omitting defects). Thinner regions have higher uncertainty due to a combination of smaller data sets (closer to the corner of red lines in raw data figures) and slight introduction of noise floor oscillations (blue/yellow data set in Figure 4.8).

The central three positions mentioned above exhibit negligible movement towards thinner response. Considering the machined defects are rather pronounced and would be cause for concern under field inspection conditions, it suggests that PEC with this probe configuration is ineffective at detecting localized corrosion. Keep in mind that these modeled pits have already dug through over half of the pipes wall thickness at that location and is not being recognized in detection. Pits often grow very quickly, so early detection is imperative in mitigating the progression. PEC’s lack of ability to detect such a large, but localized, volumetric loss also suggests that signal response must be dependent not only on the region beneath the probe but the neighbouring material, as well. Specifically, it is likely that a weighted average of angular position thicknesses, since if the material directly under the probe is the only one contributing to the response, then a very distinct localized corrosion effect would be observed. This can be explained through FEM analysis done by Fu et al. [30], where it was shown that at long-times (like those
considered by this analysis) some of the eddy currents can travel the entire circumference of the pipe. Paralleling Section 4.2.2, the next step relates the central averaged thickness at each angular position to the relative slope magnitude with the goal being to fit an inverse squared relationship. Even though the localized thickness is not the sole contribution to PEC response, this will help determine if there is some weighted averaging that could be developed. Collecting the long-time decay slope values from Pipe E and plotting them against the pipe wall thickness under the probe and fitting an inverse square model using Matlab, results in Figure 4.10 and best fit Equation (4.6).

\[ m = -236WT^{-2} - 17.1, \]  

(4.6)

Where \( m \) is the slope and \( WT \) is the wall thickness in mm. Looking at both Figure 4.10 and Equation (4.6) there are two things evident: i) The data has a large scatter relative to the fitted relationship similar to the results of Pipes A-D, which further implies a more complex weighting for thicknesses ii) the coefficient in front of the \( WT^{-2} \) is significantly smaller than the coefficient
for Pipes A-D, Equation (4.5) (approximately three times smaller), but this may be due to changes in radius [30] (as Pipe E radius is larger than Pipes A-D), conductivity, and permeability ($\tau \sim \mu \sigma W T^2$). Pipe F now needs to be analyzed in a similar manner to determine if these two trends are observed again.

It is important to recall that Pipe F does not have any machined defects and therefore, this is not a factor in this analysis. The next three figures highlight the three plot styles outlined above. Any relative information on these plots can be found in the respective captions.

Figure 4.11: Raw data for Pipe F for one direction from thinnest to thickest points. Angles 180° to 338° can be seen in Figure A2.1, and as expected mirrors this behaviour.
Figure 4.12: Pipe F slope distribution over angular position. Resembles a normal distribution due to the nature of the thickness distribution and is mirrored about 180°. The secondary Y-axis is the average thickness directly under the probe.

Figure 4.13: Pipe F inverse squared fit to Equation (4.7). Good agreement compared to Pipe E and wall thickness could not be determined with certainty.

The collection of data is fitted to an inverse square model through Matlab and is represented by Equation (4.7).

\[ m = -544WT^{-2} - 16.6, \]  

(4.7)

where \( m \) is the slope and \( WT \) is the pipe wall thickness in mm. Pipe F data shows a significant agreement to the proposed inverse square when compared to Pipe E. Data points at 0° and 338°
still suggest that probe response is still dependent on nearby thicknesses as well. This agreement is likely a biproduct of the smooth thickness transition between 0° and 180°, explained in Section 4.2.5. As mentioned previously, these models do not consider changing pipe radius within the function or the movement of eddy currents around the circumference.

4.2.4 Wall Thickness: Investigation of Deconvolution

The prior two sections explored PEC response with changing wall thickness, that is the sensitivity to semi-localized thicknesses. A COMSOL® model of a pipe paired with a co-axial solenoid probe was developed and the eddy currents through the surface were observed [30]. At early times (effectively the initial decay, or the probe-dependent decay as described in Section 2.2.1), the eddy currents are localized in the region under the probe and disperse circumferentially as time passes. In fact, some eddy currents are shown to travel the entire circumference, which is the basis for assuming that thickness contributions come from the entire ring [30]. This section discusses the attempts made to perform a seventeen-equation deconvolution to determine the percent contributions of portions of the ring. To start, the sixteen equations must be set up with the expected relationship, Equation (4.4) between wall thickness and slope, present. Figure 4.14 shows the general layout with letters A_d-P_d representing the respective fixed locations relative to the probe. Independent of where the probe is located A_d is always located beneath it. The main assumption of coefficient behaviour is stated in Equation (4.10), with a separate model including additional assumptions shown in Equations (4.11) and (4.12). In Figure 4.14, the probe is located at 0°, but this position pertains to only one of the sixteen equations derived from position (the remaining one is a boundary condition) so a moving reference point is needed.
These coefficients are paired with respective WT values beneath the probe on the pipe and all coefficients together total a value of 1. Recalling that, in a generalized format, the trends seen so far in Sections 4.2.2 and 4.2.3 can be represented as:

\[ m = \frac{const}{\mu \sigma} \times WT^{-2} + \text{vertical shift}, \]  

(4.8)

the equation derived from the map shown in Figure 4.14, with subscript angles rounded to next largest whole degree, results in:

\[ A_dWT_0^{-2} + B_dWT_{23}^{-2} + \cdots P_dWT_{337}^{-2} = Q_d m_0 + R_d. \]  

(4.9)

For this one equation, there are eighteen unknowns, with \( Q_d \sim \frac{\mu \sigma}{const} \) obtained from Equations (4.5), (4.6), and (4.7) for Pipes A-D, E, and F, respectively. This leaves 17 unknowns, with 16 of those (the first 16 letters) adding to a value of 1:
\[ A_d + B_d + C_d + D_d + \cdots + M_d + N_d + O_d + P_d = 1.00, \quad (4.10) \]

and the remaining letter representing the vertical shift (also have a starting value from those prior equations). In the simplest of cases where wall thickness is identical and has no variation around the entire circumference (effectively Pipes A-D), assuming an even distribution of eddy currents in either \( \phi \)-direction due to symmetry:

\[ B_d = P_d, C_d = O_d, D_d = N_d, \rightarrow H_d = J_d, \quad (4.11) \]

\[ A_d > B_d > C_d > D_d > E_d \ldots > I_d. \quad (4.12) \]

This assumption also results in a simplified Equation (4.9), which will change the number of unknowns to 10 with the same number of equations:

\[ A_d WT_0^{-2} + B_d (WT_{23}^{-2} + WT_{338}^{-2}) + \cdots + H_d (WT_{158}^{-2} + WT_{203}^{-2}) + I_d WT_{180}^{-2} = Q_d * m_0. \quad (4.13) \]

There are two approaches being pursued, with the initial set of equations representing the generalized system and the latter assuming symmetrical contributions. It was postulated that the \( WT \) values across Pipes A-D are too alike to provide a distinct solution. The approach then focused on Pipes E and F, where the \( WT \) change was far more drastic. It stands to reason, however, that eddy currents might not evenly travel through the pipe as thinner regions decay quicker and therefore, do not contribute the same amount. For this reason, the initial approach was utilized, and due to the matrix-like system of equations, a Matlab script was written to solve for the unknowns. This attempt was unsuccessful due in large part to a lack of complex coding prowess, along with \( WT \) values still being too similar. Advanced coding experts or COMSOL users could take this approach and possibly quantitatively determine the discrete thickness
contributions, as they are yet undetermined. The unsuccessful attempt may also be due to the fact that this averaged thickness model largely ignores that eddy currents within the pipe diffuse at different rates based on the wall thickness.

4.2.5 Wall Thickness: Windowing Results to Determine Probe Sensitivity

A simpler approach to discerning wall thickness contributions was conducted after the ambitious deconvolution attempt. The assumption was made that there is an angular window, acting as the probe footprint, which is larger than just the region beneath the probe, with the remaining circumference contributing a minimal amount. An even weighting of thicknesses within the window allows for a simplistic approximation and averaging. All windowing will be defined as $\pm \phi$ from the probe position, ranging from $0^\circ$ to $135^\circ$. This is illustrated in Figure 4.15, with a top-down view of the pipe ring showing the averaging window relative to the probe location.

![Figure 4.15: Definition of averaging window. The red line represents a window of $0^\circ$ with each subsequent widening increasing the overall number of UT measured thicknesses that are averaged together, i.e., the purple window ($\pm 67.5^\circ$) will average all thicknesses from the purple, blue, green, and red regions together for a new perceived thickness.](image-url)
This windowing process is done manually through Excel by increasing the averaging pool of thicknesses for a given window size to include all of the thickness values recorded within the window limits. To examine these window sizes and determine which size described the system the most accurately, the slope of the PEC response at every angular location on Pipes A-D were compared directly to the subsequent new perceived thicknesses for each iteration of different window size. These collections of slope values as a function of perceived thicknesses can be seen below in Figure 4.16 with each quadrant representing a different window size. As the window is increased, due to the nature of uniform averaging, the perceived thicknesses are shown to become more vertical on a slope versus perceived thickness plot. At some window size, the benefits of averaging the thicknesses and bringing the data points closer to the inverse squared relationship is outweighed by making the data too vertical. This is illustrated best by Figure 4.16, where the top left quadrant represents the un-windowed data (±0°) (previously seen as Figure 4.5), with remaining three quadrants increasing the windowing by 45° each time, as denoted by the large lettering representing the window size in degrees. The top right quadrant (±45°) is a perceived thickness of the quarter-pipe circumference closest to the probe, with bottom left (±90°) averaging half of the pipe, and remaining quadrant (±135°) averaging three-quarters of the pipe.
A window of ±45°, top right quadrant, was chosen as the ideal probe window as the fitting errors were effectively minimized, while not introducing too much verticality to the data sets. The verticality is a result of the average wall thickness no longer changing. As the window becomes larger, the overall average of the pipe wall is approached. Pipes A and B show the best grouping to the trend line where Pipes C and D still experience some scattering.

![Figure 4.16: Collection of Pipes A-D slope values with the given perceived thickness. Averaging windows of ±0° (top left), ±45° (top right), ±90° (bottom left), and ±135° (bottom right) are all present. Standard deviation of inverse-square fits are tighter with windowing, though plots become more vertical as windowing increases. Remaining three intermediary window sizes are shown in Figure A3.1.](image)

Minimizing the fitting errors was performed by taking the absolute difference between maximum fit and Equation (4.14), and plotting these differences as a function of the window size. Assuming the generalized relationship between thickness and slope, being:

\[ m = \text{Coefficient}_1WT^{-2} + \text{Coefficient}_2, \]  

(4.14)
and plotting the fitted error value of these coefficients as a function of window size, the minimum error is easily discernible as shown in Figure 4.17.

![Figure 4.17: Pipe A-D fitting error sizes for the two fitting coefficients of Equation (4.14) as a function of fitting window size. Any data point right of the red line is effectively minimized, as any variation in error size is minimal. This minimized region likely increases after 135° as data sets are near vertical, representing no further variation in WT.](image)

Essentially, the probe used in this experiment is sensitive to the quarter pipe closest to the probe location. In reality, and as suggested in Section 4.2.4, the real thickness contributions are likely not evenly weighted over this quarter pipe. The even-weighted window provides the closest set of data to the expected inverse-square relationship, at least without a fully developed percent contribution that was attempted in the deconvolution calculation.

A similar analysis on Pipes E and F was separately examined with the larger windowing causing drastically larger error bounds, as shown in Figure 4.18 and Figure 4.19. This is due to the non-concentric wall thicknesses and implies again that an evenly weighted average within the window is not entirely correct, though it can still be an effective simplification. Windowing of ±45° on both non-concentric pipes also works well in having the fitting error be at the minimum
(before more significantly increasing). The data still does not directly agree with the inverse-square fit but is closer to the expected relationship than the un-windowed response.

Figure 4.18: Pipe E windowing results at 45° intervals starting from zero windowing. ±45° provides a good windowing and shifting of the data points, with ±90° and ±135° providing an increase in fitting error. Fitting errors represent 2σ. Remaining three intermediary window sizes are shown in Figure A3.2.

Figure 4.19: Pipe F windowing results at 45° intervals starting from no windowing. ±45° also provides a decent windowing of the data, even though data seems to lie on either side of the fitted relationship. Fitting errors of any window after ±45° are too large to justify the windowing. Remaining three intermediary window sizes are shown in Figure A3.3.
Figure 4.20: Fitting coefficient errors as a function of window angle for Pipes E and F. Red line at 45° represents the largest window before fitting errors increase.

The probe responds to average WT over a 45° window across all six pipes, seemingly independent of pipe radius for the small range of pipe radii studied here. This window size provided the best averaging size to bring data sets across all 6 pipes closest to the proposed model. This is explicitly clear by comparing Figure 4.17 and Figure 4.20 and seeing that a ±45° window has the smallest coefficient error without introducing significant verticality. Windowing is a vital step in observing a truer relationship between simulated wall thickness and the transient response long-time decay constant. The even weighting within the window is likely not an exact description of eddy current interaction within the material and needs to be developed past this initial examination. A summary of the three new fitting relationships with a ±45° window, updating the relationships in Equations (4.5), (4.6), and (4.7) for Pipes A-D, E, and F, respectively are given as:

\[ m = -1043WT^{-2} - 13.8 \]  \hspace{1cm} (4.15)

\[ m = -381WT^{-2} - 14.0 \]  \hspace{1cm} (4.16)
4.2.6 INTRODUCTION OF LIFTOFF

Now that an understanding of PEC response to varying WT has been explored, it is imperative to explore the effect of introducing liftoff into this system as it addresses real field inspection conditions. Liftoff, as stated throughout this thesis, is defined as the closest distance between outer surfaces of probe and pipe. All prior raw data was taken with a liftoff of 0 mm, where the probe was in direct contact with the pipes. Liftoff is a necessary component to examine as the overriding goal of this research is to monitor or locate the presence of corrosion in pipes covered with insulation. As previously mentioned, non-magnetic and non-conducting materials (i.e., insulation, concrete, plastic, etc.) do not affect the transient response as presented. Subsequently, this liftoff or insulation thickness is studied experimentally as a variation in the air gap between probe and pipe.

In this study, all pipe sections have liftoff measurements taken at the same values of liftoff. Spacers of varying thickness were alternatingly stacked to achieve a consistent set of liftoffs. Understanding how changing the liftoff value affects response is vital as recommended insulation thickness may vary from ~25 mm to 75 mm (1” to 3”), depending on the application [36]. The following two sections look at the trends seen in Pipes A-D and then Pipes E and F, respectively. In a general sense, Section 4.2.7 presents the “guidelines” for measurements at liftoff from pipes, whereas Section 4.2.8 presents an exception to these guidelines.

4.2.7 LIFTOFF: PIPES A – D

Since PEC inspection is looking for the presence of full-circumference corrosion, a comparison of the thickest and thinnest regions of Pipes A-D is sufficient as these will, in theory,
show the effect of greatest wall thickness variation. For Pipes A and B, these were at 270° and 180°, respectively, with 90° and 293° representing these locations in Pipes C and D. The distribution and intensity of peaks and valleys was different in the two groupings (as previously mentioned). Eleven liftoff values, from 0 mm to 70 mm were examined and an intriguing effect emerged that was independent of minimum or maximum wall thickness locations.

Figure 4.21: Pipe A raw liftoff data at minimum (270°). Data sets seem to become shallower in magnitude as liftoff increases. The legend entries label the increasing liftoff due to the spacers. This image, along with all 7 other raw data sets from Pipes A and B and Pipes C and D (at the minimum and maximum of each) are found in Figure A4.1 and Figure A4.2, respectively.

The raw liftoff data of Pipe A’s minimum location shows a visible trend to a more gradual slope when compared to the steepness of the initial and final liftoff regions. This pattern is also present at the maximum WT location on Pipe A (though not shown here). Discussed in greater detail in the discussion, this trend to a higher slope value implies a widening of the effective window the probe is sensitive to. Specifically, at larger liftoffs, more of the material is being interacted with. Illustrations explaining this phenomenon are provided in Section 4.2.8 as non-concentric pipes provide a clearer demonstration of this effect (while also showing the exception
to this rule). Ensuring that this behaviour was the same across the four pipes, Figure 4.22 shows the slope values of Pipes A – D as liftoff increases. The trend towards a perception of thicker material, as indicated by a shallower slope, is present in all four pipes at both maxima and minima. In Pipe C and D, the ‘max’ and ‘min’ initial data point are reversed to what would be associated with those definitions. This is directly attributed to comparing the 90° (min) and 293° (max) locations in Figure 3.13 and Figure 4.4 and noting that the extreme thickness locales do not directly correlate to slope maxima or minima.

Figure 4.22: Collection of slope values for Pipes A-D (denoted by letter at top left of each quadrant). Independent of whether the ‘max’ or ‘min’ data sets are above the other, a trend with increasing liftoff towards that which would be seen for thicker material is seen throughout.

All four quadrants in the above image have the same Y-axis scaling, which helps illustrate the relative increase in slope values across all sections. The pairings of Pipe A/B and C/D, seperately followed similar patterns, as expected, due to their thickness distributions between
each pair (Figure 4.4). In total, all locations and pipe sections exhibit a seeming increase in WT as liftoff increases which can be explained as increasing window size with liftoff. Summarizing Figure 4.22, Table 4.1 examines the total change for each of the eight data sets, both numerically (in log(V)/s) and as a percentage. Maximum WT locations increased slightly less than minimum locations on average, though within error both regions exhibited increased slope steepness by approximately 25%. This is consistent with the suggestion that more magnetic field lines are interacting with more material and spread further around the circumference as liftoff increases.

Table 4.1: Summary of Figure 4.22 change in slope values. Left two columns of data are for maximum locales, and right two columns of data represent the minimum locales. Within error, both locations increased in magnitude by approximately 25%.

<table>
<thead>
<tr>
<th>Pipes</th>
<th>Max Change</th>
<th>Min Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># (log(V)/s)</td>
<td>%</td>
</tr>
<tr>
<td>A</td>
<td>4.45</td>
<td>20.8</td>
</tr>
<tr>
<td>B</td>
<td>5.44</td>
<td>25.7</td>
</tr>
<tr>
<td>C</td>
<td>6.33</td>
<td>24.2</td>
</tr>
<tr>
<td>D</td>
<td>6.00</td>
<td>21.3</td>
</tr>
<tr>
<td>Avg</td>
<td>5.56</td>
<td>23.0</td>
</tr>
<tr>
<td>St. Dev</td>
<td>0.82</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Intercept values can also be fit to an exponential decay as the lines are being shifted vertically downward (while also changing in slope) as shown in Figure 4.23. Following the general format of an exponential decay (as a function of liftoff):

\[
\text{Intercept} = A_f \cdot e^{-\frac{LO}{C_f}} + D_f, \tag{4.18}
\]

where \(A_f, C_f,\) and \(D_f\) represent the fitting parameters of this relationship. Using the long-time decay region highlighted in Figure 4.22, and plotting the intercepts as a function of liftoff results in an exponential decay across all pipes. Shown below in Figure 4.23 are Pipes A-D fitted
intercepts at both maxima and minima location. Both sets of maximum and minimum intercepts were pooled together for the fitted relationship as the values were tightly clustered together, with the following Equations (4.19)-(4.22) representing the fitted exponential decays of Pipes A-D, respectively.

\[
Intercept = 1.71 \times e^{-\frac{LO}{62}} - 4.45, \tag{4.19}
\]

\[
Intercept = 1.74 \times e^{-\frac{LO}{57}} - 4.39, \tag{4.20}
\]

\[
Intercept = 1.75 \times e^{-\frac{LO}{55}} - 3.80, \tag{4.21}
\]

\[
Intercept = 1.78 \times e^{-\frac{LO}{56}} - 4.18, \tag{4.22}
\]

4.2.8 LIFTOFF: PIPES E AND F

Increases in the liftoff of PEC response have demonstrated an effective simulated increase in WT for pipes exhibiting full-circumference corrosion, independent of the natural fluctuation of

Figure 4.23: Pipe A-D (as denoted by labels in the respective quadrants) intercepts of the long-time decay as a function of liftoff. Each pipe experienced exponential decay in the intercept value as liftoff increased.
WT circumferentially. Knowing that the PEC probe is sensitive to partial-circumference corrosion, the next step is to examine PEC liftoff response for the two non-concentric pipe sections. Unlike in Section 4.2.7, data sets (utilizing the same liftoff values) were taken at the minimum, maximum, and mirrored transition locations: 0°, 180°, 90°, and 270°, respectively. Comparing the change of the long-time decay slope at each angular location to the wall thickness variation will provide an exception to the guideline (shallower slope as liftoff increases). Recall briefly that the 0° position corresponds to the thinnest point, and subsequently 180° corresponds to the thickest.

Raw data from Pipe E at the thinnest and thickest positions is shown below in Figure 4.24 and Figure 4.25, respectively, to contrast the extremes. The long-time decay at the 0° position is close to full noise saturation at maximum liftoff seen in the bottom most data set in Figure 4.24. In actuality, the signal response is limited by some un-tested maximum liftoff, where the long-time decay is contained within the noise floor (1E-5 V). For the sake of all data presented within this manuscript, the project specifications of PEC response of liftoff up to ~70 mm was effectively reached, and thus further liftoffs were not considered.
Figure 4.24: Pipe E, 0° minimum WT liftoff data set. Region in the red triangle is the long-time decay.

Figure 4.25: Pipe E, 180° maximum WT liftoff data set. Region in the red triangle is the long-time decay.

The slopes obtained at all four locations are shown in Figure 4.26. It is evident that the slope is getting shallower at 0°, 90°, and 270°, which is similar to the behaviour previously seen for Pipes A-D. Departing from this trend, the thickest location (180°) shows the slopes getting steeper, simulating a diminishing WT response.

Figure 4.26: Collection of slope values every 90° for Pipe E. 0° (blue), 90° (orange), and 270° (yellow) all exhibit a similar behaviour as previously seen from other pipe sections. At the angle where pipe wall is thickest, 180° (grey), slope values decrease as liftoff increases.
The thinnest and the two transitional wall thickness sections behave as expected (even with 90° and 270° slopes moving in tandem), but the 180° section shows an opposite effect and decreases. Though initially surprising, this one set of data may provide the most effective way to monitor corrosion with PEC. Before this application is explored in Section 4.3, this phenomenon must be replicated with Pipe F, another example of partial-circumference corrosion. Figure 4.27 shows the collection of slopes at each of the four locations on Pipe F, with Figure A5.1 and Figure A5.2 showing the raw data at 0° and 180° for Pipe F.

![Figure 4.27](image)

Figure 4.27: Collection of slope values every 90° for Pipe F. 0° (blue), 90° (orange), and 270° (yellow) all exhibit a similar behaviour as previously seen in Pipes A-D. 180° (grey) slope values decrease as liftoff increases.

The thickest location, once again, exhibits a behaviour that would be interpreted as a removal of material. Considering the proposed weighted averaging of WT contributions and examining the magnetic field lines provides a potential explanation for this phenomenon. At zero liftoff (in-contact), the majority of contributions are likely to come from the regions closest to the probe with this region spreading circumferentially as liftoff is increased (thus averaging more of the pipe wall not directly beneath the probe). Figure 4.28, Figure 4.29, and Figure 4.30 show
visual representations of the proposed mechanisms at three of the locations (since 90° and 270° have very similar trends).

Figure 4.28: Modeled liftoff trends of Pipe F at 0°. Thin green line highlights new effective thickness contribution region. Simulates a trend toward thicker wall thicknesses as liftoff increases.

Figure 4.29: Modeled liftoff trends of Pipe F at 90° (similar trend at 270°). Thin green line highlights new effective thickness contribution region. Simulates a trend toward thicker wall thicknesses, but not as great an increase as at 0°.
Figure 4.30: Modeled liftoff trends of Pipe F at 180°. Thin green line highlights new effective thickness contribution region. Simulates a trend toward thinner wall thicknesses.

At 180°, results show the exception to the aforementioned guideline, namely that increasing the liftoff increases the averaging window and introduces more contributions from thinner locations on the pipe circumference. The general trend and exception also imply that there is some further intermediary position (between 90°-180°, and 180°-270°) where the slope remains constant with changing liftoff. Examining the slope changes of Pipe E and F as a function of angular position provides a visual inspection tool to determine this transitional location as shown in Figure 4.31 between angles 115° and 135°, and between 225° and 245°.

Figure 4.31: Pipe E slope values as a function of angular position. The different data sets represent the different liftoffs. The red lines represent the approximate transition location where slope remains (relatively) constant with liftoff. Transitions appear to be located between 115° and 135° (or 225° to 245°).

The same collection of data for Pipe F can be seen in the appendix, specifically as Figure A6.1.
4.3 Discussion

PEC transient response to pipes, both with the probe in contact with the pipe and also with liftoff exhibited a wide array of patterns and trends. Pipes A-D represent general outer diameter corrosion as the pipes each have the same inner radius and diminishing wall thicknesses. Pipes E and F are non-concentric pipes that simulate partial-circumference corrosion. Pipes provide a complex set of obstacles in analyzing PEC response, especially in comparison to rebar response (explored in Chapter 5, Chapter 6, and Chapter 7). Characterizing the pipes through UT mapping provides a detailed knowledge of wall thickness variations on each pipe. UT measurements were taken every 22.5° (for a full 360°) and every 50 mm down the length of each pipe. FEM has been used to show how the eddy currents disperse through the bulk material of a pipe [30]. Eddy currents are not isolated to the region directly beneath the pipe, but with a longitudinal probe orientation may travel the entire circumference of the pipes at long times [30]. This spread of eddy currents provides the basis for the majority of challenges present in using PEC as an inspection tool for pipe analysis.

Basic theory [14][16][21] suggests that when examining the long-time decay of the transient response, an inverse-square relationship between decay constant (slope, specifically) and wall thickness should be present. An average of 5 wall thicknesses directly beneath the probe (as illustrated in Figure 4.1) was initially compared to the fitted slope value of the PEC response at that location. Pipes A-D are grouped together in Figure 4.5, and while a general inverse-
squared trend is present, the data is scattered about the central fit. The scatter does not lend itself to accurately determining wall thickness from a transient response under field inspection conditions. Pipes E and F both share a similar result as with Pipes A-D (Figure 4.10 and Figure 4.13, respectively), where the general trend is present though not ideally tight to the fit. This loose-fitting trend, along with the FEM research conducted in [30], suggests that the probe is receiving contributions from locations in addition to those directly under the probe. It was assumed that the region closest to the probe contributes the largest percentage to the perceived thickness, with the diametrically opposite side contributing the least. Deconvolution of a set of 16 equations was attempted to discern the explicit percent contributions relative to probe location. This was ultimately unsuccessful but helped identify the need for a simpler solution.

Windowing is the process of averaging not only the five wall thicknesses beneath the probe, but also including the sets of thicknesses at the closest angular locations in both directions (in 22.5° increments on either side). The convention chosen in this thesis has the window sizes named by the $\pm \phi$ of one side of the window. For example, a $\pm 45^\circ$ window covers the $90^\circ$ circumference of the pipe (or quarter of the pipe) closest to the probe. Windows ranging from $0^\circ$ to $135^\circ$ were examined and two trends became apparent: i) Increasing the window reduces the fitting error up until some point and then fitting error increases, and ii) Data moves closer to the expected trend, but the data becomes nearly vertical for a given pipe as windowing increases. The verticality is explained by averaging wall thickness across nearly the entire circumference of the pipe, to the point where at each probe location, the perceived thickness is practically the same. The goal with windowing is to find the smallest window where data consistently looks
closer to the assumed inverse-square trend without increasing the fitting error. Figure 4.17 and Figure 4.20 illustrate the fitting coefficient errors of the inverse-square relationship of Pipes A-D and E-F, respectively. Whether modelling full-circumference corrosion (Pipes A-D) or partial-circumference corrosion (Pipes E and F), using a window of ±45° provides the closest example of the aforementioned goals. The even-weighting within this window is likely not an entirely correct assumption, since it does not include pipe radius, but the simplicity and results of this analysis partially validate the empirical windowing theory.

In addition to the successful demonstration of the windowing analysis, it is also important to note that the PEC probe was able to detect both general and partial-circumference corrosion. The non-concentric pipes, which simulated partial-circumference corrosion, had wall thicknesses changing from one side of the pipe to the diametrically opposite side (spanning 4.1 mm to 7.9 mm in Pipe E, and 6.1 mm to 9.2 mm in Pipe F) and was visibly affecting the PEC transient response. The four concentric pipe sections, simulating full-circumference corrosion, also notably had distinct and different PEC transient responses as the wall thickness circumferentially was reduced. Taking a small sample of measurements under field inspection conditions, however, might not result in the inspector determining the type of corrosion present. This is due to the natural fluctuation of pipe walls (12.5% under the nominal stated thickness) and the probe detecting even these small differences. Using the inverse-square models for Pipes A-D, E, and F, an approximate 10% wall thickness error estimate is possible when considering the 25% of the circumference closest to the probe. Changes in the wall thickness circumferentially (whether behaving like the natural three-lobe pattern, or a non-concentric loss of wall thickness) may not
be easily discernible if those changes fall under the industry standard of 12.5% error from the nominal thickness. Non-concentric wall thickness variations from thickest to thinnest regions of 30%-50% (Pipe F and E, respectively) are very evidently detectable from PEC transient response. The exact limit of which this non-concentric wall loss is not known, though anything under 12.5% may be considered muddled and lumped along with concentric wall loss. A direct method for discerning between the two corrosion types is important as both have different coefficients in the given inverse-square relationships as demonstrated in Section 4.2.7. All corrosion simulated in this chapter ignores crack propagation which may more significantly affect PEC transient response. As eddy-currents diffuse and travel circumferentially, severe cracks will limit the path of the currents thus resulting in, perhaps, a more defined window-edge. Specifically if the crack limits the flow of eddy currents (to nearly none passing that direction) and the probe is close enough to the crack, the effective averaging window may be skewed more in the angular direction away from the crack as the eddy-currents travel through the path of least resistance. This, of course, needs to be explored heavily in future work as cracks in pipe walls are also a serious threat to the industrial sector.

Introducing liftoff simulates the insulation that industrial pipes are often coated in, with exception to cladding which still needs to be examined in future work, and also provides the sought-after method mentioned. Holding the probe at the same angular position and increasing the distance from the surface of the pipe was how the insulation was modelled experimentally. PEC response with an air gap between the probe and the pipe acts the same as if there are non-magnetic and non-conducting materials between the probe and pipe. Research following a
similar process examining rebar response showed that introducing liftoff resulted in a stable and generally unchanging slope value (Section 5.2.2). Increasing liftoff with pipe directly affects the slope values, which is a consequence of the field spread and its interaction with more of the neighbouring pipe wall thickness variation as liftoff increases. At almost all locations examined with increasing liftoff across all six pipes, slope also increased. Since electrical conductivity and magnetic permeability can be taken as constants for a given pipe section, PEC field interactions shown in Figure 4.28 to Figure 4.30 suggest that the probe is interacting with more material, thereby affecting the critical length variable (see Equation (2.13)). This change in slope value follows what an increase in WT would produce but can be interpreted here as due to the widening of the effective sampling window of the probe. In order to effectively use the correct window size, the inspector must first know the insulation size at that location. This window widening also explains the one exception to the increasing slope, which only occurred at the thickest locations on Pipes E and F (180°). In essence, the widening window encapsulates more circumferential material but when the probe is located at the thickest location the further the material is from the probe, the thinner it appears as illustrated in Figure 4.28 to Figure 4.30. In addition, a location on the non-concentric pipes exists where increasing liftoff does not change the slope and Figure 4.31 highlights the two mirrored results. The exact amount by which the averaging window increases is not directly known yet as more liftoff data sets would have to be taken on those pipes to determine the change in resolution with liftoff. Increasing liftoff also shifts the intercept of the long-time decay downwards. In agreement with rebar PEC signal analysis in [3], intercepts decay exponentially as a function of liftoff across every location examined on each pipe.
Cladding is also a topic that was not covered in this investigation that may affect signal response. Cladding is a thin sheet of metal that is placed around the insulation layer to help prevent water ingress to the pipe surface. Initial thoughts of how this may affect the PEC transient response is that it may alter the early-time decay and knee (very slightly), though would decay off by the long-time decay window considered throughout this research. This thought would have to be examined in future work to validate the assumption, however.

4.4 CONCLUSION

Corrosion under insulation occurs on industrial pipes and is an important challenge for mitigating damage and monitoring pipe lifespan. Ultrasonic testing is effective at measuring the wall thickness of a pipe wall, but the insulation needs to be removed prior to inspection. PEC, while affected by changes in liftoff, can still be used to inspect pipe, although with lower resolution and sensitivity. PEC interacts solely with metallic objects and can effectively interact with objects at insulation thickness liftoffs. Three types of corrosion extent occur on pipes under insulation: i) localized, ii) semi-localized, and iii) general. Localized corrosion consists of pits and crevices, but the PEC probe oriented in the manner used in this report lacks the resolution to detect this. This is evidenced by the mechanically created pits on Pipe E, which seemingly did not affect the PEC response. Full-circumference corrosion occurs evenly across the entire circumference and was simulated by Pipes A-D. PEC response is able to distinctly detect the difference due to an evenly thinner wall. Partial-circumference corrosion is also directly detectable, although it may be hard to discern between general and partial-circumference corrosion with only a few measurements. For 0 mm liftoff, a wall thickness averaging window of ±45° from the probe location showed the best agreement between data and the expected
inverse-square relationship between long-time decay slope and thickness. Effectively the probe is sensitive to the quarter of the pipe closest to it. Introducing liftoff increases the slope magnitude, which could be interpreted as an increasing wall thickness. This occurs at every location except the thickest location on both non-concentric pipes. The slope trends downward at both those locations, which can be used as a method to differentiate between general and partial-circumference corrosion but would only work at the thickest section of a non-concentric pipe. This phenomenon is explained by the averaging window increasing as liftoff grows. PEC magnetic field lines are able to interact with more of the surface, thus averaging over a larger area of wall thicknesses. More work still needs to be done on determining exactly how much the window increases as a function of liftoff. A continued focus on determining the exact percent contributions within that window is also necessary as the even-weighted average is likely not an exact representation of the extended wall thickness contribution to the probe response. Ultimately, this thesis emphasizes the application of PEC as a fast-scanning tool in detecting corrosion under insulation of a pipe. While quantifiable wall thicknesses may not yet be determined as the data still does not completely follow empirical models, the general trends observed shows promise for PEC being an effective partial-circumference corrosion detection method for insulated pipe.
Chapter 5 — PULSED EDDY CURRENT RESPONSE TO CHANGES IN REBAR RADIUS AND SOLENOIDAL PROBE LIFTOFF\textsuperscript{2} [22]

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5.1 ABSTRACT

Corrosion of carbon steel rebar in concrete structures, such as highway bridges and buildings, has a direct impact on their structural integrity, since the rebar provides the tensile strength within the structure. Rebar strength depends on the remaining effective radius of a given rod. Long-time decay, up to 0.1 s, in the transient response of Pulsed Eddy Current (PEC), was examined as a potential method to quantify general corrosion in ferromagnetic rebar. The transient response of a coaxial solenoidal drive-receive coil pair, oriented parallel to the rebar axis, was analyzed over a range of distances into the concrete (liftoff) and for various rebar radii. At long times, the single exponential decay constant was largely independent of liftoff. A power law relationship for the characteristic decay time, consistent with long-time diffusion of electromagnetic fields into a rod, was observed. The intercept of a best-fit line to measured voltage decay, decreased exponentially with liftoff, and maintained a measurable response up to 110 mm distance for a 25 mm (1 in) diameter rebar. This exponential decay was present in 22

\textsuperscript{2} This title is altered from the published title (Ref. [22]) to better describe the findings within this chapter relative to subsequent chapters.
mm (7/8 in), 19 mm (3/4 in), and 15 mm (5/8 in) samples as well. Reported results demonstrate potential for PEC to quantify remaining cross-sectional area of rebar in concrete structures.

5.2 Results

5.2.1 Effect of Size Variation on Signal Response

The main factor examined in this paper is the effect of rebar radius on signal response. Figure 5.1 shows the long-time decay of the transient response obtained from the rebar samples with varying diameter at 0 mm liftoff. The linear voltage response over which slope is measured, and which is inversely proportional to \( r_D \) as shown in Equation (2.13), is indicated between the two straight lines. Above the upper straight line, voltage is attributed to additional decay times including probe characteristics [62]. The lower straight line (2E-5 V) is a conservative estimate of the noise floor, below which natural log-of-signal response is no longer linear with time. The observed trend is a decreasing slope with increasing rebar diameter, which agrees with Equation (2.13)

Figure 5.2 shows an inverse-square-power-law fit of slopes in Figure 5.1, multiplied by conductivity (see Equations (2.13) plotted as a function of rebar radius. Permeability is taken as a constant, as per the eddy current tests in Section 3.3.1. Error bars incorporate uncertainties in conductivity, radius and fitted slope.

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Chapters 5.2 and 5.3 (formerly the Introduction and Experimental Method) were removed from this published work as all relevant information was already stated within Chapters 1.1, 2.2.2, and 3.3.
Figure 5.1: Semi-log plot of transient response at long-time decay for varying rebar diameter. Slope of best fit is measured between thin straight lines.

Error in radius was larger for the larger rebar samples, due to the larger ribs found on the respective rods (see Table 3.4 columns minimum and maximum diameter). The fitted Equation slope, $m$, multiplied by conductivity, $\sigma$, to radius as obtained from Equation (2.13) is:

$$\sigma m = (-176.1 r^{-2} - 0.926) E 8$$

(5.1)
Figure 5.2: Slope of best line fit to data in Figure 5.1 multiplied by conductivity as a function of rebar radius. The solid curve is an inverse squared power law fit to the data

5.2.2 Effect of Liftoff on Signal Response

Rebar can be present at varying depths within a concrete wall. Typically, in order to avoid corrosion and mechanical failures, outermost rebar is placed between 12.7 mm and 76.2 mm within concrete for applications such as joists or concrete that is permanently exposed to the earth, respectively [63]. As the rebar is placed further from the probe, the signal response will diminish. This system limitation will prohibit the characterization of rebar at large liftoffs.

Figure 5.3 shows the semi-log plot of transient responses at long-time decay for 1” (25 mm diameter) rebar for various liftoff distances. Slope of the lines remains relatively constant up to 108 mm liftoff, beyond which signals fall below the noise floor as indicated by the horizontal straight line. The linear sections highlighted between the straight lines, were fit using Matlab and slopes were found to be similar with decreasing intercept values. As liftoff height increases signal response decreases and the range of useable data is reduced, as shown by the smaller amount of data between the lines in Figure 5.3.
Figure 5.4 shows intercepts of best-fit lines to data in Figure 5.3 as a function of liftoff, LO. Data was fit with exponential curve given by,

\[
\text{Intercept} = A_f \cdot e^{-\frac{LO}{C_f}} + D_f,
\]

where \(A_f, C_f\) and \(D_f\) are best-fit coefficients. The curve permits determination of distance of the probe to the rebar, independent of rebar diameter. Matlab curve fitting software [64] produced best fit coefficients as shown in Table 5.1.

For the 1” Sample, liftoff distances larger than 108 mm produced a signal with long-time decay saturated by the noise floor. The liftoff limit for rebar has also been reported elsewhere [4]. The 2/5” Sample was not included in this fit as introducing any liftoff resulted in long-time decay being entirely enveloped in the initial probe response, R/L region [60]. Decay constants, \(C\), in Table 5.1 tend to increase with decreasing rebar diameter, except for the 5/8” Sample, possibly due to its weaker signal.
Figure 5.4: Intercepts of best-fit lines from the 1”, 7/8”, 3/4”, and 5/8” samples as a function of liftoff. Solid curves are exponential fits to the data.

Table 5.1: Coefficients from best fit to exponential decay Equation (5.2) for various rebar sizes.4

<table>
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<th>$A_f$</th>
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<th>$D_f$</th>
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</thead>
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<tr>
<td>1”</td>
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</tr>
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</tr>
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</tr>
<tr>
<td>5/8”</td>
<td>1.57</td>
<td>58</td>
<td>-3.95</td>
</tr>
</tbody>
</table>

5.3 Discussion

The observed exponential decay of the signal response as the probe is lifted further from the rebar sample, is attributed to reduced coupling between probe and sample. All samples followed a similar exponential decay with liftoff. This supports the application of the empirical exponential fitting function used here, and as reported elsewhere for PEC liftoff response to flat plate [10].

---

4 Subscripts ‘f’ were added to the fitting constants to denote that they are derived from a Matlab fit.
It is also important to point out that while the Wwdensky solution [1] describes the transient response very well, there are assumptions in its derivation that are not strictly true in the experimental setup. The model assumes a uniform field, which is unlikely to be the case at small liftoff values. It is postulated here that the non-uniform field does not interfere with the inverse r² dependence described by Wwdensky’s solution [1].

The presented results demonstrate the potential application of PEC for independent determination of rebar diameter and its distance within concrete, with prospects of quantifying general corrosion of rebar in concrete. Remaining challenges for the technique’s implementation include, 1) increasing the range of detection by reducing the instrument’s noise floor, 2) taking account of conductivity and magnetic permeability variations, which cannot be easily discernable for concrete-imbedded rebar, 3) accounting for varying ridge sizes, which may affect signal response when ridges become large enough, 4) presence of rebar sections that pass orthogonally across target rebar and 5) potential interference by neighboring rebar. Neighbouring vertical rebar can have recommended gaps of between 4.5 cm and 6 cm, although this is not enforced [65].

With current probe design and system functionality, response to presence of rebar is limited to voltages greater than 1E-5 V. Investigating methods to lower the current noise floor would be most beneficial for detection of 1” rebar at liftoffs greater than 108 mm (4”).

These findings may be compared with results obtained by thermography using microwave excitation [66]. Thermographic images due to microwave heating show that rebar is detectable through concrete but lacks specific information of remaining rebar radius obtained here.
5.4 Conclusion

In this paper, PEC response to rebar using a coaxial solenoidal probe was investigated by varying different parameters that could change signal response in the field. The variation of long-time PEC voltage response demonstrated an exponential dependence with a diffusion time that varied as a squared power law with rebar radius, in agreement with the predicted long-time diffusion for fields into a solid rod.

Material-dependent diffusion time was largely independent of distance (liftoff) of the probe from the rebar up to 100 mm. The intercept of the linear response in semi-log space, varied exponentially with distance across all examined samples, permitting an independent liftoff determination to be made. These relationships could be further investigated for determining areas of general corrosion in concrete support structures, where water ingress and migration of corrosive elements may be prevalent. This investigation indicates a potential for using PEC to detect and quantify general corrosion of rebar in concrete structures.
Chapter 6 – PULSED EDDY CURRENT RESPONSE TO LIFTOFF LIMIT AS A PRODUCT OF REBAR RADIUS\(^5\) [68]

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6.1 ABSTRACT

Corrosion of carbon steel rebar in concrete structures, such as highway bridges and buildings, has a direct impact on their structural integrity, since the rebar provides the tensile strength within the structure. Rebar strength depends on the remaining effective cross-section of a given rod. Presence of water and migration of corrosive elements, such as chloride, may result in rebar corrosion with resulting loss of overall structural strength. In order to adequately quantify the cross-section of the ferromagnetic rod, it is necessary that the transient response is strong enough to be detected. In addition, rebar used in different applications will be placed at different depths from the outermost concrete wall. Examination of long-time decay, on four rebar samples of diameters ranging from 19 mm (0.75 in) to 57 mm (2.25 in), in the transient response of Pulsed Eddy Current (PEC) was examined as a potential method to quantify a maximum liftoff-to-size relationship. The transient response of a coaxial solenoidal drive-receive coil pair, oriented parallel to the rebar axis, was analyzed over a range of liftoffs (distance within the concrete) up to 150 mm. At long times a single exponential decay constant appeared as a

\(^5\) Title changed from published title (Ref. [68]) as to better describe findings within this chapter compared to other chapters.
constant slope, independent of liftoff in a semi-log plot. Intercept of a best-fit line to the measured voltage response in semi-log space, decreased exponentially with liftoff, and maintained a measurable response up to 85 mm, 110 mm, 125 mm, and 140 mm distances for rebar diameters of 18 mm (0.75 in), 25 mm (1 in), 38 mm (1.5 in), and 57 mm (2.25 in), respectively. Reported results demonstrate a power law dependence on rebar radius of limitations on signal analysis due to liftoff. This chapter shows the potential for PEC analysis to quantify the cross-sectional area of rebar in concrete structures up to size-dependent threshold depths.

6.2 Results

6.2.1 Liftoff Limits

PEC measurements were taken over a range of liftoffs for each rebar sample. Figure 6.1 shows the collection of data sets for the 2.25” Sample ranging from 0 mm and 155 mm. The red lines on the figure highlight the window for each data set that allowed adequate analysis.

Table 6.1: Important parameters of rods used in data acquisition. Conductivity, min and max diameters are included.

<table>
<thead>
<tr>
<th>Nominal Diameter</th>
<th>Minimum Diameter (mm)</th>
<th>Maximum Diameter (mm)</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25”</td>
<td>57.2</td>
<td>57.2</td>
<td>6.8x10^6</td>
</tr>
<tr>
<td>1.5”</td>
<td>38.1</td>
<td>38.1</td>
<td>6.9x10^6</td>
</tr>
<tr>
<td>1”</td>
<td>24.9</td>
<td>26.3</td>
<td>6.8x10^6</td>
</tr>
<tr>
<td>0.75”</td>
<td>18.6</td>
<td>20.4</td>
<td>6.7x10^6</td>
</tr>
</tbody>
</table>

6 Chapters 6.2 and 6.3 (formerly the Introduction and Experimental Method) have been removed from this published work as all relevant information was already stated in Chapters 1.2, 2.2.2, and 3.3 of this thesis.
Figure 6.1: PEC measurements for the 2.25” Sample at liftoffs ranging from 0 to 155 mm. The region between the red lines shows the temporal range over which long time decay can be confidently analyzed.

The slopes of those linear regions within the highlighted area remain consistent across all liftoff distances. When fitting the long-time decays, using the curve fitting tool in Matlab [64], the slopes can be compared and the liftoff at which significant variations appear is used to set maximum range of sensitivity. It should be noted going forward that the maximum liftoff is only an estimate (generally ± 4 mm) due to spacing between data points. The data shown in Figure 6.1 indicates that the probe is only sensitive to the 2.25” Sample up to 140 mm (5.5 in). Through analyzing the non-variance of these slopes, it was observed that the intercepts over the range of liftoffs follow an exponential decay of the form:

$$y = a \cdot \exp \left(-\frac{x}{b}\right) + c.$$  

This result was common across all four samples.
6.2.2 Liftoff Saturation vs. Radius

After performing the analysis above for all samples, the limits in signal response due to liftoff were identified as shown in Table 6.2. The errors in the table were a combination of the lack of resolution in liftoffs between data points and large fitting errors at the limit value. Radius errors are present due to the ridges on the rebar and caliper measurement errors. Figure 6.2 shows the liftoff-radius relationship of the data in Table 6.2. The fitted relationship of liftoff limit with radius follows a power law as given by:

\[
\text{Liftoff Limit} = -5600(r)\text{radius}^{-2} + 145
\] (6.2)

Table 6.2: Radius and liftoff limit with respective errors. This is graphically shown in Figure 6.2.

<table>
<thead>
<tr>
<th>( r ) (m)</th>
<th>( \delta r ) (mm)</th>
<th>LO Limit (mm)</th>
<th>( \delta \text{LO} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.6</td>
<td>0.5</td>
<td>141</td>
<td>4</td>
</tr>
<tr>
<td>19.1</td>
<td>0.5</td>
<td>126</td>
<td>4</td>
</tr>
<tr>
<td>12.7</td>
<td>1.0</td>
<td>108</td>
<td>3</td>
</tr>
<tr>
<td>9.5</td>
<td>0.7</td>
<td>84</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 6.2: Liftoff limits as a function of rebar radius. Red solid curve is best fit of the power law (6.2) to the data.
6.3 DISCUSSION

With the analysis system and probe used (100 mm long), the relative independence of liftoff on slope of the response implies that for a strong enough signal response (i.e., decay occurring over several milliseconds as shown in Figure 6.1) the size of the rebar can be determined. Any modification of the probe or circuitry used to perform the PEC measurements would alter (6.2). For example, if the noise floor were reduced by a full decade (< 1 µV), this would allow measurements at larger liftoffs. Increased probe length could also extend the field lines and thereby, the liftoff at which the probe is effective, but would reduce measurement resolution. This implies that the probe configuration be examined on a case-by-case basis to determine the limitations of the system being used for inspection. This analysis also highlights the potential need to modify the system or probe if investigation of rebar at a specified depth is required.

Future work should continue developing relationships with discrete probe characteristics and reduction of the noise floor.

6.4 CONCLUSION

In this paper, PEC response to rebar using a coaxial solenoidal probe was investigated by varying liftoff distances over rebar cylinders of different radii. The variation of liftoff demonstrated that the linear long-time PEC voltage response had an exponential decay with liftoff. The noise floor saturated the signal response and produced a limit where rebar of a particular radius could no longer be detected. The power law relationship between radius and liftoff limit identified the range of sensitivity for the system and the probe that was studied.
For future work, development of a lower noise floor and optimization of probe parameters for specific applications are recommended before in-field testing is carried out. This investigation demonstrates the potential for using PEC to detect and quantify general corrosion of rebar at the greatest possible liftoff, which is dependent on the rebar radius.
Chapter 7 – Effect of Orientation and Overlay on Pulsed Eddy Current Probe Response to Rebar

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7.1 Abstract

Carbon steel rebar is a structural support component embedded within concrete structures that provides tensile strength. Corrosion of rebar and the consequent loss of cross-sectional area, possible through water ingress and corrosive elements, decreases the effective rod strength. Detection of corrosion through non-destructive evaluation is an area of study focusing on mitigating risk of structural failure. Pulsed eddy current (PEC) response using a coaxial solenoidal drive-receive coil pair when varying rebar radius (modelled as the presence of corrosion) and liftoff (distance between concrete and rebar surfaces) has been studied. This work aims to further explore how the orientation of the PEC probe with respect to the rebar’s longitudinal axis changes the probe response. Rebar tends to be placed in a cross-hatched pattern (rods both parallel and perpendicular to the ground) within the concrete and the junctions where bars cross each other are also examined. Changing the angle (θ) between probe and rebar axes from parallel to perpendicular causes a downward shift in long-time decay voltages (with increasing angle up to 90°). Converting the probe angle to a liftoff (shortest distance from either end of the solenoid to the rebar surface), through use of \(\sin \theta\), shows a linear relationship
between the intercept and effective liftoff. At 90° a remnant signal is still present, providing minimum transient response sufficient for measurement. Junctions show a direct superposition of signals from the individual parallel and perpendicular rebar in the long-time transient decay signal. Together, these investigations highlight fundamental aspects necessary in describing the PEC transient response in the presence of rebar structures and further demonstrates the potential of characterizing rebar embedded in concrete using PEC measurements.

7.2 Results

The objective of the first part of the study is to determine the effect of varying angle, \( \theta \), between the probe and rebar longitudinal axis on the linear components (slope and intercept) of the long-time decay of the transient \( \log(\text{voltage}) \) response of the probe. As will be shown below, the maximum response to the rebar occurs when the probe and rebar are aligned (\( \theta = 0^\circ \)), which can be used by the inspector to determine the rebar orientation if it is not already known. Knowledge of how PEC response is affected by a 90° probe orientation is required for junction signal analysis. Each rebar is assumed to have constant conductivity and permeability over the entire sample (though they may differ from sample to sample). Any change in these parameters will affect slopes obtained from a fit of Equations (2.29) and (2.30) in the long-time decay. All fitting of long-time decay performed here uses Matlab and its \( \log() \) function on all voltage response (Y-axis) values [64]. Consequently, all intercept values that are collected will be negative.

---

7 Introduction, theory, and experimental methods used can be found in Chapters 1.3, 2.2.3, and 3.4.
7.2.1 Probe Angle Variation

If the probe is not parallel to the sample, then the signal strength will change. The signal response at different angles (θ) relative to the parallel orientation (Figure 3.19) was collected in order to quantify this relationship. It is expected that the slope magnitude will stay the same, as the radius of the bar does not change, but that the intercept of the long-time decay will decrease as θ approaches 90° as shown in Figure 7.1. This behaviour gives a similar response as that of the changes in liftoff (Section 5.2.2), although it is not identical. This may be viewed as the magnetic field lines having to travel further in air as the angle increases before they can interact with the rebar. Figure 7.1 shows the signal response at angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90° for the 3/4” Sample, while remaining in contact with the rebar (zero liftoff). The slopes in the region indicated in Figure 7.1 were analyzed. Table 7.1 shows the collection of slope and intercept values.

![Figure 7.1: Transient response of a 3/4" diameter rebar with varying probe angle. The region between the red lines was analyzed.](image-url)
Table 7.1: Collection of linear fit parameters between long-time decay response and stated range of angles.

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Slope (log(V)/s)</th>
<th>δSlope (log(V)/s)</th>
<th>Intercept (log(V))</th>
<th>δIntercept (log(V))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-35.3</td>
<td>0.3</td>
<td>-2.41</td>
<td>0.02</td>
</tr>
<tr>
<td>15</td>
<td>-35.1</td>
<td>0.4</td>
<td>-2.61</td>
<td>0.02</td>
</tr>
<tr>
<td>30</td>
<td>-36.1</td>
<td>0.7</td>
<td>-2.82</td>
<td>0.03</td>
</tr>
<tr>
<td>45</td>
<td>-36</td>
<td>1</td>
<td>-2.96</td>
<td>0.05</td>
</tr>
<tr>
<td>60</td>
<td>-34.5</td>
<td>0.9</td>
<td>-3.11</td>
<td>0.03</td>
</tr>
<tr>
<td>75</td>
<td>-33</td>
<td>1</td>
<td>-3.24</td>
<td>0.04</td>
</tr>
<tr>
<td>90</td>
<td>-36</td>
<td>2</td>
<td>-3.29</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The linear coefficients found from the long-time decay were consistent with increased decoupling of the field from the rebar at angles greater than 0°. Slope magnitude did not significantly change, while the intercept had a decrease in value. This behaviour is similar to a variation in liftoff with rebar (Figure 5.3 and Figure 5.4), where the intercept has an exponential dependence on angle. Converting the estimate of the change in coupling of the longitudinal probe with rotation is obtained by halving the length of the probe (L~100 mm) and multiplying it by sin(θ), which represents the shortest distance from either end of the solenoid to the rebar. This conversion is illustrated in Figure 7.2 with the conversion equation below that.
Effective Lift Off = \((L/2) \times \sin \theta\)  

(7.1)

where \(L = 100\) mm is the length of the probe coil. Performing this transformation, which effectively turns the angle into a lift off from probe tip to rebar surface, results in a plot relating the intercept with the lift off seen below. Figure 7.3 shows the intercept as function of the now transformed angle values (plotted as effective lift off).
The linear best fit is obtained as:

\[ \text{Intercept} = -0.017 \times \text{Effective Liftoff} - 2.39 \]  \hspace{1cm} (7.2)

While the actual magnetic field line interactions are more complicated than this simple geometric conversion, at the very least it suggests that similar phenomena to that of liftoff are occurring, as will be covered in the discussion. The 1” V1 sample has a similar linear response to that of the 3/4” Sample but on the scale of the intercept values shown in Figure 5.4 for the 1” Sample.

The similar transient response between liftoff and probe angle must be separated during in-field testing to effectively determine depth of rebar without contribution from angle. Rapid acquisition of data sets would allow for many measurements to be taken in succession until the strongest signal was obtained. For a vertical wall, it should be assumed that placing the longitudinal probe axis perpendicular to the floor will allow for a probe angle of 0°, but a series of small angle variations and analysis could confirm this assumption. The same concept could be applied to confirming that the probe is the closest distance possible to the rebar sample (lateral
position variations to test), as that will allow for the smallest liftoff and largest amplitude
response.

7.2.2 INSPECTION OF JUNCTION NODES

Rebar is often cross latticed within large structures in order to maximize tensile support. The probe response must be determined at these points so that they may be identified when they are encountered in an inspection. It was found that the combined signal could be described by superposition of the vertical and horizontal component signals at their respective liftoffs. Figure 3.20 and Figure 3.21 show the geometry of all six junctions, when considering two rebar of similar diameter and two rebar of differing diameter, respectively.

7.2.3 JUNCTIONS: ALIKE-DIAMETER ANALYSIS

The two probe orientations available in alike-diameter rebar, labelled Junctions A and B, each demonstrate superposition of the two individual rebar responses. The following two equations state the superposition relationship of each junction. Note the in-bracket variables define the probe orientation relative to the rebar axis and the respective liftoff. If liftoff is not shown, then it has a liftoff of 0 mm. It should also be noted that the early-time response, which primarily is the back emf of the probe and its immediate interaction with the rebar does not, in fact, superimpose, since at early times the signal response is primarily due to the probe and its immediate interaction with the rebar.

\[
\text{Signal}_A = \text{Signal}_{V1}(0^\circ) + \text{Signal}_{V2}(90^\circ, 25 \text{ mm}) \quad (7.3)
\]

\[
\text{Signal}_B = \text{Signal}_{V1}(90^\circ) + \text{Signal}_{V2}(0^\circ, 25 \text{ mm}) \quad (7.4)
\]

As shown in the prior section, the effects of a 90° probe angle without liftoff reduces the voltage response by just under 1 log(V) (Figure 7.1), while a liftoff of up to 1” (25.4 mm) only
reduces signal response by approximately 0.5 log(V) (Figure 5.3 [3]). This implies that no matter the orientation of the rebar, the signal response will be dominated by the sample the probe is parallel to, although the rebar not aligned with the probe needs to be considered. Figure 7.4 and Figure 7.5 show the two sample junction responses, along with the individual rebar responses. Those individual responses are then added together over the entire signal (although just the long-time decay superimposes) and plotted. Figure 7.4 represents Junction A, and Figure 7.5 represents Junction B. Junction B illustrates the most visually evident example of superposition as otherwise, the raw data is dominated by only one of the two rebar, effectively reverting Equation (2.33) to Equation (2.29).

Figure 7.4: Junction A signal. Superposition (yellow) of individual signals (orange and grey) lies directly over the raw data (blue). In this case, the raw data and the signal of the 1” V1 in-line without liftoff all overlap with the superposition.
The root-mean-square error (RMSE) for Junctions A or B, calculated using Equation (7.5), is collected in Table 7.2. Both junction superpositions agree within 0.05 log(V) of the raw junction data over the long-time decay.

$$RMSE = \sqrt{\frac{\sum(V_{\text{junction}} - V_{\text{superposition}})^2}{N_{\text{data}}}}$$  \hspace{1cm} (7.5)

Table 7.2: RMSE values for Junctions A and B. Both have an RMSE under 5%.

<table>
<thead>
<tr>
<th>Junction</th>
<th>RMSE (log(V))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.038</td>
</tr>
<tr>
<td>B</td>
<td>0.048</td>
</tr>
</tbody>
</table>

7.2.4 Junctions: Dissimilar-Diameter Analysis

Junctions C-F, as defined in Figure 3.21, cover the four geometrical possibilities when considering two rebar of different diameters. The main differences between these four junctions and the Junctions A or B are that these are dependent on which of the two bars are closer to the
probe. Following the idea of junctions representing the superposition of individual rebar response, another series of relationships are explored below:

\[
Signal_C = Signal_{V1}(0^\circ) + Signal_{3/4^\circ}(90^\circ, 25 \text{ mm})
\]
\[
Signal_D = Signal_{V1}(90^\circ) + Signal_{3/4^\circ}(0^\circ, 25 \text{ mm})
\]
\[
Signal_E = Signal_{3/4^\circ}(0^\circ) + Signal_{V1}(90^\circ, 19 \text{ mm})
\]
\[
Signal_F = Signal_{3/4^\circ}(90^\circ) + Signal_{V1}(0^\circ, 19 \text{ mm})
\]

where the subscripts represent the 1” (V1) Sample and the 3/4” Sample, corresponding to Junctions C, D, E and F, respectively. Three of these four junctions (C, E, and F) are dominated by one of the individual signals, mainly the signal of the in-line (0°) rebar. This is visually similar to Junction A (Figure 7.4), with Junctions C and F found below (with E found in Figure A7.1), followed by Junction D, which is the clearest example of superposition, as the other examples might otherwise be mistaken for solely being dependent on the rebar parallel to the probe.

Figure 7.6: Junction C data with individual contributions for superposed signal.

Raw data, along with superposition, is dominated by the 1” Sample as the probe is in contact with it and aligned with the sample (Figure 7.6). Greater liftoff and angular variation past
0° both reduce signal strength. Junction data is beneath superposition and 1” Sample response, this is likely a minor mistake in taking the junction data (any slight deviation from 0° on the 1” will reduce the junction’s response). That being said, the RMSE value of this is under 0.06 log(V) (later shown in Table 7.4).

Junction F (Figure 7.7) shows an important trend along when using superposition, namely that it does not agree during early decay times. The superposition should only be applied to the later decay times as it is a summation of individual probe-rebar interactions, and the earlier decay time is primarily probe related decay.

![Figure 7.7: Junction F.](image)

Figure 7.7: Junction F. Yellow, blue, and orange data sets (superposition, raw data, and 1” Sample data) all directly overlap with the grey data set (3/4” Sample) providing little to no effect. Early decay times (less than 0.03 s) shows why superposition needs to only be applied after the knee.

As mentioned, three of the four junctions follow a similar pattern to that seen above, where the signal provided by one of the two samples is insignificant and effectively not contributing to the superposition. Junction D is the clear-cut example in these four junctions, where the individual signals must be added together to reproduce the raw data set. In the long-time decay region (past 0.5 s in this case), the yellow and blue data sets agree with each other.
The superposition of Junction D (yellow) shows the weakest agreement with the raw junction data (blue). This is likely the result of shielding of the 3/4" Sample due to the 1" Sample, which is in front of it (see Figure 3.21). It is also possible that secondary decaying fields generated in the 1" Sample may affect those in the 3/4" Sample. While seemingly undetectable in the other Junctions, the two similarly independent rebar signals leave room for this minor shielding effect to be observed. The RMSE of the dissimilar junctions (C-F) is collected in Table 4. All RMSE values are below 0.06 log(V) with the two largest errors being related to Junctions C and D. As described earlier, the larger error in Junction C is likely due to experimental error in aligning the probe to the exact 0° position when collecting the raw junction data. Junction D error is explained above.

Table 7.3: RMSE data for Junctions C-F. Considering these values and Table 3, all junctions agree with superposition within 6%.
7.3 Discussion

This paper examines two separate effects, angular dependence of solenoid probe oriented relative to rebar, and superposition of response at junctions. The angle dependent response is a component of the superposed response that arises at junctions. The angle between the rebar and the probe longitudinal axes affects transient response similarly to trends seen with increasing liftoff (Section 5.2.2). The long-time decay is fit linearly with the slope containing dependence on the conductivity, permeability, and characteristic length (radius in the case of rebar, see Chapter 5). The strongest signal is seen when the probe axis is directly aligned with the longitudinal rebar axis, which is a probe angle of 0°. As the probe rotates (0° to 90°) relative to the rebar, the slope remains the same but there is a vertical shift downward in intercept value. The degree of probe coupling with the rebar is then interpreted as the distance from the ends of the probe to the rebar surface, producing an effect similar to liftoff. More explicitly, this effective liftoff goes from 0 mm (0°) to 50 mm (90°) where the maximum represents ½ of the solenoid length. Under field inspection conditions, understanding this relationship is important, as the rebar is hidden by concrete. Collecting data furthest above the noise floor will allow for optimal analysis, so determining the orientation of the probe with respect to the concrete embedded rebar is an important step to take while collecting data in the field. While it could be assumed that rebar is placed both perpendicular and parallel to the ground for vertical structures, this might not be the case due to human error or design specifications. Using a PEC probe to take an initial data set with the probe aligned in the assumed rebar orientation, followed by altering the probe orientation by small angles and taking a series of measurements will allow for rebar
orientation to be determined, which will allow for maximum signal strength and data furthest from the noise floor.

Junctions provide a glimpse into the complexity of determining rebar health within concrete. As examined in Chapter 5, using PEC to measure the changing radius of rebar. The biggest hurdle yet to be addressed is that rebar is often not isolated within a concrete structure, as perpendicular series of rebar create a strong grid-like structure within the concrete that improves the tensile strength. The simplistic analysis of an isolated rebar provides promise for PEC in this case, but the cross-hatching of rebar provides complications to the simple relations that have been identified. The junctions studied in this report begin to address this problem, but once again only in a very introductory manner. A two-rebar junction, whether of similar or dissimilar diameters, provides the groundwork for developing PEC into a viable tool to quantify concrete embedded rebar diameters. Most significantly, this study has observed the superposition of individual rebar responses when the PEC probe is directly located over the junction. This superposition is most apparent in Figure 7.5 and Figure 7.8. The other junctions that were examined also demonstrated superposition, just with one of the two added terms effectively being negligible, the signal being dominated by the rebar that is aligned with the probe axis.

Considering just one rebar, the magnetic field produced by the eddy currents will pass through the coil, inducing a voltage. Adding a secondary rebar results in a second magnetic field is created by a different set of eddy current interactions, which will increase the net flux passing through the pickup coil. As long as individual responses are strong enough to be detected this relationship
should hold true independent of the number of rebar added, although shielding effects may arise as identified in the case of Junction D (Figure 7.8)

A significant amount of work still needs to be done to help further develop PEC for this application. A few examples of future work include increasing the complexity of the rebar lattice or other neighboring ferromagnetic structures, examining PEC response approaching a junction, and discerning rebar radius from superposition response. There are other types of junctions that still need to be explored. Namely, regions where two parallel rebar are tied together, as well as at a junction over a perpendicular rebar (i.e., 2 parallel, 1 perpendicular). If the superposition theory holds with these additional rebar samples, the raw data of these should show an addition of each individual contribution. With the junctions examined throughout this chapter, the effect of superposition provides an important observation for reducing the complexity of the effect of additional ferromagnetic structures in the vicinity of the probe, since response should continue to be a summation of individual contributions. This being said, in order to eventually work towards a method of detecting corrosion or significant differences from junction to junction a series of calibrations must be done on a specific job site.

7.4 Conclusion
In this paper, PEC response to rebar using a coaxial solenoidal PEC probe was investigated by varying the angle between the probe and the longitudinal rebar axes. The variation of long-time decay intercept demonstrated an exponential decay similar to the increasing liftoff relationship previously examined (Section 5.2.2). Slope remained similar with changing probe angle (effective liftoff) from 0° to 90°. The similar effect of change in liftoff and angle on probe
response could be isolated in-field by changing the orientation of the probe for a few sample measurements and the resulting strongest signal would be the parallel orientation. In a similar fashion, taking a few sample measurements in the area believed to have a junction should result in the largest signal being the location of the junction. The general response present at junctions, where rebar samples overlap, was determined to be mostly a superposition of the two signals, while being dominated by the sample that the probe is parallel with or closest to. These applications are important due to the susceptibility of rebar to experience corrosion in concrete and the inherent risk associated with uninspected older concrete constructions.
Chapter 8 – DISCUSSION AND FUTURE WORK

Now that all investigations into PEC transient response due to pipes and rebar have been presented, it’s illuminating to discuss trends that are similar and different across the two geometries. This chapter will also discuss why the investigation into rebar was included when the industrial sponsor, Groupe Mequaltech Inc., was specifically concerned with corrosion under insulation on pipes. Finally, this chapter will examine what meaningful work still needs to be done in both cases. All of the results shown in this thesis provide a solid foundation for more experimental investigations.

Groupe Mequaltech Inc., the provider of the pipe sections and research sponsor, is interested in corrosion occurring on insulated pipes. At the beginning of the thesis process, the two non-concentric pipes were being used by Swanson [27] and the four concentric pipe sections had not been supplied yet. As part of a first semester NDT graduate course, rebar was chosen as an introductory sample and geometry to consider for study of PEC. The simpler geometry (compared to pipes) elucidates diffusion processes that are well described by basic theory. The data in Chapters 5, 6, and 7 were all collected in the first year of the Master’s degree and act as a proof of concept in the experimental methodology. Ultimately, this research shows the greatest promise for PEC inspection in concrete embedded rebar, especially as a fast-scanning tool, but was placed after the pipe findings to emphasize the sponsors focus.

PEC response to rebar showed the most significant agreement to the theory with discrete fitted relationships. There are four significant trends that were examined across Chapters 5, 6, and 7; changing rebar radius, probe liftoff, probe angle, and examining junctions. Theory
indicated that the long-time decay slope of the transient response from rebar is proportional to the inverse-square of the rebar radius. This slope is also directly proportional to the electrical conductivity and magnetic permeability of the rebar. This change in rebar radius is meant to simulate general corrosion over a decreasing inner bulk radius. PEC shows the ability to detect general corrosion in rebar and (due to agreement with theory) potentially measure remaining rebar radius.

Changing the distance between the probe and rebar increases the liftoff and simulates the thickness of concrete between the accessible wall and concrete-embedded rebar. The ability of PEC to detect general corrosion, as mentioned above, is without significance unless it can also detect the presence of this rebar at the expected distances. Many NDT methods require direct coupling to the material surface to properly categorize and inspect materials, so PEC’s ability to detect materials at up to 75 mm liftoff is beneficial. Not only was an exponential decay shown to occur between the intercept of the long-time decay and the liftoff, but the limit in which the probe can detect each rebar radius was determined. By collecting the series of liftoff data points across the majority of rebar samples, a database of exponential decays was created (for this probe and orientation). This leads to potentially determining the depth of rebar given the slope and intercept (slope to determine radius, and then determine liftoff due to respective decay equation). Further work needs to be done examining PEC response to rebar, specifically using this methodology on actual concrete-embedded rebar samples. All experiments discussed in this thesis are on exposed rebar samples with material characterization performed before PEC signal analysis. Variability in rebar material properties may be present. Collecting rebar samples within
concrete will allow for a verification of the proposed quantification of radius and liftoff to fully realize the limitations of this characterization method.

Probe angle and junction results are intrinsically linked to one another as the extremes of probe angle, being parallel (0°) or perpendicular (90°), directly relates to the two rebar samples at a given junction. Probe angle affects the long-time decay in a manner similar to increasing liftoff, though converting the angle to an effective liftoff (using a $\sin \theta$ transformation) shows a linear relationship between intercept and effective liftoff instead. It is an effective liftoff since the amount of magnetic field coupling between ends of the solenoid and rebar changes with the probe angle. Maximum signal strength occurs when the probe is directly aligned with the longitudinal axis of the rebar. Concrete structures need a perpendicular lattice-like array of rebar to maximize tensile strength. PEC response at these overlapping regions is shown to experience superposition of the individual transient responses at long-decay times. Determining exact orientation of rebar can be done by taking a series of small probe angle variations (starting with the probe being vertical) and comparing intercepts of the long-time decay. While superposition is occurring at all junctions, the junction response is often primarily dependent on the parallel rebar sample. Junction analysis needs to be expanded to examine all remaining possible junction types. This thesis only considers junctions where two rebar are perpendicular, though there may be junctions where two parallel bars are tied together and overlap a perpendicular rod. Superposition, by definition, should continue to be a valid explanation of the transient response at these junctions due to the increased flux from the new individual rod response. It may be beneficially to derive an experimental conversion between superimposed slope response and an
individual rebar radius, and how response to the probe approaching a junction behaves (useful in locating junctions). Future experiments should also include examining angle effects at a range of liftoffs, as this work only considers a liftoff of 0 mm or the case of the 90° rebar having a liftoff of a rebar diameter. Examining all of the rebar samples at 90°, fitting an inverse-square model, and comparing to the 0° case might also show how/if slope is affected by changes in probe angle or if there truly is only a downward shift.

The main difference between pipe and rebar response is the relative size of the probe and therefore, the field which interacts with the steel structure. In the case of rebar, the field was larger, but in the case of pipe, it was smaller. The long-time characteristic lengths also differed between the two media, namely radius for rebar and wall thickness for pipes. Rebar inverse-square model had very good agreement with the data whereas there was no tight agreement with pipes. Liftoff trends also had similarities and differences between the two steel structures. Both experienced an exponential decay when comparing the liftoff to the long-time decay intercept. Physically this was interpreted as the signal exponentially decaying closer to the noise floor with increasing liftoff. Liftoff did not seem to affect the long-time decay slope for rebar as intercept decayed, while the long-time decay slope from pipe response was affected by liftoff. As discussed, pipe slopes became shallower with liftoff at almost all locations, showing a trend towards a seemingly thicker wall, with the opposite occurring only at the thickest wall location for non-concentric pipes. In total, rebar and pipe PEC signal responses showed similarities, but also distinct differences, which have intrinsic ties to geometric complexities and variations in probe-structure interaction.
Pipes provided a significant increased complexity, both in terms of initial classification measurements (UT and conductivities), as well as with the analysis. Pipes have an industry standard of ±12.5% tolerance on stated wall thicknesses [52]. Specifically, the given thickness of a concentric pipe may only be 12.5% smaller than the nominal thickness but there is no limit on how much thicker the wall may be [52]. Swanson [27] derives an analytical model that simulates the transient response from an air core solenoidal probe to a perfectly concentric pipe. Swanson’s model [27] was compared to non-concentric pipes and a comparison to concentric pipes might show better agreement. Since that research [27], finite element method work by Fu et al. [30] has shown that the eddy currents travel over the entire circumference of a given pipe. The three-lobe thickness pattern seen across the four machined pipe sections affected PEC response (Figure 4.4). This biproduct of the manufacturing process helped demonstrate how PEC is sensitive to a semi-localized region on the pipe. Through windowing the responses in Chapter 4, it was clear that across all samples an averaging window of ±45°, for this particular probe and configuration, brought the signal closer to the proposed model. If slope response was identical across the entire circumference, it would imply that wall thickness contributions were evenly weighted. The variation suggests that a weighted average of thicknesses (especially near the probe) is the phenomenon present. Swanson [27] initially had limited agreement between their model and PEC response taken from the two non-concentric pipes analyzed. In hindsight, this is likely due to incorrectly modelling a non-concentric pipe as perfectly concentric, as circumferential wall thickness variations provide different PEC signal responses. These variations
in wall thickness, whether due to the manufacturing process of the pipe or corrosion, adds a significant complication to PEC signal analysis. It is important to say that the proposed model of an inverse-square relationship between ‘perceived thickness’ and the long-time decay slope omits the pipe radius, which will need to be considered in a full description of the system. The model also assumes that eddy currents decay evenly through all wall thicknesses, when eddy currents will actually decay in thinner walls faster than in thicker portions according to eddy current diffusion theory, Equation (2.38).

The most significant conclusion from the pipes analysis is how PEC can be used to detect both general and partial-circumference corrosion and how to discern between them. To reduce testing time in-field, inspectors will likely take data points every 90° (where possible) and compare the transient response of one to another. Limited data points could lead to perceiving natural wall-thickness variation as early onset partial-circumference corrosion if a parabolic variation of long-time decay slopes is seen. While the natural variation seen in a single pipe might suggest early stages of corrosion, a false-positive could be economically costly. Discerning between natural variation, full-circumference corrosion, and partial-circumference corrosion is required. Introducing liftoff between probe and pipe consistently has the response trend towards a perceived thicker base material at every location except at the thickest region on non-concentric pipes. This trend (and singular exception) highlights a methodology to determining the thickest location of a non-concentric pipe (pipe experiencing partial-circumference corrosion) as increasing the liftoff will result in a diminishing perceived thickness. The interpretation of this behaviour is that an increasing liftoff increases the averaging window, though determining to what extent was not investigated in this work.
PEC response analysis of pipes needs to be further developed to include a full system model (including radius dependence and changing wall thicknesses). This may be accomplished by finite element modelling. It may also be beneficial with this newer model to re-attempt the deconvolution as a way to determine thickness percent contributions at each location relative to the probe for the perceived thickness. The stated averaging window, while useful in a fast-scanning method, does not allow for discrete thickness quantification due to a relatively wide sensing area. Improving on these capabilities will make PEC a tool for not only detecting corrosion but also for quantifying damage and pipe characteristics.
Chapter 9 – SUMMARY

Chapter 4 examines PEC use for the detection of corrosion in insulation coated pipes, while Chapters 5, 6, and 7 examine PEC response to rebar embedded concrete. Chapters 5, 6, and 7 are a collection of manuscripts as Chapters 5 and 6 are published papers with Chapter 7 representing further work that has been examined in this area. Chapter 4 acts as the largest of the manuscripts as it examines the effect of various parameters on pipe wall thickness measurement. When comparing rebar modeled as a (relatively) smooth cylinder with pipes (a hollow cylinder), they are geometrically similar, but with increasing complexity in PEC response for the pipe. There are a number of similarities in responses, but also contain a series of differences. Only empirical formulations for wall thickness measurements were obtained for pipes, in large part due to the added complexity of non-uniform magnetic field diffusion in a hollow cylinder with varying wall thickness.

Pipes provided an increased complexity in analyzing the PEC response. Considering the probe orientation (parallel to the longitudinal axis) and COMSOL models from Fu et al. [30], it is evident that the eddy currents can travel around the entire circumference of the pipe at long times (region before noise floor). Six pipe sections, Pipes A-F, were considered and wall thicknesses were mapped through UT. UT thicknesses were measured every 5 cm down the length of the pipe and at 22.5° intervals around the circumference. PEC response was compared against averaged wall thickness. Five thicknesses (one above and below the probe, and three beneath the probe longitudinally) were averaged together and plotted against the slope of the linearly fitted long-time decay. The data exhibited inverse squared relationships between thickness and slopes but with significant scattering across all three pipe sections (Figure 4.5).
(Figure 4.10, and Figure 4.13). Even though the data fit within $2\sigma$, this model would be unreliable since slight variations in nearby wall thicknesses effect PEC transient response. These findings, along with the affect of full circumferential eddy currents, suggests that perceived thickness (transient response) is a weighted function of both semi-local wall thickness and the entire circumferential thickness distribution. Pipes A and B, 8.5-9.5 mm and 8.0-9.2 mm, minimum to maximum thicknesses respectively, show a similar circumferential wall thickness distribution (Figure 3.13), which directly mirrors the slope distribution for these pipe sections (Figure 4.22). Pipes C and D, 7.1-8.3 mm and 6.5-7.6 mm, minimum to maximum thicknesses, respectively, also share a thickness distribution, and thus the slope pattern for these pipes are alike as well. Comparing response from Pipe A through to Pipe D shows that full-circumference corrosion (even wall thinning) is detectable through use of PEC. Collecting data on the same pipe section over time, which exhibits an increasing slope in the long-time decay would indicate that full-circumference corrosion is occurring.

This weighted average is conceptually the basis of this thesis’ definition of semi-localized sensitivity. This sensitivity is clearly expressed in the slope distributions seen on Pipes E and F (Figure 4.9 and Figure 4.12). An effective thickness averaging window was proposed and, through trial and error, was found to be $\pm 45^\circ$ from probe position. The distinct differences between the response of circumferential scans to Pipes A-D and responses to Pipes E and F suggest that partial-circumference corrosion (exaggerated one-sided wall thinning) is also detectable under field inspection conditions.
Unlike rebar response to liftoff, pipe response to liftoff results in a changing slope value. At every location examined through Pipes A-D, slope increased as liftoff increased (Figure 4.22). This effectively comes across as increased wall thickness, with slopes increasing linearly by ~25% with 70 mm of liftoff (increase of 0.36%/mm on average). Pipes E and F also exhibit this increasing slope at three of the four 90° locations examined. The minimum thickness location (0°) and transitional locations (90° and 270°) show the apparently growing wall thickness with liftoff. The exception to this general observation is at the thickest location (180°). Across all six pipe sections, the thickest location on a non-concentric pipe is the only location to have a slope that gets steeper (seeming thinning wall) with liftoff increase. This exception provides the method to avoid unintentionally identifying partial-circumference corrosion as natural wall variation. Placing the probe at the perceived thickest and thinnest locations, after initial scanning, and taking a series of liftoff measurements from the insulation surface allows for a distinction between natural fluctuation or partial-circumference corrosion. Comparing the shift in slope values as liftoff increases will dictate whether it is natural fluctuation (both slopes trend to thicker perceived wall thickness), or partial-circumference corrosion (the thicker location’s slopes trend to a thinner perceived wall thickness).

Due to large error of inverse-squared fits under conditions of changing wall thickness with liftoff, PEC should only be used (in the current format) as a fast-scanning tool to identify regions of concern, whether that be general or partial-circumference corrosion. Specifically, this tool is effective in detecting and differentiating between both forms of corrosion, while not obtaining an accurate wall thickness estimate under varying wall thickness conditions. This is not
problematic, as detecting these regions will result in a limited removal of insulation and inspection of wall thickness, most likely using UT.

Geometrically speaking, PEC response to rebar is qualitatively and quantitatively simpler to compare with expected trends through experimental methods. As predicted by Wwdensky [1], the slope of the long-time decay is directly proportional to the inverse square of the rebar radius (with contributions from electrical conductivity and magnetic permeability). Wwdensky’s solution [1], while omitting internal feedback, effectively predicts the observed experimental response. For rebar, as liftoff is increased the slope remains constant and the long-time decay shifts downward on a semi-logarithmic voltage Y-axis. This results in an exponential decay relationship between intercept of the linear fit and the respective liftoff. This general exponential decay relationship was consistent across all rebar samples. Further analysis into rebar response showed that this liftoff relationship (with constant slope) holds up until a limiting distance (Chapter 6). This liftoff limitation was dependent on rebar size as smaller rebar radii response is enveloped by the noise floor (1E-05 V) at smaller liftoff values. This limiting liftoff was determined by one of two criteria; i) long-time decay window is too short to be fit, and ii) liftoff was far enough away that slope began to vary with liftoff (resulting in presumed change in detected size). The liftoff limit and rebar radius were also described by an inverse square relationship.

The final rebar manuscript, Chapter 7, examines how PEC response is affected by probe orientation (angle) and how PEC response behaves in the presence of rebar junctions. Changing probe angle from 0° to 90° produces a decreasing probe response. Plotted as a geometric conversion from angle to the shortest distance from the rotating probe tip to the rebar surface
(L/2 \sin \theta, where L is the probe coil length) the response is observed to decrease linearly to a minimum at 90°. A novel observation from rebar junctions is the superposition of two individual PEC responses (parallel and perpendicular, with one having liftoff) matching the response from a rebar junction. This superposition is only present in the long-time decay, as the earliest-time signal decay is dependent on relaxation times that include coil rebar interactions.

In summary, the thesis examines the changes in transient PEC response due to variations in experimental parameters meant to simulate either corrosion or geometry of the subject structure. Both pipes and rebar were examined with general trends showing promise for PEC inspection for pipes, especially in discerning between semi-localized and full-circumference corrosion. Rebar response shows good agreement with the theory of an inverse-square model between long-time decay slope and radius. Significant work must still be done in both areas to develop this inspection technique as a more robust inspection tool, but PEC is currently shown to be an ideal candidate for fast-scanning inspection. PEC fast-scanning inspection would be complimented by more precise wall thickness measurements through UT of pipes.
REFERENCES


Figure A1.1: Pipe B ultrasonic mapping of entire pipe. UT measurements taken every 22.5° circumferentially and every 5 cm down the length of the pipe.

Figure A1.2: Pipe B collection of all UT wall thickness values averaged down the same angular position. Green data points signify the maxima, with red representing the minima. Three lobe pattern visible, with red dots representing maxima, and green representing the minima.
Figure A1.3: Pipe B collection of averaged thicknesses of each circumferential ring as a function of the length of the pipe. Slightly thicker at the beginning of the pipe compared to the end.

Figure A1.4: Pipe C ultrasonic mapping of entire pipe. UT measurements taken every 22.5° circumferentially and every 5 cm down the length of the pipe.
Figure A1.5: Pipe C collection of all UT wall thickness values averaged down the same angular position. Green data points signify the maxima, with red representing the minima. Three lobe pattern visible, with red dots representing maxima, and green representing the minima.

Figure A1.6: Pipe C collection of averaged thicknesses of each circumferential ring as a function of the length of the pipe. Slightly thicker at the beginning of the pipe compared to the end.
Figure A1.7: Pipe D ultrasonic mapping of entire pipe. UT measurements taken every 22.5° circumferentially and every 5 cm down the length of the pipe.

Figure A1.8: Pipe D collection of all UT wall thickness values averaged down the same angular position. Green data points signify the maxima, with red representing the minima. Three lobe pattern visible, with red dots representing maxima, and green representing the minima.
Figure A1.9: Pipe D collection of averaged thicknesses of each circumferential ring as a function of the length of the pipe. Averaged thickness is thinner at the beginning of the pipe compared to the end.

Table A1.1: Collection of maxima and minima locations for Pipes A – D. Specifically data collected from Error! Reference source not found. and Figures A1.1-A1.9. The bottom two rows show the translation needed for uniform lobe distribution across the four pipe sections. All translations are relative to Pipe A, thus the N/A in the bottom two rows for Pipe A. This is collected graphically in Figure 3.12.

<table>
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<th>Pipe C</th>
<th>Pipe D</th>
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<td>202.5</td>
<td>180</td>
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<td>292.5</td>
</tr>
<tr>
<td>Maxima (°)</td>
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<td>0</td>
<td>90</td>
</tr>
<tr>
<td></td>
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<td>135</td>
<td>112.5</td>
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<td>90° CCW</td>
</tr>
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</table>
**A2 RAW DATA PIPE F (180° TO 337.5°)**

Figure A2.1: Pipe F raw PEC data. Data above is mirrored by Figure 4.11. Thicker and thinner trends shown above.

**A3 REMAINING WINDOWING SIZE COLLECTIONS**

Figure A3.1: Pipes A-D remaining window sizes not shown in Figure 4.16. Labels in top left corner symbolize the window size in degrees.
Figure A3.2: Pipe E remaining window sizes not shown in Figure 4.18. Labels in top left corner symbolize the window size in degrees.

Figure A3.3: Pipe F remaining window sizes not shown in Figure 4.19. Labels in top left corner symbolize the window size in degrees.
Figure A4.1: Complete raw liftoff data sets at maximum and minimum locations for Pipes A and B. A1 and B1 represent the minimum (270°), with A2 and B2 representing the maximum (180°) locations.

Figure A4.2: Complete raw liftoff data sets at maximum and minimum locations for Pipes C and D. C1 and D1 represent the minimum (90°), with C2 and D2 representing the maximum (292.5°) locations.
A5 Pipe F Liftoff Raw Data

Figure A5.1: Pipe F raw liftoff data at the 0° location (thinnest). Note how the region in the red lines are steeper at smaller liftoffs and become shallow at larger.

Figure A5.2: Pipe F raw liftoff data at the 180° location (thickest). Note how the region in the red lines are steeper at larger liftoffs and become shallow at smaller.
A6 Pipe F slopes as a function of liftoff and angular location

Figure A6.1: Pipe E slope values as a function of angular position. The different data sets represent the different liftoffs. The red lines represent the approximate transition location where slope remains (relatively) constant with liftoff. This estimated region lacks deep resolution due to a lack of liftoff data sets but seems to be located between close to 135° (or 225°).

A7 Junction E

Figure A7.1: Raw data of Junction E. Yellow, blue, and grey data sets (superposition, raw data, and ¾” Sample data) all directly overlap depicting a distinct dominance of the ¾” Sample at a liftoff of 0 mm with the probe longitudinal axis aligned with the rebar axis.