INVESTIGATION OF MAGNETIC SENSING SYSTEM FOR IN-PLACE CORROSION CHARACTERIZATION IN METALS

BY
GONZALO E. GALLO

DISSEETATION
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Urbana, Illinois

Doctoral Committee:

Professor John S. Popovics, Chair
Professor Imad Al-Qadi
Professor Carl Altstetter
Professor Patrick L. Chapman
Professor Paramita Mondal
Abstract

Corrosion of the civil infrastructure causes structural failures and great financial losses. Continuous and effective monitoring of corrosion can lead to failure prevention and savings. This document describes the development of magnetic sensing schemes to characterize corrosion of metals in situ. GMR magnetic field sensors are applied to overcome difficulties encountered with traditional corrosion detection methods. Magnetic measurements present a manner to monitor corrosion without damaging the structure. Active and passive magnetic sensing configurations are presented. Passive measurements rely on very near-surface magnetic field measurements. Changes in the magnetic field are associated with corrosion rates for A36 steel and 2024 aluminum in aqueous environments. Active magnetic tests rely on the interaction of imposed magnetic fields with corrosion-generated magnetic fields. Although active tests may be carried out at a larger offset distance to the corroding metal, the responses from active tests could not be consistently related to corrosion activity of metals in aqueous environments. Finally the developed magnetic techniques are applied to reinforced concrete specimens. Accurate and fast corrosion processes in the steel bar are achieved in a controlled manner using anodic applied current. The passive sensing scheme data show some promise in identifying areas where corrosion pits initiate; however the corrosion rate is significantly underestimated. The results serve as a basis to propose a robust sensor configuration capable of monitoring corrosion of steel in concrete in the field.
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Chapter 1

Introduction

1.1 Background and problem statement

Corrosion is the irreversible consumption of materials due to the interaction with the environment. The understanding, study, detection, and prevention of corrosion are of significant importance for several reasons. Corrosion introduces costs not only due to material loss, but also due to down time, replacement, services, prevention insurance, design, and even research. Corrosion is a major factor in numerous cases of injury and loss of life, which makes it very significant [1].

In general, the civil infrastructure in the United States is in poor condition. The ASCE issues report cards on the condition of the nation’s infrastructure. In the report from 2009, the overall grade given was “D” [2]. The updated values for 2008 indicate that $1.6 trillion is needed over a five-year period to restore the infrastructure to good condition. Some estimates indicate that the costs of metal corrosion damage to highway bridges alone is $6 to $10 billion per year [3]. NASA estimates that the cost of corrosion to the U.S.A. is $276 billion/year. This cost includes direct and indirect expenses associated with corrosion [4]. Since steel and aluminum are the most commonly used metals, most of the cost of corrosion losses is associated to them.

Given its importance, there is a clear need to understand, monitor and characterize corrosion of metals. Many techniques already exist for corrosion monitoring; they range from direct mass loss measurements to characterization of the kinetics and thermodynamics involved. But there is always a need to develop more sensitive measurements, to create practical sensors, and to increase the use of available information to understand the processes still exists.

Corrosion of embedded steel reinforcement in concrete is of particular interest and presents special challenges to overcome. The principal problem is that the extent and severity of corrosion is difficult to assess inside concrete structures. Reinforcement is typically not accessible, and exploratory (destructive) measurements only provide localized information [5]. Judgment is usually based on very few data points and most times damage is discovered only when corrosion products have cracked the cover concrete and preventive
actions can no longer be efficiently applied.

1.2 Thesis objectives

The main goal of this project is to develop magnetic sensing techniques that can remotely detect both the extent and rate of corrosion without contact with the corroding metal. The underlying basis of this approach is as follows. Corrosion is an electrochemical process which involves the movement of ions and electrons (currents). The corrosion currents will generate a related magnetic field, through Maxwell’s equations and the Biot-Savarat law as illustrated in 1.1, that can be monitored remotely without the need of excavation to the metal. This weak magnetic field should depend on the corrosion activity, and corrosion extent could be estimated. Studies with the use of Superconducting Quantum Devices (SQUIDs) have shown the feasibility of this approach in aluminum[6, 7]. Three subtasks comprise the overall effort:

- “Passive” magnetic sensing. Develop a sensing scheme that can determine corrosion at the moment of testing through flux density measurements. The principle is to monitor magnetic field changes associated to corrosion. This approach is analogous to the acoustic emission method.

- “Active” magnetic sensing. Develop a sensing scheme that determines the interaction of the tested object with an imposed magnetic field and relate to the response to corrosion. The interaction response is sensed an interpreted by external circuitry and the data acquisition system. This approach is analogous to the eddy current method [8].

- Packaging and electrical engineering support for sensor prototype. Develop a sensor package for both active and passive sensing, with low power consumption, which can ideally be implemented in a wireless sensor network within a reinforced concrete element or near an aluminum element.
Figure 1.1: A current through a wire (colored arrows) produces a magnetic field around the wire (black arrows) [9]. Moving charges generate a magnetic field.
Chapter 2

Corrosion Basics

2.1 Definitions and main concepts

The simplest and most common definition of corrosion is the “loss of material or degradation of material (usually a metal) due to interaction with its environment” [1]. This definition, although broad, conveys the underlaying concept of corrosion. Corrosion is a common experience for us, causing the rust that eats up the body of our cars to the collapse of whole bridge structures. The definition recognizes that materials other than metals can corrode and that the study of these phenomena is also important for the corrosion engineer [10]. There are, however, good reasons for studying metals separately from non-metallic materials. Since metals have high electrical conductivity their corrosion is electrochemical in nature [11].

Attention must also be directed to the fact that corrosion may deteriorate material properties, not just the material itself. That is, some forms of corrosion cause no apparent change in the weight of the material or no visible deterioration is found, yet the material may fail unexpectedly.

One must come to terms that corrosion is happening everyday, and it affects all metals. The aluminum soda can or the alloy steel used in construction are both susceptible. The difference between these two examples is the different types of corrosion and different mechanisms and conditions that alter rates and occurrence of the respective types. Of the 117 elements in the periodic table, the vast majority are metals, which makes the study of metals corrosion a very ample task. Understanding the mechanisms, the environmental variables, material properties, and key behaviors of corrosion is the best approach to develop control mechanisms and better more durable materials [10].

There are several variables that affect the rate and extent of corrosion. From the fundamental definition, we know that the environment plays an important role in the corrosion process. An aqueous medium will have different effects than a flue gas, for instance. The concentration of ions, oxygen, and humidity in the environment have significant effects. Temperature also has a great effect; in general, higher temperatures will accelerate corrosion. Fluid velocity and electric potential are also significant effects.

The composition of the metals is an important factor. The base metal, alloying elements, the composition,
impurities and phases all affect how that metal corrodes. The processing and fabrication influence phases and impurities. Geometry and surface condition will determine preferential sites for corrosion to take place [1].

2.2 Why do metals corrode?

Since corrosion takes place mainly in metals, it is important to understand how they are affected. The close-packed microstructure of metals dictates that electrons are shared among the constituent atoms. For this reason they are great electrical conductors. Most metals are thermodynamically unstable in atmospheric conditions. In order for them to maintain the metallic form they must absorb and store energy. Some metals require more energy, such as aluminum or magnesium, while others require little energy such as gold [10]. If this needed energy is not supplied, the metal will revert to a lower energy state, such as a covalent-bonded metal oxide. This transition from a metal to a metal oxide exemplifies corrosion.

2.3 Corrosion types

There are many different corrosion types, where the classifications are based on processes, environment, material loss, and others.

The most general form of corrosion is uniform corrosion. This type of corrosion takes place in structures exposed uniformly to the corrosive conditions and is measured as a loss of thickness or weight throughout the affected structure. Conditions for uniform corrosion are not always attained, so localized forms of corrosion are common. Localized corrosion takes place at preferential sites, such as grain boundaries or phase changes. Crevice corrosion is a localized corrosion that originates at geometrical discontinuities. Some forms of corrosion are assisted by mechanical factors such as cavitation, erosion, fatigue, or stress.

2.4 Chemistry and electrochemistry of corrosion

Chemical reaction transfer are electrochemical in nature. As with all chemical reactions, the equilibrium state is governed by thermodynamics, while rates, effects of electrical potential, temperature, pressure, and concentrations are governed by kinetics.

Following normal chemical convention, when an atom gains electrons the positive valence is reduced and the reaction is a reduction. When an atom gives away electrons, oxidation has taken place. The following
equation describes the oxidation of a metal which is the usual an anodic reaction for corrosion [1].

\[ M \rightarrow M^{n+} + ne^-, \]  

(2.1)

where \( M \) represents the oxidizing metal. In a similar fashion, the opposite reaction is also known as a cathodic reaction. In that case the electrons are supplied to the metal,

\[ M^{n+} + ne^- \rightarrow M. \]  

(2.2)

These two equations are each known as half-cell electrochemical reactions.

As in all chemical reactions, the direction and intensity of is governed by the energy involved. These energy changes provide the driving force and control the spontaneous direction for a chemical reaction. When the reaction products have a lower energy than the reactants, the change in free energy (\( \Delta G \)) is negative and the reaction is spontaneous. These two equations are each known as half-cell electrochemical reactions. Each half-cell reaction has a free energy associated with it, which in turn can be related to electrochemical potential, \( E \), at equilibrium by \( \Delta G = -nFE \), where \( n \) is the number of electrons exchanged in the half-cell reaction and \( F \) is Faraday’s constant: 96,500 coulombs per equivalent.

The potential related to each of these half-cell reactions at a standard state are established. When expressed in terms of reduction reactions, those with the most positive potentials, metals such as Au and Pt, are known as “noble”. Those with more negative potential values are known as “active”, which are more likely to corrode. All potentials must be measured against a reference half-cell. The standard hydrogen electrode (SHE) is often taken as the zero voltage, and all measurements are expressed with respect to it [1].

### 2.5 Potential/pH (Pourbaix) Diagrams

Several factors influence the “corrosiveness” of a medium and the rate at which corrosion reactions take place within that medium. Solution concentration of the medium plays an important role. Half-cell electrode potential depends on activity and concentration of species, particularly the concentration of hydrogen ions. The hydrogen ion is a common and important oxidizer. This dependence on hydrogen ion concentration can be interpreted in terms of pH, since \( pH = -\log[H^+] \). [1, 11].

Potential/pH diagrams are very useful to describe corrosion states in different environments. The Pourbaix diagram shows the redox potential of the corroding system on the vertical axis versus the pH on the horizontal axis. In the plot it is possible to establish defined regions, within which the metal itself or some
of its components are stable [11].

In many cases, however, thermodynamic data are incomplete and uncertain, so the clear derivation of all boundaries cannot be obtained. Therefore, diagrams are constructed at a fixed temperature, usually \(25^\circ\text{C}\), and a specific metal ion concentration (\(10^{-6}\) mol is common) in the environment. Typical Pourbaix diagrams are shown in figure 2.1. The plots also show lines for the redox potentials of solutions in equilibrium with hydrogen and oxygen, where oxygen is 1.23V more noble in the presence of hydrogen [11, 1]. These lines are shown in figure 2.1 as dashed lines \(a\) and \(b\).

The main advantage of Pourbaix diagrams is that they allow the user to define the different regions where the reaction products are stable, and thus determine if the metal is likely to be immune, passive, or active. **Immunity** is a the state where the metal is the stable phase and so corrosion is unlikely to occur. **Passivity** is an state in which the corrosion products are stable and form a protective layer that slows down considerably the corrosion rate. In the **active state** the corrosion products are stable, but they do not slow down or otherwise affect the corrosion rate [11, 1].

Pourbaix diagrams say nothing about corrosion rates but do let us know how a metal is likely to behave in a given environment. Also the diagram provides insight to modify corrosion. For example:

1. the electrode potential can be lowered down into the immune region. This could be achieved by making the specimen a cathode in a galvanic cell with a sacrificial anode material, this is called cathodic protection;

2. the electrode potential can be brought up into a region of passivity by usually making the metal the anode in the galvanic cell. This is called anodic protection. One way to do this is to add an anodic inhibitor, often an oxidizing agent, which forms a passivating film on the metal surface;

3. the pH or alkalinity of the solution can be changed to move the metal into another state region..

Conversely, Pourbaix diagrams also let us know how to allow for corrosion or how to increase corrosion rates.

### 2.6 Corrosion Kinetics

Thermodynamics indicate likelihood that corrosion will take place in a certain environment. It is also important to know the rate of the reactions, which is explained by kinetics. Electrochemical reactions produce and consume electrons. The electron flow, which is quantified as a current, can be related to corrosion activity by Faraday’s law.
where $m$ is the mass reacted; $t$ is the time; $a$ is the atomic weight; $I$ is the current; $z$ are the number of equivalents in the associated half-cell reaction; and $F$ is Faraday’s constant. If equation 2.3 is divided through by time and anodic area, we can determine a corrosion rate in terms of current density. Each electrode has an equilibrium current density $i_0$ [1].

Electrochemical cell reactions have an equilibrium or reversible potential ($E_{rev}$) associated with them. A deviation from equilibrium (constituents, concentrations or temperature) will bring about a change in the potential, which is called polarization, and is shown if figure 2.2. This relationship is explained by Nernst’s Law [1]

$$E_{rev} = E_0 - (RT/zF)\ln([prod]/[react])$$

(2.4)

$T$ is the temperature, $R$ is the ideal gas constant, $[prod]$ is the concentration of the products, $[react]$ is the concentration of the reactants, and $E$ is the standard half-cell potential. Understanding of corrosion kinetics is achieved by varying the potential above or below equilibrium. This is known as polarization and can be anodic or cathodic. While varying the potential, the current produced is recorded. A higher current density relates to a higher corrosion rate. Hypothetical polarization curves are shown if figure 2.2 [1, 13].
Figure 2.2: Anodic and cathodic polarization [13]

Corrosion kinetics contribute to the understanding of passivity. Passivity is an increased corrosion resistance in oxidizing conditions or anodic potential due to a thin film barrier formed at the anodic site. Figure 2.3 shows the polarization curve for an active-passive metal. Transition from the active to passive state can be observed on a polarization plot using a potentiostat and slowly scanning the potential of the metal from its “rest” potential. In this plot, the anodic branch follows a linear or Tafel behavior until it reaches a critical point at maximum current density ($i_{\text{crit}}$). At this point, passivation starts current density drops dramatically for increasing potentials. However, at higher potentials the current density rises again where the protective film abruptly undergoes electrical breakdown, reaching what is called the trans-passive region [1, 13].

2.7 Corrosion of Steel in Concrete

Corrosion of reinforcing steel in concrete is a major problem in civil infrastructure. There is no major difference between corrosion of steel in concrete and other corrosive processes: an anode, a cathode, an electrolytic connection, and an electrical connection are needed. One unique aspect is that the electrolyte, instead of being an aqueous solution, is the solution in the concrete. Since electrical resistivity of concrete is much higher than in aqueous solutions, the electrical resistivity of concrete is a controlling factor for the corrosion rate [14]. The chemistry of the concrete pore solution is in equilibrium with the hydrated pastes. The pore solution in concrete is highly alkaline. The composition evolves during hydration, but for mature concrete the pore fluid is a solution of alkali hydroxides, whose concentration is controlled by the alkali content of the cement. With low alkali cements, the pH of the pore solution is around 13 and for high alkali cements it can reach 13.5 [15].
Figure 2.3: Active-passive corrosion behavior [13].

Considering the Pourbaix diagram of iron (steel), one can see that the high pH values associated with concrete pore water, passivates steel for the oxygen reduction process. Therefore, concrete is usually a great environment to protect steel from corrosion. However, as time passes, concrete deteriorates, cracks, and alkalinity drops because of carbon dioxide ingress (carbonation). Chloride ion ingress breaks the passive layer and enables corrosion to take place[14, 16].

The main variables to consider when analyzing corrosion in concrete are:

- Carbonation
- Chloride ion penetration
- Critical chloride content
- Oxygen supply
- Electrical resistance of concrete
- Humidity
- Chloride binding
- Concrete porosity/Diffusivity

The anodic half-cell reaction involved in the corrosion of steel reinforcement in concrete is

$$Fe \rightarrow Fe^{+2} + 2e^-.$$  \hspace{1cm} (2.5)
The cathodic half-cell reactions depend on oxygen availability, pH of the solution, and the electrochemical potential:

\[
2H_2O + O_2 + 4e^- \rightarrow 4(OH)^- \quad (2.6)
\]

in the presence of sufficient oxygen, otherwise

\[
2H_2O + 2e^- \rightarrow 2(OH)^- + H_2. \quad (2.7)
\]

The iron ions can further react with hydroxyl ions to form ferrous hydroxide:

\[
Fe^{+2} + 2OH^- \rightarrow Fe(OH)_2. \quad (2.8)
\]

The ferrous hydroxide can further react with oxygen to form various metastable oxide species, such as hydrated ferric oxide and hydrated magnetite, depending on pH and availability of oxygen[14, 16].

In concrete, oxygen is usually able to diffuse through the pore network and micro-cracks to the steel surface and equation 2.6 becomes the prevailing cathodic reaction. Active corrosion develops when alkalinity is reduced usually caused by carbonation (uniform) or by buildup of chloride ion close to steel (localized) [16].

Corrosion in concrete is often not uniform spatially. Some areas are more corroded than others due to non-homogeneity, cracks in concrete, or localized chloride ion concentrations. An example of an event which may lead to localized corrosion is a patch repair, since the patch has different properties than the surrounding concrete [16].

Macrocell corrosion may occur between passive and active steel. In a concrete structure, most steel is electrically connected and some are more prone to corrosion since they are closer to cracks or chloride ion ingress. These electrically connected reinforcement have different corrosion potentials and will tend toward equilibrium. This galvanic coupling protects the remote steel and accentuates the corrosion in the near one [16].

The interest in steel corrosion in concrete has triggered several studies, some have even involved the development of equations to estimate time to corrosion. The most notable of this efforts was performed by Bažant who presented a theoretical equation for estimating the time to corrosion cracking, particularly in sea structures. The calculation involves rates of corrosion, bar diameters, bar spacing, and densities. The author did consider several effects previously discussed such as oxygen transport and diffusion [17, 18, 19]. The
equation, however, has been found to under-estimate the time to corrosion cracking for the single vertical cracking case [20].

### 2.8 Aluminum Corrosion

The anodic half-cell reaction involved in the corrosion of aluminum is

\[
{Al} \rightarrow {Al}^{+3} + 3e^-, \tag{2.9}
\]

while the cathodic reaction can be the reduction of oxygen or hydrogen [1].

As with steel, aluminum may also react to form a metal hydroxide or an oxide. For aluminum, the corresponding equation is:

\[
2{Al} + 3{H}_2{O} \rightarrow {Al}_2{O}_3 + 6{H}^+ + 6e^- \tag{2.10}
\]

High pH solutions may dissolve \(Al_2O_3\). In general, however, aluminum and aluminum alloys are resistant to neutral atmospheres and are therefore used extensively. At low pH solutions, aluminum experiences an increase in corrosion rates. A great risk for aluminum is intergranular corrosion, since some of the alloying elements will corrode preferentially with respect to the matrix. Stress corrosion cracking may cause as well serious problems for aluminum alloys [1].
Chapter 3  

Traditional NDE Techniques

Corrosion is an electrochemical process. This implies that electrons are involved, lost at one location and acquired at another. Each of the half-cell reactions has a potential, and the combined potential is directly related to the corrosivity of a metal in a given environment. It is clear that corrosion is highly dependent on the environment, ion concentration, temperature, and other external factors. These behaviors have lead to the development of several non-destructive techniques for the in-place evaluation of corrosion activity. Most of the described methods are for applications to steel corrosion in concrete.

3.1 Potential Measurements

Potential measurements are simple and are often used to evaluate corrosion in concrete structures. Potential measurements establish the likelihood of corrosion activity within a localized region of the structure.

3.1.1 Principles

Half-cell potential tests measure potential differential formed during corrosion of steel in concrete. As corrosion takes place, electrons are lost at the anode and move to the cathode. To maintain neutrality, ferrous ions move to the cathode to react and form oxides. As the ions move, electrons left behind in the bar give it a negative charge. So the transformation from passive to active state of the steel causes the potential measured against a reference electrode to shift to more negative values[14, 21].

3.1.2 Instrumentation

ASTM C876 gives a standard procedure for this test. The principal test instrument is a reference electrode. Connecting cables and a high-impedance voltmeter are also required. The most common electrode used in the field is the copper/copper sulfate electrode due to its ruggedness and thermal stability. This electrode is composed of a copper rod inserted in a saturated copper sulfate solution. Other electrodes include the calomel and silver/silver chloride electrodes. These are considered to be better than the former and are
commonly used in the lab. The half-cell electrode makes contact with the concrete surface through a porous plug and a sponge that is moistened by a wetting solution[21, 14].

When electrons flow from the corroding bar to the half-cell, they are consumed reducing copper ions in the copper sulfate solution into copper atoms deposited on the rod. In the voltmeter, the negative terminal is connected to the half-cell and the positive to the bar. The more negative the reading, the higher the likelihood that the bar is corroding[21]. Table 3.1 gives guidance about data interpretation.

Potential measurements are usually taken along a previously arranged grid on the surface of the tested structure. To ensure that reinforcement is electrically connected, electrical resistance measurements are taken across widely separated bars. The potential measurements need to be stable, and this is achieved by assuring proper moisture at the concrete surface [21].

3.1.3 Analysis

Half-cell potential measurements are usually carried out in conjunction with other measurements such as chloride ion content in concrete. Survey data are usually presented as equipotential contour maps on a scaled plan view over the test area[21].

According to the ASTM standard, two techniques can be used to evaluate results. The first is the numeric technique, in which the potential is used as an indicator of the likelihood of corrosion. Table 3.1 shows the suggested limits for this type of analysis.

<table>
<thead>
<tr>
<th>Potential</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>P &gt; 0.2V</td>
<td>High probability corrosion is not occurring</td>
</tr>
<tr>
<td>-0.20V &gt; P &gt; -0.35V</td>
<td>Corrosion activity uncertain</td>
</tr>
<tr>
<td>P &lt; -0.35V</td>
<td>High probability corrosion is occurring</td>
</tr>
</tbody>
</table>

Table 3.1: Numerical interpretation of half-cell measurements for copper-copper sulfate [21].

The second analysis option is the potential differential technique, in which the areas of active corrosion are identified on the basis of corrosion gradients. High gradients are indicated by close spacing of the voltage contours. High corrosion activity is related to these closely spaced contours [21].

3.1.4 Disadvantages

The main disadvantages of half-cell potential method is that direct electrical contact with the reinforcement is needed. Also the concrete needs to be sufficiently moist to ensure reproducible and reliable data. The method does not work with coated rebar. Since only the likelihood of corrosion is established, the actual rate of corrosion cannot be determined [21, 22].
3.2 Linear Polarization Resistance (LPR)

The linear polarization resistance method overcomes the inability of half-cell potential measurements to establish in-place corrosion rates\[21, 23\].

3.2.1 Principle

“Polarization” refers to the change in the open-circuit potential as a result of passage of a small amount of current. The corrosion interface can be represented by a simple circuit, the Randles circuit; the corrosion interface at the steel surface is represented by a double-layer capacitance in parallel with a resistance, which is known as the polarization resistance $R_p$. This capacitance and resistance, in turn, are connected in series with a simple resistance, which represents the surrounding concrete. When a small perturbation is induced in the open circuit potential, a linear relationship exists between the change in voltage ($\Delta E$) and the change in current density($\Delta i$). Their ratio is the polarization resistance

$$R_p = \frac{\Delta E}{\Delta i} \quad (3.1)$$

assuming the potential change is kept below $\pm 30$mV [21, 23]. The units of $R_p$ are Ohms area.

3.2.2 Instrumentation

LPR measurements are usually carried out using a three-electrode system. A stable reference electrode enables the corrosion potential and “polarization” of the steel to be measured between the steel reinforcing bar and an auxiliary electrode placed on the surface of the concrete. The corroding steel is the working electrode (WE), the stable electrode such as the copper/copper sulfate electrode is known as the reference electrode (RE), while the third electrode is known as auxiliary electrode (AE). This device can be operated in a potentiostatic testing mode, in which the current is varied to maintain constant potential of the working electrode. An additional option is to vary the potential to keep a constant current from the counter electrode to the working electrode; this is known as the galvanostatic testing mode [21, 23, 14].

The following steps are necessary for LPR measurements on steel on concrete:

- Locate steel reinforcement
- Record steel cover depth and bar diameter
- Make an electrical connection to the steel reinforcement
- Measure corrosion potential of WE against a reference electrode
• Measure current from CE to WE necessary to produce a potential drop of 4mV in the WE.

• Repeat previous steps for different potential drops (8mV, 12mV, and so on)

• Determine influence area of reinforcement

• Plot potential versus current per unit area and determine the slope of best fit line. This slope is the polarization resistance.

A significant uncertainty in this procedure is the calculation of the influence area of the working electrode. Certainty in the area can be improved with the addition of a fourth ring electrode, called the guard electrode, which surrounds the counter electrode. This confines the current to a defined region beneath the counter electrode [21].

The most common commercial equipments used for linear polarization measurements are GECOR 6, CORROCATCH, PR Monitor, and 3LP–NBS1. The differences in the equipment lie in their structure and electrodes. Some, like GECOR provide a ring–electrode that confines the current to a known region for a better calculation of the influenced area and the polarization resistance. Confinement seems to work only for actively corroding steel. Other differences include storing capacity and weight. In general, they all behave similarly and site preparation such as pre-wetting concrete is recommended [24].

3.2.3 Analysis

The polarization resistance, or the ratio of the change of potential over the change in current density, is inversely related to the corrosion current density by the following equation

\[ i_{corr} = \frac{B}{R_p} \]  \hspace{1cm} (3.2)

where \( i_{corr} \) is the corrosion current density in A/cm\(^2\) and \( B \) is a constant value. \( B \) is normally assumed to be 25mV for actively corroding steel in concrete and 50mV for passivated steel [23, 21]. The corrosion currents estimated using LPR can be converted into penetration rates using Faraday’s law or a generic conversion chart.

3.2.4 Disadvantages

LPR corrosion measurements in concrete depend on several factors such as oxygen availability, temperature, and moisture content of concrete. For this reason, measurements need to be taken during different times of the year and at different locations. Additionally, contact electrical connection to the steel with reinforcement
is required. LPR measurements do not work on coated reinforcement or if the concrete has an impermeable layer. Steel cover depth is also a limitation; it should be less than 100mm, and at the same time steel has to be at least 300mm away from discontinuities such as edges and joints.

3.3 Electrochemical Noise Measurements

Electrochemical noise measurement is considered a controversial subject since no established methods and no consensus on data interpretation yet exist. Electrochemical noise measurements (ENM) are usually defined as current or potential fluctuations, typically at low frequencies (<10Hz). These fluctuations have been well recognized but in the 1980s the interest grew and noise measurements were considered a viable technique [25].

3.3.1 Principles

ENM from corrosion systems are observed as low spontaneous low-frequency fluctuations of current and potential. In the case of localized corrosion, distinct anodic and cathodic currents are observed. ENM data can be obtained galvanostatically, potentiostatically, or at natural corrosion potentials. In all cases, the potential and current behaviors are both random in manner across the corroding surface and random throughout the measurement period [25].

Sources of electrochemical noise vary. Propagation of stress corrosion and abrasion of metallic surfaces serve as mechanical sources of noise. Chemical sources include chloride adsorption onto passive films or the growth and detachment of hydrogen bubbles [25]. There are also extraneous sources of noise which may affect ENM, for example all data acquisition equipment and power supplies introduce noise [26].

3.3.2 Instrumentation

The random nature of noise implies that each corrosion system has different oscillation speeds, at different sites and with different amplitudes. Therefore, one must tune the measuring system for each case. However, the basics for the measurements are the same. The measurements are similar to potentiostatic and galvanostatic LPR measurements. Two or three-electrode setups are possible, connected in pairs. The first pair of electrodes is connected by a zero resistance ammeter and the other two electrodes by a high impedance voltmeter. The first one registers currents while the other records voltage fluctuations [25, 27].

Equipment such as the one described, usually samples at a rate of about 1 sample per second. Several hundreds of points are usually acquired and processed in the time and frequency domains. ENM data
obtained with computerized equipment may have lower sensitivity limits of $10^{-12}$ A and $10^{-17}$ V, although these values may fluctuate [25, 28, 27].

3.3.3 Analysis

Analysis of electrochemical noise measurements is done by computing the ratio of the standard deviations of the voltage ($\sigma V$) and current ($\sigma I$) fluctuations. This ratio defines the noise resistance $R_n$

$$R_n = \sigma V/\sigma I. \quad (3.3)$$

In theory, there should be no current flow between the electrodes, even though the statistical variation of corrosion rates across the surface implies that a current flows. The concept is built on the assumption that the working electrode surface can be divided into a large number of patches. On each patch, small chemical changes at the interface lead to short-lived changes in the inter-facial resistance. These in turn cause changes in the anodic and cathodic partial currents. Instantaneous deviations from a zero net current in each patch, summed over the whole area, will drive the electrode potential to reach compensation between the anodic and cathodic current. It is also assumed that the resistance changes of the various patches are statistically uncorrelated [25, 27].

The particular analysis procedure depends on the mode of corrosion. Most information is obtained from uniform or pitting corrosion. Several researchers have analyzed different metals and environments and have found great correlations between noise resistance and traditional parameters for uniform corrosion [25, 27, 29]. Pitting corrosion usually produces short-lived transients which are observed. Despite the fact that several factors may adversely influence the results, the method can characterize the onset and process of pitting corrosion [26, 25, 30]. The ENM responses of other corrosion processes, such as crevice and stress corrosion cracking, resemble that of pitting corrosion.

3.3.4 Disadvantages

ENM measurements present several disadvantages. First, there is no consensus on testing and analysis procedures. Therefore comparison and analysis of results are more difficult. A trained experimentalist is required to process the data. Additionally, the method has the same limitations as LPR and half-cell potential in that access to reinforcement is required and will not work if there is a coating on the rebar.
3.4 Eddy Currents

An eddy current (also known as Foucault current) is an electrical phenomenon discovered by French physicist Lon Foucault in 1851. It is caused when a conductor is exposed to a changing magnetic field due to relative motion of the field source and conductor; or due to variations of the field with time. This causes a circulating flow of electrons, or a current, within the conductor. These circulating eddies of current create secondary magnetic fields that oppose the incident magnetic field. The stronger the applied magnetic field, or greater the electrical conductivity of the conductor, the greater the currents developed and the greater the opposing field. The method is applicable only to conductive materials [31, 32, 33]. EC has seen applications for corrosion characterization, since the oxide layer is non conductive and practically acts as a coating on top of a metal, which can be measured [34].

3.4.1 Principles

Eddy current (EC) relies on two basic electromagnetic concepts. First, that current flow in a wire generates a magnetic field that encircles the wire and decreases with radial distance. Second, a magnetic field in proximity to a conductor produces a voltage, or electromotive force (EMF), in the conductor. Assuming a closed circuit, current will flow, which is driven by the potential. Figures 3.1 and 3.2 show the principles of Eddy Current generation and detection [35].

![Figure 3.1: Eddy Current generation [35].](image)

The wire in the source is shaped into loops to concentrate the magnetic field and several loops are added to increase the intensity. The field strength is responsible for a flux density ($B$) and a flux ($\Phi$), which is defined as the integral of the flux density over the relevant area ($da$) in the direction normal ($n$) to that surface [32, 33]
In EC testing, the magnetizing coil is generally close to the test sample, so that the flux it creates strongly affects the sample. This flux is a function of the coil parameters and primary excitation current, $I_p$. This current is generally assumed to be a sinusoidal in nature with angular frequency ($\omega$),

$$I_p = I_0 \sin(\omega t)$$ \hspace{1cm} (3.5)

where $I_0$ is the maximum current. Faraday’s law of electromagnetic induction relates the total captured magnetic flux and the number of wire turns in the coil ($N$) to the induced voltage, $V_{emf}$,

$$V_{emf} = -Nd\Phi/dt.$$ \hspace{1cm} (3.6)

The negative sign indicates that the resultant current flow due to the induced voltage will flow in such a direction as to oppose the change in magnetic flux. This is a statement of Lenz’s law. The current to magnetic flux relationship is

$$\Phi = LI$$ \hspace{1cm} (3.7)

where the constant of proportionality $L$, is the inductance. The value of $L$ accounts for geometric factors of the wire, such as the shape, size, number of the loops, and core permeability[33].
### 3.4.2 Instrumentation

Eddy Current testing is most often carried out with a pair of coils. The first, called excitation coil, is excited by an AC signal. The other is a pickup coil connected to a voltmeter. The excitation coil produces a primary magnetic field, part of which couples with the pickup coil. When the coils are placed near a conductive material, the primary field produces eddy currents in the conductor. The pickup coil detects the drop in the total magnetic field owing to the secondary EC field. A perfect conductor would result in perfect cancellation of the primary magnetic by the secondary one [33].

Several coil configurations may be used. The excitation coil may also act as the sensing coil, so that the voltmeter detects changes through self-inductance. A separate coil may be used as the sensing coil; this coil can be inside, close to, or remote from the exciter coil, and can be split into differential or “cross-axis” configurations. Hall sensors can also be used as sensors, although they require their own circuits [32].

### 3.4.3 Analysis

EC is analyzed by interpreting the flux changes set up in the inspected piece. The equilibrium flux $\Phi_e$ is the difference between the principal excitation flux $\Phi_p$ and the secondary flux $\Phi_s$

$$\Phi_e = \Phi_p - \Phi_s.$$  \hspace{1cm} (3.8)

With the test sample far from the coil, the dominant flux is $\Phi_p$. But as the coil approaches the test sample, $\Phi_s$ is induced and the net flux in the coil changes. If the sample is not ferromagnetic, then $\Phi_s$ is less than $\Phi_p$ and the net flux in the coil falls. Since the flux linkage with the coil controls its impedance, then there is a decrease in the coil impedance. If the sample is ferromagnetic, $\Phi_s$ may exceed $\Phi_p$ because of the high average permeability. This results in an increase in coil impedance. The impedance-inductance plot is usually used to interpret the behavior of the inspected piece [32].

EC is a powerful and sensitive technique. However, several parameters influence the results of EC testing such as geometry of coils, size and shape of inspected piece, proximity to edges, ferromagnetic properties of material, and proximity of sensor to the inspected piece [32]. Thanks to these different variables, EC can be useful in sorting metals and finding flaws. EC in this way has been used to find cracks initiated by fatigue corrosion and stress-corrosion cracking [36]. Since EC is also very sensitive to the separation distance from of the sensing coil and the sensing piece, it can determine coating thickness, such as the thickness of a corrosion oxide layer on a metal. This is what is referred to as liftoff distance characterization [34, 33].
3.4.4 Disadvantages

Although EC has proved to be sensitive to thickness of a corrosion layers, the main limitation is that it is restricted to that task. It provides little direct information on corrosion process and rates of corrosion.

3.5 Other novel measurements of corrosion

3.5.1 pH measurements

pH measurements have been recently proposed to characterize corrosion. In a recent project, pH-induced fluorescence was used to monitor, spatially and temporally, corrosion in aircraft aluminum metal 2024-T3. pH measurements were made through a pH meter and the surface morphology through CCD camera and optical microscopy. The basic concept is that a corroding metal surface is exposed to solutions that contain selected redox chemicals that will react with local anodic or cathodic regions. Redox couples that produce or consume protons in their electrochemical reactions are used so that local pH gradients will indicate activity by inducing fluorescence of chosen dyes [37].

In the experiment a controlled chamber for steel corrosion is accompanied by an UV light source and a CCD camera. As the pH changes, the fluorescence of the dye either increases or decreases, causing a light or dark spot when exposed to ultraviolet light. This spot indicates corrosion initiation. Experiments showed that pH fluctuates significantly until pitting initiates, then it slowly decreases and remains constant [37].

3.5.2 Ultrasonic guided wave measurements

Research on cylindrical with guided waves shows promise for the detection of corrosion of steel reinforcing bars in concrete. Pitting of steel causes reflection and an attenuation loss in the received signal. Conversely, a loss of bond due to uniform corrosion leads to less leakage of the wave energy into the surrounding concrete, and a higher amplitude of the received signal [38].

In the testing configuration, two transducers were used, one for sending and one for receiving. Transducer frequency ranged form 50 kHz to 2 MHz. Accelerated tests were performed and occurrence of corrosion was identified [38]. The major limitation is that to the ends of the rebar is required and, in this case, access to both extremes which makes it even less suitable for field testing.
Chapter 4

Traditional corrosion sensors

4.1 Corrosion of steel in concrete by sacrificial anodes

The most simple sensor which can be used to monitor corrosion of steel in concrete are sacrificial anodes placed at different depths. The anodes are usually black steel to simulate reinforcement. They are electrically connected to a cathode and the current flow between them is measured, and current density is computed. As long as the current densities between the anodes and the cathode are close to typical values for the passive state, corrosion is assumed to be negligible. As carbonation or chloride front reaches the anode, the current rises and the potential drops. If a series of anodes are embedded between the surface of concrete and the steel, the anodes will depassivate one by one, and an estimate can be made to determine when the corrosion front will affect the reinforcement [14].

Embeddable, self-contained LPR probes have also been developed. These sensors contain one or more exposed mild steel working electrodes. The working electrodes represent the embedded steel reinforcement if they are embedded at the same depth and experience the same concrete consolidation conditions as the bar. The sensors are embedded in new concrete construction, with a wire running to a connection at the surface of the concrete. In some cases, the sensor contains a series of parallel working electrodes arranged at increasing depth, from the concrete surface to the reinforcing bar. As each successive working electrode depassivates and indicates increased corrosion currents, the rate of chloride ion or carbonation front ingress can be monitored over time [39]. The Florida Department of Transportation (FDOT) has developed another embeddable probe that measures $i_{corr}$ within a reinforced concrete element. The probe is a 50mm length of #4 (US standard) steel bar with a copper wire connected to one end. The wire and bar are sealed such that only 25mm of bar length are left exposed. The probes are embedded in the concrete nearby the internal steel reinforcement, so they are exposed to an environment that is similar to that experienced by the reinforcement itself. Holes are cored into the concrete and the probes are oriented parallel to the steel reinforcing bars. The holes are then sealed with mortar. Thus the magnitude of the corrosion currents is monitored by the probes. To enable the current flow within the system, however, the electrical circuit
must be completed. This requires that the reinforcing bars be electrically connected and grounded to the sensors. Thus, an access hole to the reinforcing system must be cored and an electrical connection made by tapping with a stainless steel rod that protrudes to the surface. Electrical junction boxes provide connection between the probes and the ground lead, and allow regular data collection from the system. The sensors are relatively large and are wired, which causes some practical problems if applied in a large-scale ubiquitous sensing network [40].

Researchers at the University of Texas recently developed an embedded, wireless, non-powered corrosion sensor for concrete structures [41]. The objective of the sensor is to detect corrosion threshold levels within the concrete, by providing a “binary” output: corroded or not corroded. The sensors are designed to be attached to the concrete reinforcing cage before the concrete is placed. The principle of the sensor is the following. The sensor contains a simple inductive-capacitive (LC) closed electrical circuit, which is represented by a characteristic frequency. When the circuit is “opened” because an external metal wire “switch” has corroded, the resonance frequency shifts to an appreciable higher value. Steel wire is used to fabricate the sacrificial corroding switch in the circuit, which is exposed to the internal concrete environment. This steel wire corrodes and eventually fractures, altering the circuit. The time required for the wire to fracture increases with wire diameter, and different wire diameters can be used to establish different corrosion thresholds. The resonance frequency of the embedded circuit can be interrogated by an external inductive coupling circuit. The sensors are inexpensive to fabricate, are rugged and durable, and can provide information about the initiation of corrosion potential in concrete. Also, the sensors are long-lived, as they do not contain an internal battery and the wireless nature is a great benefit. However, the sensor does not monitor the steel reinforcement directly, but rather indicates the presence of a corrosion-inducing environment in the vicinity of the steel [41].

Most embeddable sensors are inexpensive and rugged. However, the corrosion currents in the rebar system itself are not directly measured; only the corrosive potential of the environment is monitored. In addition it takes time to obtain proper readings because installation of the sensor disturbs the state of equilibrium.

4.2 Concrete resistance

Concrete electrical resistance is a method to measure one of the controlling factors for the corrosion rate of reinforcement. In addition, concrete resistance gives an idea of particular risk zones within a structure. Corrosion resistance depends on geometry between the measuring electrodes, the size of the pore system,
and the ionic mobility of the pore system [42]. Concrete resistance is measured with two or four electrodes arrays. Embedded sensors are preferred since changes in resistivity, for instance due to carbonation, may be measured accurately. The main advantage of these sensors is the possibility of recording the depth-dependent resistivity at small intervals [14].

4.3 Oxygen transport

Oxygen measurements in concrete are based on the assumption that oxygen reduction is the dominant cathodic reaction. By applying a constant negative potential to an embedded electrode, oxygen transport may be inferred as electrical current through Faraday’s law. This is important since it is assumed that oxygen transport rate is the same as the rate of oxygen reduction at the electrode and, therefore, directly related to corrosion rates. Measurements are carried out with a potentiostat, a reference electrode, a counter electrode, and the working electrode (which is the reinforcing steel). Oxygen measurements may vary from location to location [14].

4.4 Humidity sensors

Concrete humidity is a crucial factor for all degradation processes in concrete. Moisture, for instance, influences ion flow and therefore corrosion. Direct measurements of internal relative humidity are difficult in concrete, but can be achieved with electronic sensors placed within drilled holes in the concrete. The sensors have benefited from improvements over the last years, but calibration is still a must. Measurements need to be accompanied by resistance measurements since humidity measurements may differ at each sensor location [14].

4.5 Temperature

Chemical and electrochemical processes, such as corrosion, depend very much on temperature. Most temperature measurements are obtained with thermocouples, preferably embedded in the structure. A thermocouple consists of two metal alloys coupled in a loop. The potential within the loop is an almost linear function of the temperature difference between the couplings and the temperature. Field use requires temperature compensating devices [14].
Chapter 5

Corrosion detection based on magnetic sensing methods

5.1 SQUID magnetic sensors

Superconducting Quantum Interface Devices (SQUIDs) are highly sensitive magnetometers that have been under development for about three decades. These are the most sensitive detectors of magnetic flux currently available. They are versatile and can be used for extremely sensitive measurements, such as monitoring the tiny magnetic fields produced by the brain [43].

SQUIDs combine two physical phenomena: flux quantification, or the fact that the flux in a closed superconducting loop is quantized in units of flux quantum $\Phi_0 \equiv h/2e \cong 2.07 \times 10^{-15}$ Wb, and Josephson tunneling. A Josephson junction consists of two superconductors separated by a thin insulating barrier. There are two types of SQUIDs. The first consists of two parallel Josephson junctions in a superconducting loop. The second operates as single junction interrupting a current flow around a superconducting loop, and it is operated with a radio frequency flux bias [43].

Corrosion in metals has been monitored using SQUID technology. Bellingham and MacVicar placed zinc in different concentration solutions of HCl and showed a direct relationship between the magnetic field and the strength of the corrosive environment using spectral density analysis at low frequencies [44]. Similar tests have been performed on aluminum showing promising results [45].

Although SQUIDs are highly sensitive, they present two major limitations. First, SQUIDs are very costly. The necessary equipment may cost hundreds of thousands of dollars. The other major limitation is that SQUIDs require cryogenic environments and need shielding, which renders them impractical for realistic applications, for example to civil engineering structures [43].

5.2 Hall sensors

A Hall sensor is a transducer that varies its output voltage in response to changes in magnetic field. Typically, the sensor is integrated with a wound core or permanent magnet that surrounds the conductor to
be measured. Some researchers have used the sensors to investigate defects in metals that could arise from corrosion, abrasion, or wear [46].

These sensors have been used to investigate flux leakage and disruptions in the magnetic flux leakage due to defects. Kalwa and Pierkarski worked with steel ropes and found that the width and intensity of the disturbance of the leakage flux depend strongly on the depth level of the defect [47]. They constructed Hall sensors with magnetic concentrators that allowed them to pick both radial and tangential components of the leakage flux, both of which served as strong indicators to the presence and depth of defects in steel ropes [47].

5.3 Giant Magneto-Resistive Sensors

Giant Magneto-Resistive (GMR) sensors are commercially available magnetic field sensors that offer broad sensing range, favorable environmental performance and low power consumption. Miniaturized GMR sensors may be integrated into a single small chip, as shown in figure 5.1. GMR technology was initially developed in 1988 by Baibich et al. with subsequent contributions from Binasch et al. [48, 49]. Since then, GMR technology has spread to several technical areas, from data storage to industrial and road sensing.

The principle behind GMR is now summarized. Layers of ferromagnetic and non-magnetic materials are stacked, originally facing opposite directions due to anti-ferromagnetic coupling. The top and bottom layers are usually soft magnetic layers of iron, nickel and cobalt. The non-magnetic layers are usually comprised of a non-magnetic conductor such as copper. These layers are usually just few micrometers in width. As an external magnetic field is applied, the anti-ferromagnetic coupling is overcome. As this happens, electrical resistance dramatically drops, usually in the range of 10% to 15% [50].

![Figure 5.1: Single GMR chip AA003.](image)

GMR magnetometers are usually configured as a Wheatstone bridge. Their maximum signal output is
typically 350 mV at 100 Gauss with a 5V power supply, although this is sensor dependent. The output from the sensors in volts is converted to Oersteds by the following equation:

\[
Field(Oe) = \frac{Output(V)}{(Sensitivity(1/Oe) \times InputVoltage(V))}
\]  (5.1)

where the sensitivity depends on the sensor used.

The size of GMR sensors is in the order of 1400 µm in length and 350 µm in width. They are highly efficient and have very low power consumption and cost, compared to other magnetic sensors, as illustrated in figure 5.2 [51].

Figure 5.2: Cost and power comparison for different magnetic sensors. The size of the circle indicates the relative size of the device [51].

GMR sensors have been used for NDE efforts and for the inspection of different materials. The most common application is in eddy current inspection, particularly for airplanes. GMR sensors are able to detect holes as small as 0.75mm in diameter and 0.25mm deep within the eddy current test. The use of GMR sensors was also expanded to find cracks [52].

More recently, GMR sensors have been applied to detect corrosion. In a simple test, a multi-layer laboratory specimen was placed between an excitation coil and a GMR array. The maximum thickness was 5.3 mm. A series of magnetic measurements were done removing a layer each time. The magnitude of the data over the frequency range inspected dropped as the thickness grew larger. This could be a useful setup to determine thickness loss due to corrosion [53].

The initial testing with GMR sensors for corrosion sensing were limited to determining thickness loss. The current investigation is focused on developing a technique that can make use of this technology to
determine the location and rate of corrosion.

5.3.1 Testing configuration

During the course of this research GMR sensors were selected to characterize corrosion with magnetic measurements. GMR sensors were either used independently or by constructing a gradiometer which is two aligned sensors separated a fixed distance (20 mm) along their sensing axis. The gradiometer response is computed as the difference of the responses from the two sensors. This acts to compensate for spatially large field variations in the environment.

GMR sensors and gradiometers were placed with their sensing axes perpendicular to the inspected metal sample. In some cases, samples were placed in glass-walled tanks with different solutions while the sensors were outside the tank. Figure 5.3 shows two aligned AA002 sensors in a gradiometer setup taking measurements from a steel plate immersed in an acid solution. GMR sensors were also placed parallel to the testing sample in the corrosive solution with a polymer casing for protection. Table 5.1 shows the magnetic characteristics of the sensors used.

Figure 5.3: Two AA002 sensors in a gradiometer setup for data acquisition from a steel plate. The plate is immersed in a solution inside the glass-walled tank.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Sensitivity (mV/V-Oe)</th>
<th>Saturation field (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA002</td>
<td>3.6</td>
<td>15</td>
</tr>
<tr>
<td>AA003</td>
<td>2.6</td>
<td>20</td>
</tr>
<tr>
<td>AA004</td>
<td>1.1</td>
<td>50</td>
</tr>
<tr>
<td>AA005</td>
<td>0.55</td>
<td>100</td>
</tr>
</tbody>
</table>
5.3.2 Preliminary tests

The first task of this research was to understand how to power and interpret the signals obtained with GMR sensors. Different power sources for the GMR sensors were evaluated. Initially GMR sensors were powered with 1.2V batteries. The GMR sensors allow input voltages up to 24V. One advantage of using a higher input voltage is the magnification of the output voltage and an improvement in the signal-to-noise ratio, as seen in equation 5.1. Several trials were performed with different power supplies. Most AC power supplies introduce significant noise at 60Hz and higher resonances (AC effect). A clean AC power supply with variable output voltages was selected. The power supply was built by Kenwood and has a range of operating currents of up to 10A and 56V. The input voltage was set at 23V to maximize the output voltage of the GMR sensor.

Trials with different GMR sensors and a permanent bar magnet showed the magnetic field decayed as expected in a $1/r$ fashion with increasing source-sensor separation distance ($r$). The measured field was not affected by the presence of a non-ferromagnetic material, such as concrete, placed in between the magnet and the sensor (figure 5.4). After the initial trials, sensor AAH002-02 was selected for all tests since it has the highest nominal sensitivity (14.5$mV/V − Oe$).

![Figure 5.4: Sensor responses to bar magnet at different distances through air and concrete. Responses from two sensors with different sensitivities are shown. Sensors used are AA003 (2.6$mV/V − Oe$) and AA005 (0.55$mV/V − Oe$).](image)

The GMR AA002 sensor was used to characterize a plain bare steel reinforcing bar. The sensors can detect the residual magnetic field in the bar. It is clear that steel bars can possess a strong residual magnetic field, particularly near the bar ends (poles). This field can vary significantly from bar to bar, or even within each bar along the length. Tests on several different bar samples verify this phenomenon, as shown in figure
5.5. These residual fields may mask the magnetic signal resulting from corrosion. As shown in figure 5.5, the shape of the residual field along the bars was not altered by the corrosion although the data show some variability.

Figure 5.5: Residual magnetic field from steel reinforcing bars prior (dashed) and after (solid) accelerated corrosion tests. Two bars are shown for reference, B2 and B8.

Figure 5.6 shows a comparison between the response of the individual sensors that make up the gradiometer owing to the residual magnetic field of a reinforcing bar 19cm long. Sensor 1 is closest to the reinforcing bar and sensor 2 lies behind it with a separation distance of 2mm. The shape of the response from the individual sensors is similar with respect to location and the residual magnetic field from the reinforcing bar is greatly counteracted by taking a gradiometer response, although not completely. The use of gradiometers can be useful to eliminate environmental variability or the effect of residual magnetic fields.
Figure 5.6: Residual magnetic field from steel reinforcing bars along its length. Comparison between individual sensors (S1 and S2) and gradiometer.
Chapter 6

Accelerated corrosion tests

6.1 Standard procedure to generate and monitor steel corrosion in concrete

6.1.1 Description of test procedures

There is no realistic way to simulate corrosion of steel embedded in concrete in the laboratory. The task has an initial difficulty since the basic pore solution in concrete normally passivates steel. There is however an ASTM standard, ASTM G109 - 07 Standard Test Method for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments, which simulates the corrosion of steel reinforcement as a way to look at the effectiveness of chemical inhibitors on corrosion. This method measures changes in electrical potential during cycles of wetting and drying. This simple test requires a voltmeter and a 100Ω resistor [54].

The test specimen is a concrete beam 11.4 cm wide, 14.2 cm tall, and 30 cm long. Three 38cm long parallel reinforcing bars are embedded in each, leaving 2 inches exposed at each end. One bar is placed 2cm to 2.5cm beneath the top surface of the beam, while the other two are placed 2.5cm above the bottom face. The bottom bars act as cathodes and the top bar as an anode. The resistor connects both cathodes to the anode. The bars are epoxy covered on the exposed ends, leaving only 8 inches of bare steel within the concrete. A 3 inch wide, 2 inch tall, and 6 inch long reservoir is built on the top surface with plexiglass. This reservoir lies on top of the exposed area of the reinforcement [54]. See figure 6.1.

Testing follows a specific schedule. A 3% by weight NaCl solution is placed in the reservoir for two weeks followed by two weeks with the solution removed. These wet and dry cycles start 28 days after removal of the beams from a moist curing room. Testing continues until the average integrated macrocell current reaches 150 Coulomb, which is calculated by multiplying the macrocell current (Amps) by the total time for which the measurements are taken (seconds) [54]. Equation 6.1 shows how to calculate the total corrosion (TC) in coulombs at time \( j \) based on measurements from a previous time \( j-1 \). The time is measured in
seconds and the current \( I \) is the macrocell current obtained by dividing the potential measurement by the 100Ω resistance across the anode and the cathodes

\[
TC_j = TC_{j-1} + [(t_j - t_{j-1} \times (I_j + I_{j-1}))/2].
\]  

(6.1)

The procedure relies on the fact that as chloride diffuses through the concrete the upper bar begins to corrode, with the bottom bars remaining passive and acting as cathodes. If an effective inhibitor is added to the mixture it will increase the time for initiation and continuation of corrosion and detrimental solutes will reduce that time [54]. The test is stopped once the average integrated macrocell current reaches 150 coulombs.

### 6.1.2 Results using standard procedure

Based on the ASTM standard, 6 beams were constructed during May and June, 2007. Two concrete mix designs were used with three beams cast using each, for repeatability measurements. The mix designs are shown in Table 6.1. The major difference in the mixtures is the w/c. Higher w/c creates a more porous and weaker concrete. Companion cylinders were cast for each mixture. Their compressive strengths were tested at 28 days following ASTM Standard C39. The average strengths were 36.8 MPa for the lower w/c ratio mix and 29.3 MPa for the higher one.

Figure 6.1: Beams for standard macrocell tests.

Voltage data were taken every week. Additionally, LPR measurements across the anode and cathode terminals were carried out when the beams were ponded. The LPR tests were carried out using commercial
Table 6.1: Macrocell concrete mixture designs

<table>
<thead>
<tr>
<th></th>
<th>w/c = 0.5</th>
<th>w/c = 0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Aggregate (kg/m³)</td>
<td>1779</td>
<td>1779</td>
</tr>
<tr>
<td>Fine Aggregate (kg/m³)</td>
<td>815</td>
<td>887</td>
</tr>
<tr>
<td>Adjusted Water (kg/m³)</td>
<td>292</td>
<td>293</td>
</tr>
<tr>
<td>Cement (kg/m³)</td>
<td>561</td>
<td>467</td>
</tr>
</tbody>
</table>

equipment and software. For the LPR measurements, a copper/copper sulfate half-cell was used as the reference electrode and a copper mesh was immersed in the saline solution in the reservoir as the counter electrode. The VersaStat II, a potentiostat/galvanostat from Princeton Applied Research, was used to control the LPR measurements. The equipment performs $i_R$ compensations and has a minimum current range of $1\mu A$. It then calculates the polarization resistance and from that the corrosion current density may be determined. Figure 6.2 shows the progression of the polarization resistance for two representative beams with time. Values showed a progression with time but had sudden spikes. Results on the additional specimens did not show this progression and fluctuated about zero.

![Figure 6.2: Evolution of polarization resistance for two representative beams. Beam 3 has a w/c of 0.5 and beam 4 has a w/c of 0.6.](image)

The LPR and potential data showed little variation during a year long testing period. Two test specimens were opened and the reinforcing bars analyzed directly for corrosion loss, one for each mixture, after 45 weeks of testing. Although the higher w/c ratio mix showed more visible corrosion, the standard test cycles were not intensive enough to corrode the bars significantly, and mass loss did not exceed 1%. Table 6.2 shows the calculated total corrosion for the different specimens. None of the values approximates the integrated...
macrocell current needed to stop the test based on the ASTM standard. The calculated values are very small implying that there is no corrosion taking place, and this is shown in the progression of the total current shown in figure 6.3 for two representative beams, one for each concrete mixture design.

The data show that there is no existing procedure to generate controlled corrosion. The corrosion process is not only unpredictable but very slow. If a procedure to accurately measure corrosion is to be developed, it should have predictable and time-efficient corrosion generation.

Table 6.2: Total corrosion calculated following ASTM G109 procedure

<table>
<thead>
<tr>
<th>Beam</th>
<th>w/c</th>
<th>Time (weeks)</th>
<th>Total corrosion (Coulombs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>45</td>
<td>1.42</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>55</td>
<td>1.55</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>105</td>
<td>4.24</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>105</td>
<td>5.75</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>105</td>
<td>8.07</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>45</td>
<td>3.01</td>
</tr>
</tbody>
</table>

Figure 6.3: Evolution of integrated macrocell current for two representative beams. Beam 3 has a w/c of 0.5 and beam 4 has a w/c of 0.6.
6.2 Accelerated procedure to generate and monitor steel corrosion in concrete

Results from the standard macrocell procedure, described in the previous section, do not provide rapid and predictable generation and measurement of corrosion. A fast and accurate approach to conduct and control corrosion in metals is needed.

One option available for the generation of controlled and accelerated corrosion in concrete is the application of an electrical potential between the reinforcing steel (anode) and a cathode. As it has been previously discussed, corrosion is an electrochemical reaction, which involves the production and consumption of electrons. The electron flow or current can be related to corrosion activity by Faraday’s law. If a potential difference exists between two metals, then the one with the lower potential (or being less noble metal) will corrode in favor of the other metal (cathode). Electrons flow in a particular direction, leaving the anode and moving to the cathode, thus consuming the anode in the process.

For controlled corrosion tests the electrical potential should vary to maintain a constant impressed current density. An externally applied potential can also drive this process. Keeping a constant current, or current density, enables mass loss calculations using Faraday’s law. Maaddawy and Soudki [55] summarize work on the impressed current technique for steel reinforcing bars in concrete and describe the potentials and current densities used. The current densities range from 200 to 3,000 $A/cm^2$. The specimens, generally beams or slabs, are usually placed in aqueous solutions and actual mass loss due to corrosion in general show good agreement with that predicted by Faraday’s law. Maaddawy and Soudki built concrete prismatic specimens 150x250mm in cross section, and 300mm long. The prisms had two #10 (11.3mm in diameter) steel bars as anodes and a 6mm stainless steel bar as cathode for impressed current testing. Their results showed that the crack width in concrete was directly related to the imposed current, although the crack pattern does not seem to be affected. Cracks generally developed at the side surface adjacent to the reinforcing bar and did not progress internally to the cathode, except for very high impressed currents. The researchers believe that for their test set-up, low applied current density levels give opportunity for corrosion products to spread through the concrete pores, whereas high current densities generate a concentration of corrosion products around the reinforcement and allow for the extension of surface cracks internally [55].

6.2.1 Specimens

Impressed current measurements performed by other researchers showed the feasibility to accurately control and monitor corrosion. A series of tests were run to look at the applicability of the method.
Accelerated corrosion specimens for impressed current testing were built based on specifications from ASTM G109 described previously. The concrete mix had a w/c of 0.5 and was uniform for all specimens. The mix design is shown in table 6.1. Initially, six beam specimens were built. Three beams contained 10% by weight, with respect to the mass of water, of sodium chloride added to the mixing water; this dosage achieves a chloride ion saturated solution. Beams were cured for 28 days in a moist room and were tested after this time. The remaining three beams had no sodium chloride added. A picture of the six constructed beams is shown in figure 6.1.

6.2.2 Estimated corrosion (Faraday’s law)

All six macrocell beams were connected in series. Figure 6.4 shows the connection scheme for the beams. The beams were kept dry, that is they were not ponded with solution during tests. After two weeks of testing, maintaining an electrical current of approximately 0.01A throughout, cracking was observed on the top of the beams which had chloride ion in their mix. A typical cracked beam is shown in figure 6.5. For example, one test was run for 27.8 days in total and current was recorded throughout this period. From Faraday’s law, mass loss can be calculated as follows:

\[ m = \frac{Ita}{zF} \]  
(6.2)

where \( m \) is the mass lost in grams; \( I \) is the current in amps (0.01A); \( t \) is the time in seconds; \( F \) is Faraday’s constant (96500C/mol); \( a \) is the atomic weight (56 for steel) of the metal; and \( z \) is the valence of the metal (2 for steel). Replacing the assumed values above in equation 6.2 yields an expected mass loss of 8.29 grams.

6.2.3 Direct verification

After the testing period, all bars were extracted, polished with a wire power brush, and weighed to determine mass loss. Actual mass loss was determined by subtracting the weight at the end of the accelerated corrosion tests from the initial weight measured before casting of the concrete specimens. A correction was included in the calculations due to the cleaning process. For this correction, the average weight loss from the polishing of the cathodes that exhibit no corrosion is used to establish the mass loss due to polishing. In the results, only the anodes of the bars in concrete with added chloride in the mixture exhibited significant corrosion. Table 6.3 presents the corrected mass loss (considering cleaning losses) and the percentage error with regard to the theoretically predicted value.

These test results show that significant and controlled corrosion can be obtained with impressed current.
Figure 6.4: Layout of accelerated corrosion series circuit. Steel bar anodes indicated by white circles and steel bar cathodes indicated by black circles. Grey lines indicate conducting wire.

Figure 6.5: Corrosion damage in concrete due to accelerated corrosion in steel reinforcement with imposed current.
Table 6.3: Steel mass loss due to corrosion in impressed current samples. The theoretically predicted value is $8.29g$.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Bar</th>
<th>Mass loss</th>
<th>Corrected mass loss (g)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With chloride ions in mixture</td>
<td>Anode 1</td>
<td>8.52</td>
<td>7.85</td>
<td>-5.29</td>
</tr>
<tr>
<td></td>
<td>Anode 2</td>
<td>8.60</td>
<td>7.93</td>
<td>-4.33</td>
</tr>
<tr>
<td></td>
<td>Anode 3</td>
<td>8.78</td>
<td>8.11</td>
<td>-2.16</td>
</tr>
<tr>
<td>Without chloride ions in mixture</td>
<td>Anode 1</td>
<td>0.76</td>
<td>0.11</td>
<td>-98.7</td>
</tr>
<tr>
<td></td>
<td>Anode 2</td>
<td>0.85</td>
<td>0.2</td>
<td>-97.6</td>
</tr>
<tr>
<td></td>
<td>Anode 3</td>
<td>0.65</td>
<td>0</td>
<td>-100</td>
</tr>
</tbody>
</table>

If the chloride ions are dosed in the concrete mixture, there is no need to submerge or pond the samples with an aqueous solution. However, a dry specimen without chloride ions will not corrode significantly, even when impressed current is applied.

### 6.3 Accelerated corrosion test results

Results from standard procedures to generate and monitor corrosion of reinforcement in concrete showed the need to develop a faster and more controlled set-up. The application of impressed currents is one possible solution. There are however several variables to consider when performing impressed current tests in concrete beams. First, most researchers use an aqueous solution to immerse or pond concrete specimens to promote corrosion. Therefore, it is important to understand the effect of ponding on corrosion. The results from the initial macrocell impressed current tests showed good agreement with theoretical values when sodium chloride was added to the mix. But the effects of the level of sodium chloride in the mixture on corrosion must also be studied. The level of the impressed current and the effect on corrosion is a final variable that needs to be understood.

#### 6.3.1 Effect of ponding

The initial test results illustrated the need for chloride ions in the mix to generate corrosion in dry specimens. The ASTM G109 procedure establishes a two week ponding period followed by a two week dry period to promote corrosion. Moisture is then an important parameter to consider. Therefore it was necessary to test the effect of ponding on corrosion. Two sets of six beams each were cast. The mix design had a water/cement ratio of 0.5 and is shown in Table 6.4. The first set had chloride ions, 10% by weight of the mixing water, added to the mixture. The other set had no chloride ions added. In each set, three beams followed a ponding procedure. Ponding was done for two weeks with water followed by two weeks with the water removed.

The concrete beams were left 28 days in a moist room for curing and the compressive strength was
tested at 3, 14, and 28 days. The chloride and non-chloride mixtures compressive strengths were similar. The compressive strength for the mixture with chloride ions at 28 days was 41 MPa and 39 MPa for that without chloride ions. After the 28-day curing period, all beams were connected in series and a current of 0.01 Amps was passed through the system to induce corrosion. Simultaneously, the ponding routine was applied to half of the beams. The test was run continuously for 71 days. At the end of this period, the beams with chloride ions in the mixture exhibited significant corrosion whereas the beams without chloride ions had no observable corrosion. Beams were opened and the reinforcing bars were extracted and polished to determine mass loss. Theoretical values were calculated based on Faraday’s law (equation 6.2). Table 6.5 shows a comparison of the expected and actual mass loss for concrete beams with chloride ions added to the mixture. Results seem to indicate that ponding generates an additional mass loss. Results for the set without chloride ions in the mix were similar with and without ponding. No mass loss was observed in either case.

Table 6.4: Macrocell concrete mixture designs for ponding tests

<table>
<thead>
<tr>
<th></th>
<th>( w/c = 0.5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Aggregate (kg/m(^3))</td>
<td>1163</td>
</tr>
<tr>
<td>Fine Aggregate (kg/m(^3))</td>
<td>599</td>
</tr>
<tr>
<td>Adjusted Water (kg/m(^3))</td>
<td>215</td>
</tr>
<tr>
<td>Cement (kg/m(^3))</td>
<td>429</td>
</tr>
</tbody>
</table>

Table 6.5: Comparison of theoretically predicted and experimental mass loss between beams with and without ponding. All beams had chloride ions added to the mixture.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Bar</th>
<th>Theoretical mass loss (g)</th>
<th>Experimental mass loss (g)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams with ponding</td>
<td>Anode 1</td>
<td>18.50</td>
<td>19.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Anode 2</td>
<td>18.50</td>
<td>21.31</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Anode 3</td>
<td>18.50</td>
<td>20.43</td>
<td>10</td>
</tr>
<tr>
<td>Beams without ponding</td>
<td>Anode 1</td>
<td>8.29</td>
<td>7.85</td>
<td>-5.29</td>
</tr>
<tr>
<td></td>
<td>Anode 2</td>
<td>8.29</td>
<td>7.93</td>
<td>-4.33</td>
</tr>
<tr>
<td></td>
<td>Anode 3</td>
<td>8.29</td>
<td>8.11</td>
<td>-2.16</td>
</tr>
</tbody>
</table>

Results for the set without chloride ions in the mix were similar with and without ponding. Table 6.6 shows a comparison of the expected and actual mass loss for concrete beams without chloride ions added to the mixture. No mass loss was observed in either case. The addition of moisture alone is not sufficient to generate corrosion, whereas the addition of chloride ions to the mixture is.

41
Table 6.6: Comparison of theoretically predicted and experimental mass loss between beams with and without ponding. All beams had no chloride ions added to the mixture.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Bar</th>
<th>Theoretical mass loss (g)</th>
<th>Experimental mass loss (g)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams with ponding</td>
<td>Anode 1</td>
<td>18.50</td>
<td>0.01</td>
<td>-100</td>
</tr>
<tr>
<td></td>
<td>Anode 2</td>
<td>18.50</td>
<td>0.03</td>
<td>-100</td>
</tr>
<tr>
<td></td>
<td>Anode 3</td>
<td>18.50</td>
<td>0.02</td>
<td>-100</td>
</tr>
<tr>
<td>Beams without ponding</td>
<td>Anode 1</td>
<td>8.29</td>
<td>0.11</td>
<td>-98.7</td>
</tr>
<tr>
<td></td>
<td>Anode 2</td>
<td>8.29</td>
<td>0.2</td>
<td>-97.6</td>
</tr>
<tr>
<td></td>
<td>Anode 3</td>
<td>8.29</td>
<td>0</td>
<td>-100</td>
</tr>
</tbody>
</table>

6.3.2 Effect of current levels

Since the imposed current level has an effect on the level and type of corrosion [55], a test series was carried out to study this. Beam specimens with a fixed w/c of 0.5 were cast and all had a chloride ion addition of 10%, by mass of water. The concrete mix design is shown in table 6.4. Construction once again followed that of ASTM G109 and beams were left in the moist room for curing 28 days before testing. Three beams were tested at each current level. The imposed current density levels ranged roughly from $200 \text{ A/cm}^2$ to $500 \text{ A/cm}^2$, in $100 \text{ A/cm}^2$ steps. When significant concrete surface cracking and staining was observed, the applied current was stopped, and the rebar was extracted and polished to allow for mass loss calculations. Experimental mass loss was then compared to the theoretically predicted loss based on Faraday’s law.

Table 6.7 shows the percentage error with relationship to the theoretical expected value for each case. Test duration and mass loss in grams are also shown.

Table 6.7: Comparison of theoretically predicted and actual mass loss caused by different imposed current levels.

<table>
<thead>
<tr>
<th>Imposed current (A)</th>
<th>Time (days)</th>
<th>Charge (C)</th>
<th>Theoretical mass loss (g)</th>
<th>Average experimental mass loss (g)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>29.74</td>
<td>51384</td>
<td>14.91</td>
<td>15.19</td>
<td>2</td>
</tr>
<tr>
<td>0.027</td>
<td>16.55</td>
<td>38601</td>
<td>11.20</td>
<td>10.92</td>
<td>-3</td>
</tr>
<tr>
<td>0.042</td>
<td>10.38</td>
<td>37664</td>
<td>10.93</td>
<td>10.38</td>
<td>-5</td>
</tr>
<tr>
<td>0.05</td>
<td>6.82</td>
<td>29475</td>
<td>8.55</td>
<td>8.51</td>
<td>-1</td>
</tr>
</tbody>
</table>

The results show good agreement between the predicted and measured mass loss, in all cases below 5% error. Macrocell concrete beam specimens with 10% chloride ion addition experience predictable corrosion regardless of the imposed current level. The change of the imposed current level affects the time to reach concrete surface cracking and staining, with shorter periods needed as the imposed current level increases.
6.3.3 Effect of chloride ion concentration

Imposed current levels affect the rate at which corrosion takes place. The results indicate that the predicted values calculated from Faraday’s law match the experimental values well, regardless of imposed current value. All the previous tests were carried out with the same concrete mixture and the same saturation level. It is interesting to study as well the effect of different chloride ion concentration levels when the imposed current level is kept constant.

In order to study the effect of chloride ion addition, concrete beams based on the description on ASTM G109 were once again built. Their mix design was that shown in table 6.4. However, in this case, chloride ion concentration was lowered from the saturation level. Saturation is reached by adding sodium chloride equal to 10% of the water’s weight in the mix. The reduction in sodium chloride added in the mix was done decrementally in steps equivalent to 1% of the water’s weight in the mix, or a 10% reduction from saturation. Current levels were kept constant for all concentration levels at 0.03 Amps. Table 6.8 shows the corrosion results for the different chloride ion concentrations.

Table 6.8: Theoretically predicted and actual mass loss caused by varying chloride ion concentrations

<table>
<thead>
<tr>
<th>Percent of chloride ions by weight of water (%)</th>
<th>Time (days)</th>
<th>Charge (C)</th>
<th>Theoretical mass loss (g)</th>
<th>Average experimental mass loss (g)</th>
<th>Average error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>14.60</td>
<td>37712</td>
<td>10.94</td>
<td>10.58</td>
<td>-3</td>
</tr>
<tr>
<td>8</td>
<td>9.86</td>
<td>25599</td>
<td>7.42</td>
<td>7.3</td>
<td>-2</td>
</tr>
<tr>
<td>6</td>
<td>13.88</td>
<td>35820</td>
<td>10.39</td>
<td>10.40</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>9.87</td>
<td>25333</td>
<td>7.35</td>
<td>7.57</td>
<td>3</td>
</tr>
</tbody>
</table>

Chloride ion concentration level, within the levels tested, does not affect the accuracy of the theoretical predictions of corrosion mass loss. Estimated and actual mass losses show acceptable agreement, implying that chloride ion saturation is not needed to generate significant levels of corrosion by imposed current. Table 6.8 shows that a longer test duration causes more corrosion independently of chloride ion concentration.

6.4 Conclusions

The need for a predictable, controlled and fast procedure to generate and measure corrosion of reinforcing bars in concrete comes from the limitations of existing procedures. The impressed current method in prismatic concrete specimens is a suitable solution. The procedure is predictable and controllable within a wide range of imposed currents and does not require surface ponding if sufficient chloride ions are added to the mixture. These results will enable the study of corrosion with magnetic sensors providing a solid and efficient reference point for corrosion.
The optimal environment for accelerated corrosion for future tests requires the addition of chloride ions to the mixture. Addition should be above 5% with respect to the total mass of water. Impressed current levels should be above 200 $\mu A/cm^2$, to reduce the time of testing. Higher impressed currents result in faster and more aggressive corrosion. However, higher impressed current demand higher voltages which are not always available. Ponding or submerging the samples in water or in a solution of water and chloride ions is not required if chloride ions are already present in the mixture. The combined effect of chloride ion addition and ponding caused higher errors between theoretically predicted and experimental measurements. Figure 6.6 shows all the experimental data obtained in this chapter as a function of the charge in Coulombs. A reference theoretical line is shown. There is general good agreement between theoretical and experimental results with exception of fully saturated specimens that underwent a water ponding cycle or those specimens that had no chloride ions added to the mixture. The mean squared error in this case is $36.62 g^2$. If these outliers are removed from the plot, the mean squared error reduces to $0.162 g^2$. Figure 6.7 shows the theoretical values after outliers were removed.

![Figure 6.6: Experimental and theoretical mass loss as a function of charge for impressed current accelerated corrosion tests.](image-url)
Figure 6.7: Experimental and theoretical mass loss as a function of charge for impressed current accelerated corrosion tests. Non chloride and ponding specimens removed.
Chapter 7

Passive magnetic sensing

Using passive magnetic measurements or flux density, I seek to develop a sensing scheme that can determine corrosion at the moment of testing of metal samples. The principle is to monitor magnetic field changes associated with corrosion activity. This approach is analogous to the acoustic emission method, where elastic waves generated by moving dislocations, cracks, fiber breaks, etc. are used for defect detection in solids [1].

This passive sensing scheme requires that the sensor is able to detect a magnetic field caused by corrosion. It also should be applicable to different metals, for example steel which has ferromagnetic properties and aluminum which does not. Finally, passive sensing should be able to differentiate between different levels of corrosion activity (corrosive environments) on the same sample.

7.1 Description of sensors

GMR sensors were used either independently or in a dual setting configuration. The GMR sensors were placed parallel to the immersed testing samples. While immersed, the sensors were protected by a 0.5mm polymer layer and placed adjacent to the test specimens, separated only by the thickness of this polymer layer. A sketch of this configuration with sensor and sample location is shown in figure 7.1.

7.2 Description of test specimens and environments

7.2.1 Test specimens

Steel and aluminum plates were tested. Steel samples where comprised of A36 steel, which is a mild carbon steel with a carbon content of about 0.25%, without significant alloying. A36 steel is a commonly used structural steel. Aluminum samples were constructed from 2024 aluminum, which has high strength but poor corrosion resistance. 2024 aluminum has copper and magnesium as its alloying elements. Samples were generally 90mm by 25mm in area and with thicknesses varying from 1.6mm to 3.2mm. Most measurements used 3.2mm thick plates. These plates were either bare (uncoated) or “notched”. A bare sample is shown
in the upper portion of figure 7.2. The “notched” specimens were used to simulate localized corrosion. Their surface was polished then coated with epoxy. An additional tape layer was used to ensure the coating impermeability. A 2 millimeter wide, 10 millimeter long strip of coating was removed in the center of the plate face to expose a “notch” for localized corrosion, as shown in figure 7.3.

A third type of specimen was used to study the effects of geometrical differences in the sample, an approach similar to that of other researchers [44]. In theory, the geometrical unbalance cathodically protects the largest part of the piece while the smaller portion preferably corrodes. Figure 7.2 shows an asymmetric sample underneath the bare sample.

### 7.2.2 Test environments

Corrosive environments were designed for each particular metal sample. Based on the Pourbaix diagrams shown in 2.1, aluminum will likely corrode in alkaline environments and steel in acidic environments. Basic solutions were prepared by adding sodium hydroxide to water. The alkalinity of the solutions, determined by the pH, ranged from 12 to 13. This requires that 0.4g to 4g of sodium hydroxide were added to one liter of water. Acidic solutions to corrode steel were prepared by diluting 1M hydrochloric acid. The prepared solutions had a pH in the range of 1 to 2. This requires an addition of at least 10mL of the strong acid to water. The pH measurements were taken using a IQ 150 hand-held pH meter and a direct pH probe.

Some test environments also involved electrolytes for galvanic cell studies. These electrolytes were prepared by adding 20 mg of sodium chloride to 200 ml of water, or 6 grams of copper sulfate to enhance the cationic flow. These solutions were used for proof of concept rather than to generate corrosion, as it will be...
7.3 Description of analysis schemes

7.3.1 Time domain analysis

Signal voltage, which is transformed to magnetic field, is obtained from the GMR sensors at regular intervals, giving a time signal. The data were collected using a range of temporal sampling rates, from 20S/s to 1MS/s. The most common sampling rate was 10kS/s. 8192 points were acquired each time to create a single signal.

In order to correct signal variability due to both sensor inconsistency and ambient noise, two approaches were taken. First, a set of sensors, such as that shown in 7.1 can be used to correct for ambient noise at the
moment data are taken. The signal from two or more sensors can be used to differentiate random ambient noise from the magnetic data of interest. The signal from the sensor close to sample is compared to the signal from the companion sensor which is further away. If both sensors present a signal feature such as a spike, this implies that the change in the signal originates from an external source. In contrast, if the near sensor measures a change in the magnetic field when corrosion takes place and the companion sensor presents a steady behavior, then this is a true measurement since the change is not caused by an external source. The second approach to correct for variability is to take accompanying ambient magnetic field measurements and use them as reference to correct the measurements from the sample. In this case, instead of comparing magnetic measurements between two sensors, the behavior of the same sensor in different environments is used to eliminate sensor inconsistencies. Random variability in the time signal can be reduced by averaging several consecutive signals. This is called time averaging.

### 7.3.2 Frequency domain analysis

Frequency-domain responses were also investigated in an effort to understand the dynamic characteristics of the magnetic field set up by corrosion currents. In this representation the signal content at each frequency is given. In order to obtain a signal in the frequency domain, the time domain signal must be operated by a mathematical transform; in this case the Fourier transform is used. This transform can be envisioned as decomposing the time signal into a series of sine wave components with varying amplitude, frequency, and phase. Numerically this transform is accomplished using the FFT algorithm.

Magnetic time domain data were converted to the frequency domain using the FFT algorithm in Matlab and the magnitude of the data are presented. Different characteristics of the frequency plots were used to interpret the responses. For example, one approach was to look at spectral peak frequencies in the magnitude (amplitude) spectrum.

### 7.3.3 PSD analysis

Power spectral density (PSD) analysis was also investigated; PSD is also a frequency domain representation. PSD is often used as a signal processing tool for analysis of random processes. PSD is a positive real function of frequency associated with a stationary stochastic process, or a deterministic function of time, which has dimensions of power per Hz, or energy per Hz. The spectral density captures the frequency content of a stochastic process and helps identify periodicities. A simple analogy is the following. Just as a time signal may be described in terms of its frequency amplitude spectrum, an autocorrelation function has a counterpart in the frequency domain. This counterpart will have a number of spectral lines representing the
power at the various components. In other words, the PSD shows the strength of variations (energy) as a function of frequency. Thus PSD describes how the power of a signal is distributed with frequency, so it shows where frequency variations are strong and where they are weak \[56, 57\].

The PSD, \(S_x(f)\), of the time-domain signal \(x(t)\) can be expressed as the average of the Fourier transform magnitude squared, over a time interval \(T\):

\[
S_x(f) = \lim_{T \to \infty} E \left\{ \frac{1}{2T} \left| \int_{-T}^{T} x(t)e^{-j2\pi ft} dt \right|^2 \right\},
\]

(7.1)

where \(j = \sqrt{-1}\) and \(E\) is the average energy defined by:

\[
E = \int_{-\infty}^{\infty} |x(t)|^2 dt.
\]

(7.2)

### 7.4 Experimental results

#### 7.4.1 Preliminary tests

Preliminary measurements were performed to determine if the GMR sensors are capable of detecting small magnetic fields. First, a single GMR sensor was used to measure the magnetic field generated by a wire carrying a 40mA DC current. The field value is obtained by taking the average value of the magnetic field within the time domain signal. Each time domain signal has 8192 points acquired at 10kS/s. The result is shown in figure 7.4. The single sensor can clearly identify when the current running through the wire.

The next step is to monitor if a current running through an asymmetric aluminum plate can be monitored by a GMR sensor. The electrodes were connected to the larger portions of the plate. The GMR sensor was placed parallel to the thin section connecting the two portions of the asymmetric sample, such as that in figure 7.2. Figure 7.5 shows that there is reasonable agreement between the 40mA input current, which was set to be of the order of the current measured through galvanic coupling, and the resulting magnetic field. The result shows that this field can be monitored through the thin section of the asymmetrical plate.

#### 7.4.2 Galvanic cell studies

GMR sensors can detect small magnetic fields. The next step is to look at the corrosion currents and magnetic fields generated by those currents. A galvanic cell is a good starting configuration to investigate
Figure 7.4: Magnetic field (top) and current (bottom) measurements across a current carrying wire. An AAH002 GMR sensor was used.

Figure 7.5: Magnetic field (top) and current measurements (bottom) across a current carrying aluminum plate. An AAH002 GMR sensor was used.
the process by which corrosion takes place under known and controlled environments. A galvanic cell with
dissimilar metals was constructed. Aluminum and steel samples were used as the anodes and a copper plate
as the cathode. Copper was selected since it has a higher reduction half-cell potential than either steel or
aluminum. The setup is shown in figure 7.6. The electrode metals are placed in the same tank with the
electrolyte. They are connected by a copper wire which allows current to flow from anode to cathode. That
same wire was coiled into several loops around a ferromagnetic core. The purpose of the coil is to generate a
steady unidirectional magnetic field for the GMR sensors to measure. The current flow was measured with
an ammeter.

Figure 7.6: Setup for magnetic sensing of galvanic magnetic fields

Several different electrolytes were evaluated. The first was prepared by adding 20 mg of sodium chloride
in 200 ml of water. Magnetic and current measurements were also acquired with both metals without
electrolyte (ambient measurements), and with the container filled with plain water. Once the electrolyte
was placed in the environment, measurements were taken at different times to investigate the evolution of
the fields and currents.

Figure 7.7 shows results for magnetic field measurements and corresponding current measurements for
a galvanic cell composed of aluminum and copper in a sodium chloride solution. The magnetic field values
were obtained by subtracting the average of the raw signal in air. The magnetic field measurements show
similar trends as corresponding current measurements over time. Both the current and the magnetic field
are not large, which is probably related to the electrolyte. The result proves that GMR sensors can detect
the magnetic field set up by corrosion currents.

The frequency domain analyses of the time signals do not provide much useful information about the
Figure 7.7: Magnetic field (dotted line) and current (solid line) responses from a galvanic cell between aluminum (anode) and copper (cathode) in sodium chloride solution. Measurements in solution were taken from 0 to 10 minutes.

dynamics of the currents. Figure 7.8 shows that the principal difference between the ambient noise measurements in air and the galvanic couple in a sodium chloride solution lies on the lower frequencies related to the DC offset. The spectral peak frequencies are the same for reference measurements and measurements with the electrolyte in the environment. The PSD analysis shows similar results. Once again there are no differences in spectral peak amplitude. Figure 7.9 shows that the main difference is related to the very low frequency region.

Figure 7.8: Amplitude frequency domain representation of magnetic field data for a galvanic cell between aluminum (anode) and copper (cathode) in a sodium chloride solution. Mean responses in air and at ten minutes after the addition of solution are shown.

The galvanic measurements were improved by adding copper ions to the solution to enhance cationic
Figure 7.9: PSD representation of magnetic field data for a galvanic cell between aluminum (anode) and copper (cathode) in a sodium chloride solution. Mean response in air and at ten minutes after the addition of solution are shown.

flow. Six grams of copper sulfate were added to a 200 ml solution of sodium chloride. An aluminum plate was the anode while a copper sheet was the cathode. Magnetic and current measurements were taken at different times.

Figure 7.10: Magnetic field (dotted line) and current (solid line) responses from a galvanic cell between aluminum (anode) and copper (cathode) in a solution with sulfate ions. Measurements in solution were taken from 0 to 10 minutes.

Figure 7.10 shows the result, which verifies that corrosion generated magnetic fields are measured. But in this case, the current and magnetic measurements are about one order of magnitude larger than those obtained with the sodium chloride electrolyte. The frequency domain and PSD analyses did not show any meaningful dynamic characteristics and the same conclusions as in the previous case are drawn. Figures 7.11
and 7.12 show that neither the spectral peak frequencies nor their amplitudes vary between the reference case and the measurements with the solution in the environment.

![Amplitude frequency domain representation of magnetic field data for a galvanic cell between aluminum (anode) and copper (cathode) in solution with sulfate ions. Mean response in air and at ten minutes after the addition of solution are shown.](image1)

**Figure 7.11:** Amplitude frequency domain representation of magnetic field data for a galvanic cell between aluminum (anode) and copper (cathode) in solution with sulfate ions. Mean response in air and at ten minutes after the addition of solution are shown.

![PSD representation of magnetic field data for a galvanic cell between aluminum (anode) and copper (cathode) in solution with sulfate ions. Mean response in air and at ten minutes after the addition of solution are shown.](image2)

**Figure 7.12:** PSD representation of magnetic field data for a galvanic cell between aluminum (anode) and copper (cathode) in solution with sulfate ions. Mean response in air and at ten minutes after the addition of solution are shown.

The effect of a corrosive (to anodic electrode) electrolyte is investigated next. This environment best simulates the corrosion processes of interest. Different basic solutions were prepared. An aluminum sample was immersed with a copper plate and magnetic and current data were taken.
Figure 7.13 shows an individual sensor response with time. The responses of current and magnetic measurements are similar with respect to time. The responses obtained are comparable to those from the galvanic cell with sodium chloride and sulfate ions in solution.

![Figure 7.13: Magnetic field and current response from a galvanic cell between aluminum (anode) and copper (cathode) in basic solution.](image)

Similar measurements were taken with a steel anode in acidic solutions. A copper sheet was used as the cathode. Figure 7.14 shows the results of the galvanic couple in pH 0.74 solution. Ambient noise measurements were taken with the galvanic couple in air. The corrosive solution was then added and the current and magnetic field were monitored at the moment of addition and after 10 minutes. Ten repetitions were taken each time. When the corrosive solution is added, the field and current sharply rise. Then, both drop with time and stabilize at a lower value, but once again there is good agreement between them. Results are smaller from those with an aluminum anode since the reaction is much more aggressive for aluminum.

Galvanic cells using two samples of the same metal, one acting as a cathode and the other as the anode, were constructed. The test was performed using a large aluminum block as the cathode and a smaller and thinner aluminum plate as the anode. The metals were immersed in a corrosive electrolyte. The electrolyte was prepared with sodium hydroxide and had a pH of 12.88.

Figure 7.15 shows that there is agreement between magnetic and current measurements. Current and magnetic field are measurable and increasing with time. This configuration most closely simulates aluminum’s environmental corrosion proving that passive sensing of corrosion currents is possible for this case.
Figure 7.14: Magnetic field (top) and current response (bottom) from a galvanic cell between steel (anode) and copper (cathode) in acid solution.

Figure 7.15: Magnetic field (dotted line) and current (solid line) response from a galvanic cell between small aluminum plate and large aluminum block in a basic solution.
7.4.3 Asymmetric guided corrosion sample

Results from the galvanic couples and current carrying plates showed that small magnetic fields can be detected by a GMR sensor in proximity to the sample. Now, the ability to detect magnetic fields set up by corrosion currents is investigated. Uncoated asymmetric corrosion samples, such as the one shown in the bottom of figure 7.2, were tested to determine if a geometrical imbalance enhances the corrosion magnetic field by guiding corrosion currents along the thin section of the sample between the smaller to the largest section [44]. This configuration should provide similar results to those already shown in the preliminary tests, such as those in figure 7.5. The geometrical imbalance should protect the bigger section at expense of the smaller section, thus generating a current and a related magnetic field.

The magnetic field measurements were taken across the thin strip connecting both sections, placing the sensor adjacent to that region, using the configuration shown in figure 7.1. Data from the sample in air were first collected for reference purposes. Then data were collected from the sample at different time intervals after it was placed in a basic solution. Five repetitions were taken for each case. Both sensor and sample remained fixed during the process. Figure 7.16 shows the average magnetic field of the time domain signal.

![Figure 7.16: Magnetic field measurements from a corroding asymmetric aluminum plate. An AAH002 GMR sensor was used and data were sampled at 10kS/s. Five repetitions of measurement of plate in air and in solution at 1 and 5 minutes after immersion are shown.](image)

Results in figure 7.16 show that the magnetic field set up by a corroding sample can be detected. The field values measured during corrosion remain relatively constant and are clearly larger than the reference measurements in air. There is a 50mOe increase in the field over the air case.

Figures 7.17 and 7.18 show the spectral contents of the time signals. There is no clear distinction between corroding and reference cases, neither in amplitude nor PSD spectra. Again, most of the spectral energy is
Figure 7.17: Frequency domain representation of magnetic field data for an aluminum asymmetric plate in air and after 5 minutes in a corrosive (basic) environment.

Figure 7.18: PSD representation of magnetic field data from an asymmetric aluminum plate in air and after 5 minutes in a corrosive environment. Energy is concentrated in the lower frequencies, below 10Hz.
contained at the very low frequencies, below 10 Hz.

The effect of different corrosion environments was also studied. An asymmetric aluminum plate was monitored using an AAH002 GMR sensor in air, water, and two basic solutions with varying pH. Measurements in air collected on the sample were used for reference. A single measurement was taken in each environment. Table 7.1 shows the average magnetic field value after subtracting the reference field value in air. The results show an increase in the field value with the corrosivity of the medium (measured as pH).

Table 7.1: Magnetic field measurements for a corroding asymmetrical aluminum plate. An AAH002 GMR sensor was used and data were sampled at 20S/s.

<table>
<thead>
<tr>
<th>pH</th>
<th>Average increase in the magnetic field (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.48</td>
<td>0.01165</td>
</tr>
<tr>
<td>12.41</td>
<td>0.02051</td>
</tr>
<tr>
<td>12.63</td>
<td>0.07094</td>
</tr>
</tbody>
</table>

The results from the asymmetric samples show that magnetic field set up by corrosion currents can be detected with GMR sensors in close proximity to the sample. Two questions arise from these results. First, is the asymmetric geometry actually enhancing the magnetic field by guiding the corrosion currents? Second, can the same results be obtained with a bare symmetrical plate, eliminating the need for production of special samples? In order to study this issue a bare, symmetric aluminum plate was corroded and the results were compared to those from the asymmetric sample. For each sample type, two measurements were taken in a highly corrosive basic solution (pH 12.91). The magnetic fields were monitored as the solution was added. The sensor for the bare, asymmetric sample was placed near the center of the plate to avoid edge effects. Figure 7.19 shows the responses from two independent asymmetric samples in the same corrosive environment. Ten repetitions were taken each minute during four minutes after the addition of the solution. The time signals were zeroed by subtracting the average value of the time signals collected on the sample in air from the corrosion samples. There is great agreement with each other, implying that the results are repeatable in the same environment for the same sample type.

For comparison purposes, the same test was run with two independent solid symmetric plate samples. The responses are shown in figure 7.20. Again the behaviors of both samples are very consistent with each other.

Now the responses of the asymmetric and solid symmetric plates are compared in a single graph, for one of the measurements; this comparison is shown in figure 7.21. The magnetic field response in the time domain shows no difference between the response of the asymmetric plate and the symmetric, bare plate. The overall behavior is an increase in the average magnetic field and the ultimate magnetic field is the same. There is however a small difference in the rate at which the ultimate magnetic field value is attained. After
Figure 7.19: Zeroed magnetic field responses for two asymmetric aluminum samples in the same basic solution. Hollow markers represent the first sample and solid markers the second one.

Figure 7.20: Zeroed magnetic field responses for two symmetric aluminum plate samples in the same basic solution. Hollow markers represent the first sample and solid markers the second one.
the addition of the corrosive solution, the behavior was immediately monitored. This transition zone shows
the small difference in the rate at which the ultimate magnetic field value is reached. The value for the
asymmetric sample seems to rise more sharply than the response of the solid plate.

![Graph](attachment:image.png)

Figure 7.21: Zeroed magnetic field comparison between asymmetric and symmetric aluminum plates in the
same basic solution. Hollow markers represent the solid plate and solid markers the asymmetric one.

The spectral responses of the asymmetric plate are essentially similar to that of the solid plate, except for
some minor additional peaks. The spectral data are shown in figures 7.22 and 7.23. As before, the spectral
energy of the signals are contained in the same very low frequency ranges.

The results suggest that the asymmetric and symmetric samples corrode at the same rate, meaning that
the asymmetric shape does not meaningfully enhance corrosion along the thin connecting strip. To verify
this assertion the thickness loss along the asymmetric sample was measured directly. If the asymmetric
shape should favor corrosion, the smaller section should lose more material. Measurements were done with
a caliper before and after a one hour and half of immersion in a basic solution. Measurements were taken
for both the asymmetric and solid plates at ten locations, shown in figure 7.24.

Table 7.2 shows the change of the thickness for both plate types. There is no particular trend observable,
and the thickness loss over the narrow connecting section is on the same order of magnitude as the thickness
loss everywhere else in the plate. The change in thickness across the length for both plate types is illustrated
in figure 7.25. In conclusion, the measurements in asymmetric and symmetric samples are identical within
the error of the measurement. This eliminates the need to produce special samples to measure corrosion and
studies can be performed on bare symmetric samples.
Figure 7.22: Frequency domain representation of magnetic field data for aluminum plates in a corrosive environment. The behaviors of an asymmetric sample and a solid plate are compared.

Figure 7.23: PSD representation of magnetic field data for aluminum plates in a corrosive environment. The behaviors of an asymmetric sample and a solid plate are compared.

Figure 7.24: Sketch showing locations for thickness measurements on the asymmetric aluminum sample.
Table 7.2: Thickness measurements for asymmetric and solid aluminum plates prior to and after corrosion. All measurements are in millimeters. Test locations indicated in figure 7.24.

| Specimen type | Time   | a   | b   | c   | d   | e   | f   | g   | h   | i   | j   |
|---------------|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Asymmetric    | Before | 3.06| 3.06| 3.06| 3.07| 3.08| 3.10| 3.10| 3.10| 3.10| 3.14|
|               | After  | 3.03| 3.03| 3.04| 3.05| 3.05| 3.06| 3.06| 3.08| 3.09| 3.12|

Figure 7.25: Thickness change due to corrosion along asymmetric and solid plates. Change for solid plate is shown as white bars and change for asymmetric plate is shown as black bars. Locations $a$ through $j$ are shown in figure 7.24.
7.4.4 Bare plate: aluminum

The results from the asymmetric samples show that the geometric imbalance is not needed to guide corrosion currents in the sample. GMR sensors can detect the small magnetic fields from uniform corrosion on symmetric, bare plates. Measurements can therefore be then done on bare plates to develop a generalized relationship between corrosion and measured magnetic fields.

The relationship between the corrosivity of the medium and the measured magnetic field was studied first. Aluminum samples were placed in different solutions and the corrosion rate was monitored by measuring mass loss. Corrosion rate \((R)\) is calculated by the following equation:

\[
R(\text{mm/y}) = \frac{87.6(W)}{\rho AT}
\]

where \(W\) is the weight loss in milligrams, \(\rho\) is the density in grams per cubic centimeter, \(T\) is the time in solution in hours, and \(A\) is the area measured in square centimeters [1]. The constant, 87.6, is a conversion factor which depends on the units used.

![Figure 7.26: Magnetic field (time domain) measurements and corrosion rate loss for an aluminum sample as a function of pH. Corrosion rates are shown as empty circles and magnetic field measurements as solid circles.](image)

Magnetic measurements were taken with an AAH002 sensor and data were sampled at 10kS/s using configuration shown in figure 7.1. Ten magnetic field time signals were collected for each case and all values were corrected for ambient noise. Measurements in the solutions were zeroed by subtracting the average value of the time signal collected on the sample in air. Figure 7.26 shows both the average magnetic field from the time signal and corrosion rate as a function of pH. It is clear that magnetic field data and corrosion rates follow the same trend, with increasing value as the environment becomes more basic. A relationship between corrosion rates and magnetic field measured using this testing configuration is established based on
the data of the aluminum samples, shown in figure 7.27.

Figure 7.27 shows an apparent linear relationship between the corrosion rate and the emitted magnetic field for aluminum in basic environments. This relationship remains linear when plotted in a logarithmic scale, which is shown in figure 7.28. The equation for the established linear relationship between corrosion rate \( (R) \) and emitted magnetic field \( (MF) \) based on data from 7.27 is \( R(\text{mm} / \text{y}) = 5523 \times MF(\text{Oe}) + 1.31 \). The coefficient of determination \( (R^2) \) for this fit is 0.98.

Figure 7.27: Observed relationship between the corrosion rate and emitted magnetic field for bare aluminum samples. A linear trend is shown.

Figure 7.28: Logarithmic plot of the observed relationship between the corrosion rate and the emitted magnetic field for bare aluminum samples.
The dynamics of the corrosion process were studied by looking at the frequency domain and power spectral densities of the magnetic field time signals. Figures 7.29 and 7.30 shows that there is little difference in the spectral response between the base noise measurements in air and the measurements taken from an aluminum plate after it has been submerged five minutes in a corrosive solution. Figure 7.30 shows that most of the spectral energy is concentrated at the very low frequencies, below 10Hz. Once again both signals follow similar trends, and little difference is observed between them.

Figure 7.29: Frequency domain representation of magnetic field data for a bare aluminum plate in air and after 5 minutes in a corrosive (basic) environment.

Figure 7.30: PSD representation of magnetic field data for a bare aluminum plate in air and after 5 minutes in a corrosive environment.
7.4.5 Bare plate: steel

The tests on bare steel plates followed the same procedures as those for bare aluminum plates. Samples were immersed in solutions of different acidity, with pH ranging from 0.45 to 2.1. A GMR sensor set was placed adjacent to the sample, as shown in figure 7.1. Measurements in air were taken to set a reference for the magnetic noise level in the laboratory. The average value of the time signal collected on the sample in air was subtracted from the data to zero the measurements. Figure 7.31 shows the average magnetic field amplitude signals from air, water, and in a corrosive solution. The reactive solution has $pH = 0.84$ and was obtained by adding 30 ml of HCl to 1000 ml of water. The results show that there is a slight increase in the average field amplitude when the steel is immersed in water and a larger increase when it is immersed in acid.

![Figure 7.31: Magnetic field measurements for a corroding bare steel plate. An AAH002 GMR sensor was used and data was sampled at 10kS/s. Measurements in air, water (pH=8.98), and in a corrosive solution (acid/pH=0.84) after 30 minutes of immersion are shown.](image)

Figure 7.31: Magnetic field measurements for a corroding bare steel plate. An AAH002 GMR sensor was used and data was sampled at 10kS/s. Measurements in air, water (pH=8.98), and in a corrosive solution (acid/pH=0.84) after 30 minutes of immersion are shown.

The frequency domain and PSD plots of the magnetic time signals are shown in figures 7.32 and 7.33. As in the case of aluminum, the spectral plots show little or no distinction between corrosion and baseline noise measurements with respect to frequency. This suggests that there are no clear dynamic parameters in the magnetic field data that indicate corrosion activity. Also, the spectral energy content is again dominated by very low frequencies, which indicates a process dominated by DC (zero frequency) currents. Thus, the average field value of the time domain signal will likely serve as a sufficient indicator of corrosion activity.

Corrosion of steel in acid solutions occurs at a slower rate than that of aluminum in basic solutions. Steel was immersed in acid solutions for 48 hours to obtain significant mass loss. Figure 7.34 shows the relationship of corrosion rate (mass loss) computed with equation 7.3 and emitted magnetic field as a function of pH.
Figure 7.32: Frequency domain representation of magnetic field data for a bare steel plate in air and after 15 minutes in a corrosive environment (acid).

Figure 7.33: PSD representation of magnetic field data for a bare steel plate in air and after 15 minutes in a corrosive environment (acid).
A relationship between corrosion rate and average magnetic field in the time signal is observed. Magnetic field and corrosion rate both tend to decrease with higher pH. This relationship is shown on a linear scale in figure 7.35 and in logarithmic scale in figure 7.36. We could use these relationships, and also the ones established for aluminum, to determine corrosion rate from magnetic field measurements. The linear relationship between corrosion rate \( R \) and emitted magnetic field \( MF \) is \( R(\text{mm/y}) = 4.7 * MF(\text{Oe}) + 0.19 \). The coefficient of determination \( (R^2) \) for this fit is 0.88.

The relationship between corrosion rate and emitted magnetic field is linear in the logarithmic space.
as shown in figure 7.36. A linear relation in logarithmic space was also observed for aluminum, but the differences in the corrosion rates result in a distinct relationship. The logarithmic equation relating emitted magnetic field and corrosion rate is \( \log(R(\text{mm/y})) = 0.164 \times \log(MF(\text{Oe})) - 0.251 \). This fit has a coefficient of determination \( (R^2) \) of 0.95.

Figure 7.36: Logarithmic plot of observed relationship between directly measured corrosion rate and emitted magnetic field measurements for A36 steel.

### 7.4.6 Effects of demagnetization

Ferromagnetic materials may exhibit a residual magnetic field. The processing and magnetic exposure history of the sample affects the magnitude of the residual field. It is therefore important to determine the effect of the residual magnetic field on the passive magnetic measurements.

A36 steel samples were studied prior to (untreated) and after demagnetization. A Bergeon number 2321 demagnetizer was used to demagnetize the plates. Plates were slowly passed ten times across the demagnetizer to remove all residual magnetic fields.

The daily fluctuations of the plates’ magnetic field with the sensors in close contact were studied prior to and after de-magnetization. Figure 7.37 shows the raw magnetic field fluctuations over time for both a demagnetized and untreated steel plate. The magnetic field from the de-magnetized plate is smaller than that from the untreated plate, as expected. The field from the de-magnetized steel plate is nearly zero. Fluctuations are noticeable.

A zeroing procedure is applied to the raw data from both plates. Zeroing is achieved by subtracting the daily average response from each plate, centering their daily fluctuation around zero. The data in figure 7.38 show that the zeroed data give consistent results, independent of the magnetization level of the steel.
Figure 7.37: Raw magnetic field comparison between an untreated and de-magnetized steel plate in air.

Figure 7.38: Zeroed magnetic field comparison between a untreated and de-magnetized steel plate in air.
The influence of the steel’s magnetization level on the ability to detect active corrosion was studied. An A36 steel plate was submerged in an acidic solution with pH 0.89. Magnetic field data were collected from the plate prior to and after the submersion in the solution. The sensing configuration used was shown in figure 7.1. Passive magnetic measurements were taken in air for reference and after one hour of immersion in the corrosive solution. The plate was then removed, cleaned, and demagnetized. Passive magnetic measurements were then repeated. Figure 7.39 shows that the magnetization level does not alter the zeroed passive magnetic results. The same zeroing procedure was used to eliminate the effect of the residual magnetic field from the untreated sample.

Figure 7.39: Zeroed magnetic field measurements for a corroding bare steel plate prior (solid bars) and after demagnetization (hollow bars). An AAH002 GMR sensor was used and data were sampled at 10kS/s. Measurements in air and in a corrosive solution (acid/pH=0.84) after 60 minutes of immersion are shown.

7.4.7 Notched plate: aluminum

The results of tests on bare aluminum and steel samples immersed in corrosive environments demonstrate that magnetic field measurements can detect active corrosion, and therefore could be used to estimate the rate of general corrosion. Another point of interest is to establish if localized (pitting-type) corrosion can be detected and quantified. For this purpose notched samples, such as that shown in figure 7.3, were used.

The corrosion rates of the notched samples were compared to those of bare plates to determine if there are similarities in the corrosion process itself, and further to establish if the magnetic field-corrosion rate relationships developed for bare plates can be applied to the “notched” plate case. Table 7.3 shows the measured corrosion rates for both specimen types computed using equation 7.3. Their differences are within 10%, which suggests that the same corrosion process is taking place in both sample types. This implies that
a similar relationship between magnetic field measurements and corrosion rate can be used for the “notched” plates, and the same passive measurement approach could be applied to characterize localized corrosion.

Table 7.3: Comparison of bare plate and “notched” aluminum samples corrosion rate in corrosive solutions with varying pH.

<table>
<thead>
<tr>
<th>pH</th>
<th>Bare plate corrosion rate (mm/y)</th>
<th>“Notched” plate corrosion rate (mm/y)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.54</td>
<td>10.12</td>
<td>9.28</td>
<td>-8.29</td>
</tr>
<tr>
<td>12.79</td>
<td>14.49</td>
<td>15.25</td>
<td>5.25</td>
</tr>
<tr>
<td>13.06</td>
<td>25.24</td>
<td>23.81</td>
<td>-5.65</td>
</tr>
</tbody>
</table>

The experimental tests that apply magnetic field measurements to detect localized corrosion for “notched” plates are comprised of two steps. First, the samples were scanned with GMR sensors along locations of exposed and coated metal in air to obtain reference measurements. Then, the plates were immersed in a corrosive solution and the scan along the same line on the sample was repeated.

The corrosion results were zeroed with respect to the reference values obtained in air at each test location by subtracting the average value of the time signal collected on the sample in air. A typical result is shown in figure 7.40 where three measurements were taken over the notch region and four measurements were taken over coated metal region, two at either side of the notch. The figure illustrates that measurements over the notch, where corrosion is taking place, are higher than measurements over the coated metal, at either side. However this difference is not significant compared to signal variability likely introduced by sensor movement.

![Figure 7.40: Zeroed average magnetic field across a notched aluminum sample in corrosive solution.](image)
Another approach to improve the results is to employ a second sensor to monitor ambient magnetic field away from the tested plate as a reference, instead of performing two independent scans with one sensor. A sketch of this configuration was shown in figure 7.1. This simultaneously reduces spatial and temporal variability in the data. Near sensor measurements are zeroed by subtracting the companion’s sensor average magnetic field data. Figure 7.41 shows a comparison of measurements over the notch and a coated portion of the plate. Base ambient noise measurements ("nothing") are also shown. Ten repetitions were taken at each location. Base ambient measurements fluctuate about zero. Measurements over the coated portion of the plate and over the notch are higher than the ambient noise, but great variability is still observed.

Figure 7.41: Zeroed magnetic field across a notched aluminum sample in corrosive solution.

The averaged response of the ten repetitions across each location, shown in figure 7.41 indicates improved identification of corrosion. Figure 7.42 shows this averaged response which clearly indicates a differentiation between the measurements over the notch and coated regions, where the average magnetic field over the notch is notably higher.

The dynamic response of the magnetic field is examined with the frequency amplitude and PSD analyses, which are shown in figures 7.43 and 7.44. These analyses show again that there are no significant spectral differences between the response over a coated area of the plate and the notch, although there is some additional spectral content for the measurements over the notch; this is particularly visible in the 200 to 300 Hz range in the PSD plot in figure 7.44. However, this distinction is not considered as significant.
Figure 7.42: Average magnetic field across scan along a notched aluminum sample in corrosive solution. Measurements were zeroed with respect to the ambient noise measurements.

Figure 7.43: Frequency domain representation of magnetic field data for a notched aluminum plate in a corrosive environment. The behaviors over coated metal and the notch are compared.
7.4.8 Notched plate: steel

Magnetic field measurements were also carried out along notched steel samples. Magnetic field data were collected from notched samples in air and in corrosive solutions. Data were collected at three locations: well away from the range of influence of the plate (reference), over a covered or coated section of the plate, and over the notch or exposed area. Ten repeated data sets were taken at each location.

Figure 7.45 shows the raw average magnetic field from the time signal collected across a steel notched sample in air (solid bars) and in a corrosive solution (hollow bars). The magnetic field varies significantly from location to location, to the extent that the reference measurement away from the plates is larger than the measurements nearby the plate. This behavior could be due to the spatially variable ferromagnetic properties of steel. Since each steel sample is processed differently, the residual magnetic fields could be different at each location. The history of each steel sample is unknown. The results also show some time variation.

The problem of the spatially varying magnetic field can be addressed with the application of the reference magnetic field. Initially a zeroing approach, such as that applied for the notched aluminum samples, was used. Zeroing by simple subtraction of the reference measurements did not prove to be useful, however, since reference measurements themselves are variable and larger than the measurements near the sample. The data were then normalized by dividing the measurements nearby the plate by the mean value of the reference measurements taken away from the plate in the different environments. Figure 7.46 shows these normalized values. By following this procedure, the magnetic field data over the notch in the corrosive environment clearly stands out, whereas all other non-corroding measurements are similar. Magnetic field measurements
Figure 7.45: Magnetic field measured across a notched steel sample. Solid bars represent measurements in air and hollow bars represent measurements when corrosive solution was present.

over the notch in the corrosive solution (hollow bars) are clearly larger than the magnetic field measurements in air (solid bars).

The spectral data plots show no significant distinction between the magnetic field over the notch and the coated plate as a function of frequency, as shown in figures 7.47 and 7.48, although the PSD plot does show some distinction (increase in spectral content) between coated and notched regions at frequencies below 50Hz. These differences lie in the amplitude and not in the content of the spectral components, thus it is difficult to differentiate the behavior between the coated metal and the notch using spectral data.

Figure 7.46: Normalized magnetic field across a notched steel sample. Solid bars represent measurements in air and hollow bars represent measurements when corrosive solution was present.
Figure 7.47: Frequency domain representation of raw magnetic field data for a notched steel plate in a corrosive environment. The behaviors over coated metal and the notch are compared.

Figure 7.48: PSD representation of raw magnetic field data for a notched steel plate in a corrosive environment. The behaviors over coated metal and the notch are compared.
7.5 Sensor separation distance effects

Passive magnetic sensing tests have been performed with GMR sensors placed in close contact to test samples, separated only by a thin polymer layer. However, the separation distance between the sensor and the test plate is an important parameter that needs to be understood for effective application of magnetic sensing for corrosion.

In order to study the effect of separation distances on the corrosion-induced magnetic field, magnetic field data were collected at fixed separation distances between an aluminum sample and the GMR sensors. The magnetic field was monitored at these distances, using a constant corrosion environment. In all cases, magnetic field data were taken from the sample in air for reference, prior to the addition of the corrosive solution. These reference measurements were taken with the sample in contact with the sensor, separated only by a thin polymer layer labeled as 0mm separation distance. Magnetic field measurements were zeroed by subtracting the mean value of the magnetic measurements in air for each case. The fixed separation distance between the GMR sensor and the test sample was achieved by introducing a set of polymer shims. Each shim had a thickness of 1.08mm.

Figure 7.49 shows the results for aluminum in a particular corrosive solution (pH=12.68). From the previous test data we expect the magnetic field data to lie between 20mOe and 26mOe for the 0mm separation distance. The results show that the magnetic field drops rapidly with separation distance, and already at 1.08mm millimeters away it has reached base noise levels. This implies that passive magnetic measurements with GMR sensors can be carried out only with close contact to the sample (generally less than 1mm) for the corrosion levels studied here. Higher corrosion rates may generate stronger magnetic fields that can be measured at larger separation distances however.

7.6 Conclusions

A passive magnetic sensing scheme was applied to detect the occurrence of active environmental corrosion in metals. Measurements on current-carrying wires and plates confirmed that GMR sensors could detect small magnetic fields set up by imposed currents. Tests on galvanic couples showed that the magnetic field generated by corrosion currents can also be detected using GMR sensors, where the current was enhanced with a coil.

Magnetic measurements were then applied to corroding bare (uncoated) aluminum and steel plates. Asymmetric specimens designed to enhance and guide corrosion currents (and magnetic fields) in a specific direction were evaluated. The results, however, did not show benefit over symmetrically shaped samples.
The magnetic field values are similar for both geometries. Thus a special sample shape is not needed, and tests on symmetric samples will suffice. These measurements on symmetrical samples showed that uniform corrosion of a bare plate can be detected by GMR sensors if they are placed parallel to the sample in close proximity. However, a more remarkable result is that the amplitude of the emitted magnetic field, based on the average amplitude of the time signal, is related to the corrosion rate of the bare plate. Relations between magnetic field and corrosion rate were established for A36 steel and 2024 aluminum. Relationships can be constructed between the measured corrosion rate and the zeroed magnetic field measurements to predict the corrosion rates for other materials, at a fixed location, over time.

Frequency domain and PSD analyses of the magnetic field data did not provide additional insight to the corrosion process. It appears that most of the magnetic field spectral energy, which is set up by dynamic corrosion current processes, is concentrated at the very low frequencies, essentially represented by DC current processes. Thus, additional useful information is not likely obtained from spectral analysis.

The effect of separation distance between the sensor and the test plate was studied. Corrosion induced magnetic field drops rapidly with increasing separation distance between the sensor and the plate. At distances larger than 1mm the magnetic field reaches base noise levels for the corrosion levels and sensors studied here.

The magnetic field data are spatially variable, for example when data are collected along different locations in a scanning configuration. Such data from steel samples are particularly variable, due to the localized residual magnetic fields in the ferromagnetic material.
Based on the work presented here, an appropriate application of GMR sensors to monitor active corrosion using a passive configuration is to place them in very close contact with the sample being studied. Since the magnetic field data are disturbed due to material spatial variability, a single sensor should be fixed at one location, and comparative field measurements made over time. Reference measurements are needed to correct for sensor and ambient variability, which can be achieved with the use of a companion sensor. An established relation between magnetic field and corrosion rate can then be used to predict total corrosion over time at the sensed location.
Chapter 8

Active magnetic sensing

Active magnetic sensing implies the interaction of an imposed magnetic field with that set up by a corroding metal sample. This approach is somewhat analogous to the eddy current method for non-destructive testing of metals. The active approach is implemented in an effort to overcome the limitations from passive sensing. The major limitations with passive sensing were the following: it requires a small separation distance between the sensor and corroding surface; inherent residual magnetic fields in ferromagnetic samples disrupt the measurements; and the inherent sensitivity variability of individual GMR sensors. Another limitation of passive testing is the inherent low signal to noise ratio of the data. Active sensing was tried to perform magnetic measurements at larger distances reducing variability.

8.1 Description of sensor configuration

GMR sensors are placed nearby to the metal sample, which is immersed in a tank containing corrosive and non-corrosive solutions. Additional GMR sensors are placed nearby but away from the metal sample to ensure repeatability and for comparison purposes. The sensor configuration is shown in figure 5.3.

The imposed magnetic field was generated by a controllable AC current coil, which is part of the MIZ-21B hand held eddy current (EC) test unit manufactured by Zetec. The unit has a 50-ohm probe and can excite dynamic magnetic fields in a frequency range from 50 Hz to 8 MHz [58]. The probe is also manufactured by Zetec and it is a T/D 375SP spot driver pickup shielded type. The probe has an attached handle and cable with 4-pin Fischer connector. The probe’s diameter is 0.95 cm. Figure 8.1 shows the test unit and figure 8.2 the probe.

The effect of the imposed magnetic field on the GMR sensors themselves was studied; the ability of GMR sensors to detect the field generated by the EC coil, when placed directly in front of it, was evaluated. The sensors acquired ambient magnetic field data (time signals) for ten repetitions. Then the operating coil was placed in front of the sensors and data collected for another ten repetitions. Different coil excitation frequencies were used. Figure 8.3 shows that the external field generated by the coil is easily detected by
Figure 8.1: Handheld MIZ-21B eddy current tester [58].

Figure 8.2: T/D 375SP spot driver pickup shielded probe.
the GMR sensors when the data are represented in the frequency domain, as indicated by the large peak at the excitation frequency.

Variability of the external field generated by the coil was studied and compared with ambient magnetic field variability. Time domain data were gathered every hour without the incident field (coil off) for 24 hours to investigate ambient noise variability. Then, an incident field was applied from the coil and magnetic data were acquired every hour for 24 hours. Ten time signals were collected at each hour. The average value and standard deviations of the ten repetitions taken each hour were computed. Figure 8.4 shows the results of the time domain data. The imposed field raises the measured signal level from the sensor and allows for a more consistent measurement, since the standard deviation is reduced. However, there is great variability in the time domain, even when the coil emits a fixed field: the coefficient of variation for the ambient noise is 59% and it reduces to 30% with an imposed magnetic field.

The imposed field data are also analyzed in the frequency domain. The peak amplitude at the excitation frequency, such as the peaks shown in figure 8.3, was monitored. The average peak amplitude and the corresponding standard deviation are shown in figure 8.5. The figure shows that the peak amplitude at the excitation frequency remains relatively constant, compared to the time domain results. In this case, the coefficient of variation drops to 0.35%, or two orders of magnitude lower than for the time domain data.
Figure 8.4: Average amplitude of magnetic field of time signal from a single sensor. Responses of sensors and statistical spread of data with the coil off (shown in black) and with the coil on with an excitation frequency of 10kHz (shown in red).

Figure 8.5: Average amplitude at 10kHz of frequency domain representation of data in figure 8.4. Sensor is directly exposed to 10kHz field from coil. Response of sensor (hollow points) and statistical spread (solid points) are indicated.
The spectral data indicate that the coil-generated external magnetic field has a very narrow band of frequencies about the driving frequency. The spatial dimensions and directionality of the generated magnetic field was investigated next. This was done by moving the relative position of the coil with respect to the sensor. The coil was moved from 5 cm to the left of the fixed GMR sensor to 5 cm to the right, at 1 cm increments. An illustration of this configuration is shown in figure 8.6. The coil was excited at 60 kHz and ten time signals were taken at each location. The results in figure 8.7 show that the combined generated field of the coil and sensed field of the GMR sensor are highly directional.

![Figure 8.6: Testing setup for directionality investigation.](image)

Next the effect of the presence of a nearby metal plate on the response of the external magnetic field measured by the GMR sensors was evaluated. Using a coil excitation frequency of 60 kHz, measurements were taken with the coil at a fixed angle pointing at the plate with the GMR sensors beneath the coil and perpendicular to the plate. The setup is shown in figure 8.8. The tests were carried out with steel and aluminum plates. Ten signals were taken without a plate and without coil excitation, establishing the base magnetic field noise level in the laboratory. These measurements were then followed by measurements of the field when the coil was turned on and the plate was present. Finally, with the coil still running, the plate was removed. In this way, all possible combinations are considered and the effect of the coil and the plate can be clearly identified.

The spectral results are shown in figure 8.9. The peak value at the excitation frequency is clearly magnified by the presence of the aluminum plate. This effect includes the interaction of both plate and coil. A similar test was run with a steel plate and the results are shown in figure 8.10. The response is similar to that of the aluminum plate. The increase in the peak value at the excitation frequency is related to the
Figure 8.7: Amplitude of magnetic field time signal as excitation coil is moved perpendicular to fixed GMR sensor.

Figure 8.8: Picture of testing setup (left) and setup sketch (right). A bare plate, excitation coil, and single GMR sensor are shown.
presence of the nearby conducting metallic plate. For comparison, a non-conductive asphalt concrete slice was placed in front of the sensors and the experiments were repeated. As expected, the value of the peak excitation frequency did not change, as shown in figure 8.11.

8.2 Description of specimens and test environments

The testing approach is similar to that for the passive tests. Specimens are A36 steel and 2024 aluminum symmetric plates, generally 25mm by 25mm in area and with thicknesses varying from 1.6mm to 3.2mm. The plates were bare (no coating) and were polished before each test with fine polishing paper manufactured by Buehler.

Different corrosive environments were prepared for each metal sample. Basic aqueous solutions were prepared with sodium hydroxide to corrode aluminum samples. The alkalinity of the solutions, determined by the solution’s pH, ranged from 12 to 13. Acid solutions to corrode steel were prepared by diluting 1M hydrochloric acid with water. The solutions had a pH in the range of 0.2 to 2. The pH measurements were taken using a IQ 150 hand held pH meter and a direct pH probe. Later, a Ross pH meter manufactured by Thermon was used.
Figure 8.10: Sets of PSD plots of GMR response to 60 kHz excitation coil and bare steel plate (middle set) and just to coil (far set). The set of near measurements serve as reference of ambient magnetic field levels with neither plate nor external applied magnetic field.

Figure 8.11: Sets of PSD plots of GMR response to 60 kHz excitation coil and asphalt concrete slice (middle set) and just to coil (far set). The set of near measurements serve as ambient magnetic field reference with neither plate nor external applied magnetic field.
8.3 Investigation of testing configuration

8.3.1 Description of analysis schemes

Analysis of the collected data was done in the time, frequency, and PSD domains. The analysis in the frequency and PSD domains were expected to be effective since the field is imposed at a known frequency. Frequency and PSD domain analyses were performed using a commercial software: Matlab. The description of the principles behind each analysis method were explained in section 7.3.

8.3.2 Illustration of concept

The possibility that a magnetic field set up by corrosion can interact with an externally imposed magnetic field and be measured is investigated. Bare aluminum and steel plates were placed in passive and corrosive environments, and an external field was generated by a controllable coil. The excitation frequency of the coil was changed from 10 to 60 kHz, in 10 kHz increments. During testing, the coil pointed at a fixed angle at the plate and the GMR sensor was placed perpendicular to the sample (see figure 8.8). The offset distance is 5mm, immediately close to the wall of the tank. Ten time signals were collected at each excitation frequency. Figure 8.12 shows the ten-signal average spectral peak amplitude at each excitation frequency for both plates in different environments.

Figure 8.12: Spectral amplitude of magnetic field from passivated and corroding aluminum and steel plates to imposed magnetic fields at different excitation frequencies. Hollow circles represent ambient noise reference values.
The behaviors of the steel and aluminum plates are distinct. In both cases the presence of the plate affects the response. The presence of the aluminum plate increases the response about 8%, while the average increase due to the steel plate is about 23%. The data also show that this active testing configuration has potential to detect active corrosion in steel. The amplitude is significantly higher at all excitation frequencies for the corroding steel plate when compared with the passive steel plate. The active response is more consistent and sensitive to corrosion in steel (figure 8.13) than in aluminum (figure 8.14). In the figures, the percent change in the spectral amplitude from the corroding plate with respect to the non-corroding plate is shown. Two repetitions were taken for comparison purposes. The average percent change between the passivated and corroding aluminum plate across all frequencies is 0.19%, varying between positive and negative changes. The average change for the steel plate is 13.59%, where the change is always positive for coil frequencies less than or equal to 50 kHz. Thus, the active sensing approach shows promise for corrosion characterization in steel.

8.3.3 Effects of incident angle

The incident angle of the imposed magnetic field is now studied, since it may cause significant changes in the observed response. In this test series, the GMR sensors were left fixed such that the sensing direction is perpendicular to the studied sample; and the angle with respect to the horizontal of the excitation coil was modified from 15° to 55°, in 10° increments. The test setups is shown in figure 8.8. The separation distance for this test was kept constant at 5mm between the tip of the sensor and the surface of the metal samples.

Figure 8.13: Percent change of spectral amplitude from a corroding steel plate with respect to the spectral amplitude of a non-corroding steel plate. Effect of excitation frequency is shown.
Figure 8.14: Percent change of spectral amplitude from a corroding aluminum plate with respect to the spectral amplitude of a non-corroding aluminum plate. Effect of excitation frequency is shown.

Figure 8.15 shows the percent change in the spectral amplitude when an aluminum sample is present with respect to the base coil value for different incident angles. The aluminum plate causes an increase of less than 30% in the spectral amplitude at all incident angles and for all excitation frequencies. The incidence angle does not seem to be a dominant factor, although lower incident angles (below or equal to $35^\circ$) generate the largest percent change in the spectral amplitude.

Similar tests were carried out with steel samples. Figure 8.16 shows that the steel plate causes an increase of larger than 30% at an incident angle of $35^\circ$. This incident angle generates the largest percentage change and thus it will be used for future testing.

### 8.3.4 Effects of separation distance

One aim of the active sensing approach is to be able to detect corrosion without the need to be in close contact with the testing specimen. For this reason, the effect of separation distance on the field response is a crucial part of the analysis. In a series of tests, the separation distance between the GMR sensor and coil array (GMR sensor and coil were fixed together), with respect to the metal sample was increased. The sensor configuration and the description of separation distance can be observed in figure 8.8. A 5mm increment in sensor and coil separation distance, from 0mm to 30mm, was applied. Data were normalized with respect to spectral peak values when no plate was present, that is, with only the base coil value. Figure 8.17 presents the percent change with respect to the base coil value for different separation distances at a fixed incident angle ($35^\circ$) using AAH002 GMR sensors. The change drops with increasing distance, and at distances larger
Figure 8.15: Percent change of spectral amplitude of aluminum plate in air with respect to the base coil value. AAH002 sensor was used. Effects of different incident angles and excitation frequencies are shown. GMR sensors and aluminum plate position remained fixed.

Figure 8.16: Percent change of spectral amplitude of steel plate in air with respect to the base coil value. AAH002 sensor was used. Effects of different incident angles and excitation frequencies are shown. GMR sensors and aluminum plate position remained fixed.
than 10mm the response reaches the value of the base coil level. This implies that the optimum separation distance should be equal or less than 10mm in order to monitor the interaction field.

Figure 8.18 shows the response for a steel plate at the same separation distances with a fixed incident angle of 35°. The values do decay with distance, but a clear response is still obtained 30mm away, which is different from the aluminum case. In addition, percent changes are much higher than those for aluminum. In aluminum the percent change was less than 20% and for steel the percent change reaches 400% when the separation distance is 0mm.

Figure 8.17: Percent change of spectral amplitude of an aluminum plate in air with respect to the base coil value. An AAH002 GMR sensor was used. Effects of separation distances and excitation frequencies are shown at a fixed angle of 35°.

8.4 Active test results: aluminum

Active magnetic sensing was applied to detect corrosion in aluminum samples. The aluminum samples were submerged in a tank with corrosive (basic) solutions, with the sensor and coil outside the tank. Several excitation frequencies were used with a fixed incident angle of 35°. The incident angle was selected based on the incident angle study presented in section 8.3.3. At 35° there is at least a 10% change when the plate is present with respect to the base coil value at all excitation frequencies. Figure 8.19 illustrates the change in the average magnetic field (time domain) with respect to the base magnetic field. The signal’s percent change (PC) is calculated by \( PC(\%) = \frac{[MF(Oe) - BN(Oe)]}{BN(Oe)} \times 100 \), where \( MF \) is the measured magnetic field (time domain) in Oersted for the different environments and \( BN \) is the base magnetic field (time domain) in Oersted taken with the incident field present and without a metal sample. Results from the
corrosive basic solution (pH 12.75) show significant increase with respect to the base coil value. However, the data are variable. The average magnetic field (time domain) measurements in non-corrosive environments should remain constant, and yet the percent change fluctuates at different times for measurements taken in air and water.

Variability from average magnetic field (time domain) data may be overcome by looking at spectral amplitudes. Figure 8.20 shows the percent change of spectral amplitude from an aluminum plate with respect to the base coil value. The incident angle was kept at 35° and the separation distance was 5mm. Testing setup is shown in figure 8.8. The test was repeated with two different sensors. The results for the first sensor decrease in the corrosive solution, and the magnitude of this decrease becomes larger with time. This is shown in the left of figure 8.20. The second GMR sensor’s response is shown in the right in figure 8.20, and is opposite to that observed from the first sensor. A distinction between corrosive and non-corrosive environments is still visible but is not consistent to that of the first sensor. In conclusion, active magnetic testing in aluminum is highly variable with both time domain and frequency domain data. No consistent behavior is observed, and application of active magnetic testing to corroding aluminum samples does not seem feasible.
Figure 8.19: Percent change of average magnetic field (time domain) from a time signal from an aluminum plate with respect to base coil values. Effects of excitation frequency and exposure time to a corrosive environment are shown for two independent repetitions (left and right). The pH of the base solution was 12.75.

Figure 8.20: Percent change of spectral amplitude from an aluminum plate with respect to the base coil value. Effects of excitation frequency and exposure time to a corrosive environment are shown for two independent repetitions (left and right). The pH of the base solution was 12.75.
8.5 Active test results: steel

The active corrosion measurements for steel follow a similar format as those for aluminum. A steel sample was immersed in a corrosive solution after a base magnetic measurement field of the incident field itself and that of the plate in air were taken. The data from the corrosive medium were taken at different times after immersion to analyze the response of the plate to the incident field as corrosion progresses. The test setup is shown in figure 8.8, where the incident angle was $35^\circ$ and the separation distance was 3mm. Figure 8.21 illustrates the change in the average magnetic field (time domain) with respect to the base magnetic field. The signal’s percent change is calculated with respect to the base magnetic field (time domain) taken with the incident field present and without a metal sample, following the same calculations as for the aluminum case. Results from the corrosive acidic solution (pH 0.91) show significant increase with respect to the base coil value after one day in the corrosive solution. However, the data are variable and the increase is not significant.

![Diagram](image)

Figure 8.21: Percent change of average magnetic field (time domain) from a time signal from a steel plate with respect to base coil values. Effects of excitation frequency and exposure time to a corrosive environment are shown for two independent repetitions (left and right). The pH of the base solution was 0.91.

The corresponding frequency domain analysis for the time domain results shown in figure 8.21 is presented in figure 8.22. The percent change of the signal is calculated by $PC(\%) = \frac{MSA(Oe) - BSA(Oe)}{BSA(Oe)} \times 100$; where $MSA$ is the measured spectral amplitude for the different environments and $BSA$ is the base spectral amplitude with incident field present and without a metal sample (base coil value). Some distinction is noticeable at all frequencies after one day after initiation of corrosion, where the spectral amplitudes are notably larger than the base noise levels. Only minor changes are observed in all other environments. The
The fact that corrosion of steel in an acid medium occurs at a lower rate than corrosion for aluminum in an alkaline environment likely explains why the percent change in spectral amplitude is noticeable only one day after initiation of corrosion.

The results in steel show promise. Tests were carried out with a larger separation distance between the sensor-coil configuration and plate (10 millimeters) maintaining a 35° incident angle with the coil. A steel sample was immersed in different acid solutions, with a pH ranging from 0.02 to 2.50. The purpose of these tests was to determine if active testing was able to discern corrosion at different rates (as characterized by the different environments) and if detection could be carried out a larger distance, without being in close proximity to the specimen.

Figure 8.22: Percent change of spectral amplitude from a steel plate with respect to the base coil value. Effects of excitation frequency and exposure time to a corrosive environment are shown. The pH of the acid solution used was 0.91. Sensor to sample separation distance is 3mm.

Figure 8.23 shows the spectral peak response from GMR sensor at one fixed test location at different times after immersion in a corrosive environment. The percent change of the spectral peak amplitude is calculated with respect to the values obtained from the sample in air. On average, a 4% increase is observed after one day in corrosive solution. The results are more consistent at the lower excitation frequencies, below 50kHz. There is about a 1% increase in the response when the solution is first added, the the response increases notably after one day.

Figures 8.24 and 8.25 show the responses from the same sensor configuration when different, less corrosive, solutions were used, with solution pH of 1.43 and 2.50, respectively. Inconsistent results were obtained. At the intermediate pH of 1.43, the results after one day of corrosion became more negative. On average, the
response after one day of corrosion was about 2.5% less than the reference value. In the least corrosive solution (pH=2.50), the results were variable at all excitation frequencies.

Some of this variability was found to be caused by sensitivity to testing setup configuration and alignment. An improved setup was built in which the GMR sensor and the excitation coil were more firmly fixed together relative to the steel sample. In general, the testing setup remained similar to that shown in figure 8.8. The separation distance was 15 millimeters and the incident angle 35°. As before, the sample was placed in different corrosive solutions and the change in spectral peak amplitude with respect to the value of the plate in air was monitored. The results with the new fixed testing configuration are more consistent. Figure 8.26 shows the results for a steel plate in a solution with pH 0.26, where the spectral amplitude increases with time immersed in corrosive solution for excitation frequencies below 60kHz. Collected data from other corrosion environments suggest the spectral ratio data at a particular frequency and immersion time can be related to the corrosion rate. Figure 8.27 shows the relationship between corrosion rate (mass loss) and percent change of spectral peak amplitude with a 30kHz excitation frequency, as a function of pH. The data show that corrosion rates drop with increasing pH, although some scatter in the data is seen. Active magnetic field data show high scatter and no strong trend. The largest amount of scatter in magnetic field data is observed at lower pH values.

The same analysis performed for the time domain data gathered after one hour of immersion time for a 30kHz excitation frequency. Figure 8.28 shows the relationship between corrosion rate (mass loss) and
Figure 8.24: Percent change of spectral amplitude from a steel plate with respect to the base coil value. Effects of excitation frequency and exposure time to a corrosive environment are shown. The pH of the acid solution used was 1.43. Sensor to sample separation distance is 10mm.

Figure 8.25: Percent change of spectral amplitude from a steel plate with respect to the base coil value. Effects of excitation frequency and exposure time to a corrosive environment are shown. The pH of the acid solution used was 2.50. Sensor to sample separation distance is 10mm.
Figure 8.26: Percent change of spectral amplitude from a steel plate with respect to the base coil value. Effects of excitation frequency and exposure time to a corrosive environment are shown. The pH of the acid solution used was 0.26. Sensor to sample separation distance is 15mm using the modified testing fixture.

Figure 8.27: Percent change of spectral amplitude (solid squares) and corrosion rate loss (hollow circles) for steel as a function of pH. The percent change of spectral amplitude was taken after one hour in corrosive solution using a 30kHz excitation frequency. Sensor to sample separation distance is 15mm using the modified testing fixture.
percent change of spectral magnetic field amplitude with a 30kHz excitation frequency, as a function of pH. Again, great scatter is observed at the lower pH values.

Figure 8.28: Percent change of magnetic field (time domain) amplitude (solid squares) and corrosion rate loss (hollow circles) for steel as a function of pH. The percent change of magnetic field amplitude was taken after one hour in corrosive solution using a 30kHz excitation frequency. Sensor to sample separation distance is 15mm using the modified testing fixture.

Figure 8.29 shows a plot of corrosion rates versus the change in spectral amplitude for a steel plate after one hour of immersion in different corrosive solutions for an excitation frequency of 30kHz. This plot is built from the data shown in figure 8.27. The plot shows no definitive trend and high data scatter.

Figures 8.30, 8.31, and 8.32 show plots of corrosion rate versus change in spectral amplitude at additional excitation frequencies (60kHz) and immersion times (one day). Although in general there is some increase in the spectral amplitude with higher corrosion rates, no clear trend is observed amid the data scatter.

8.6 Conclusions

Active magnetic field tests have been applied in an attempt to characterize active corrosion in aluminum and steel. The principal objective is to characterize the corrosion non-invasively and at a distance away from the metal. The active configuration does allow data to be collected from a larger offset distance from the sample than possible with passive sensing. This feature represents an important advantage of active testing. Active test data also exhibit high signal-to-noise ratio.

Although some distinction between corroding and non-corroding states can be observed, consistent data
Figure 8.29: Corrosion rate as a function of percent change of spectral amplitude from a steel plate with respect to the base coil value. Measurements taken after one hour in solution with a 30kHz excitation frequency. Sensor to sample separation distance is 15mm, using the modified testing fixture.

Figure 8.30: Corrosion rate as a function of percent change of spectral amplitude from a steel plate with respect to the base coil value. Measurements taken after one hour in solution with a 60kHz excitation frequency. Sensor to sample separation distance is 15mm, using the modified testing fixture.
Figure 8.31: Corrosion rate as a function of percent change of spectral amplitude from a steel plate with respect to the base coil value. Measurements taken after one day in solution with a 30kHz excitation frequency. Sensor to sample separation distance is 15mm, using the modified testing fixture.

Figure 8.32: Corrosion rate as a function of percent change of spectral amplitude from a steel plate with respect to the base coil value. Measurements taken after one day in solution with a 60kHz excitation frequency. Sensor to sample separation distance is 15mm, using the modified testing fixture.
and meaningful relationships between the active magnetic response and corrosion rate could not be established. However, some differences in the responses from steel and aluminum are still observed. Corrosion in steel appears to be associated with an increase in spectral amplitude of the magnetic field. On the other hand, corrosion in aluminum appears to be associated with decrease in field; however, high levels of data scatter restrict definitive conclusions. Active testing appears to be very sensitive to sensor and coil positioning and alignment, which causes some difficulties during experimentation. As a result, the testing configuration, which provides a fixed sensor and coil placement, provides more consistent active magnetic data.
Chapter 9

Magnetic sensing application to reinforced concrete specimens

The development of active and passive magnetic sensing schemes has been applied with varying success to aluminum and steel specimens under aqueous environmental corrosion conditions in a laboratory setting. These results show promise. But these approaches need to be verified in a manner that more realistically represents in situ corrosion in the civil infrastructure. Steel reinforced concrete samples were selected for this purpose, and the passive and active testing schemes were applied to these samples.

9.1 Experimental test description

9.1.1 Test samples

In order to simulate corrosion in reinforced concrete structures, beam specimens similar to those specified by ASTM G109 were constructed. An image of the specimen configuration is shown in figure 6.1. Three reference beams had no chloride ions added to the mixture, while three test beams contained chloride ions added to the concrete mixture. Table 9.1 shows the mix design of the concrete the beams. The beams were left in a moist curing room for 28 days after casting prior to testing. The top (anodic) rebar was located close to the surface covered with a thin layer of concrete. The cover depth of the top anodic bar was approximately 3mm.

<table>
<thead>
<tr>
<th>Composition (kg/m³)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Aggregate</td>
<td>1163</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>599</td>
</tr>
<tr>
<td>Adjusted Water</td>
<td>215</td>
</tr>
<tr>
<td>Cement</td>
<td>429</td>
</tr>
<tr>
<td>Sodium chloride</td>
<td>17.2</td>
</tr>
</tbody>
</table>

Table 9.1: Concrete mixture design for reinforced concrete test samples (w/c = 0.5).

A controllable DC current, ranging from 0.01 to 0.04A, was applied to all samples in order to promote rapid corrosion. These levels of corrosion were selected based on the results on accelerated corrosion described
in section 6.3.2. A Kenwood power supply was used to supply a controlled and constant current input. The corrosion rate of the bars in the test sample can be predicted using Faraday’s law (equation 6.2) knowing the current input.

9.1.2 Sensor configuration and test sequence

The beams were tested in pairs: one “test” beam (with chloride ion addition) and one “reference” beam (without chloride ion addition). A total of three beam sets (pairs) were tested. The main objectives behind the testing series were to determine if the sensors can detect corrosion fields set up by the imposed current and to study the effect of different current levels and sequences on the corrosion of steel. Figure 6.4 shows how the beams were connected together and the current was applied. Table 9.2 details the imposed current sequence and duration applied to each beam set for the passive sensing tests.

<table>
<thead>
<tr>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (A)</td>
<td>Time (days)</td>
<td>Current (A)</td>
</tr>
<tr>
<td>No current</td>
<td>2</td>
<td>No current</td>
</tr>
<tr>
<td>0.04</td>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>No current</td>
<td>2</td>
<td>0.02</td>
</tr>
<tr>
<td>0.04</td>
<td>2</td>
<td>0.03</td>
</tr>
</tbody>
</table>

After passive magnetic sensing was completed, active magnetic sensing tests were carried out. Table 9.3 details the imposed current sequence for each beam set for active sensing tests.

<table>
<thead>
<tr>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<td>2</td>
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<tr>
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<td>2</td>
<td>0.04</td>
</tr>
<tr>
<td>No current</td>
<td>2</td>
<td>No current</td>
</tr>
</tbody>
</table>

Sample sets 1 and 2

The sensors were placed at a fixed locations and maintained throughout the tests for the first two beam sets to avoid problems due to spatially-varying fields from residual magnetic fields and test set-up inconsistency. The sensors were placed parallel to the longitudinal axis of the reinforcing bar over the exposed area of the steel. Data were acquired every 30 minutes, where ten time signals were recorded each time. Each time
signal was composed of 8192 points acquired with a 10kHz sampling rate. The sensor positioning is shown in figure 9.1.

![Sensor location diagram](image)

Figure 9.1: Sensor location for test sample sets 1 and 2. Sensing locations indicated by letters. The reference beam (without chloride ions in the mixture) only had the two central sensors at location “c”.

In total, eight sensors were used for each beam set for the passive sensing tests. Five sensors were placed on the test beam and three on the reference beam. On each beam, one companion sensor was used as a reference. This companion sensor was placed 10mm away from the top surface of the beam.

For the active magnetic sensing tests, GMR sensors and the excitation coil were placed 10mm away from the top surface of the concrete beams, using the configuration shown in figure 8.8. The incidence angle was 35°. Excitation frequencies ranged from 10kHz to 60kHz. Locations a, c, and d were selected for active magnetic testing on sample set 1. Location a serves as reference since it is over a coated region of the anodic reinforcing bar. corrosion is not expected there. The other two locations coincide with those used in the passive sensing tests. Active magnetic sensing was carried out with imposed current alternated with no imposed current, as described in table 9.3.

**Sample set 3**

For the third sample set, a single sensor set was used to collect field data at different locations along the beam. This sensor set was comprised of a pair of sensors near the beam surface and a companion sensor further away from the surface to monitor ambient noise variations. Figure 9.2 shows the test locations where magnetic sensing was carried out. Locations include both regions over coated and uncoated steel bar. Magnetic field data were collected at five instances during each 24-hour current level step: 0, 4, 8, 12, and 24 hours.
For active magnetic tests, GMR sensors and an excitation coil were placed 10mm away from the surface of the concrete beams, using the configuration shown in figure 8.8. The incidence angle was 35°. Excitation frequencies ranged from 10kHz to 60kHz. Active sensing tests were carried out after the passive magnetic testing concluded at three locations: locations b, d, and e, shown in figure 9.2. Location b serves as reference since it is over a coated region of the reinforcing bar, where corrosion is not expected to occur. All locations coincide with those used in passive sensing tests. The imposed current sequence for active testing is described in table 9.3.

9.2 Test results: sample set 1

9.2.1 Passive magnetic sensing

Passive magnetic sensing was carried out at the established locations with fixed sensors. The sensor locations were maintained throughout the test sequence. Sensors 1 and 2 were placed at the center of the beam (location c), sensor 3 at location b, and sensor 4 at location d. The raw data for the test and reference beams are shown in figure 9.3. The raw data show several important results. First, the companion sensor for the reference beam sensed a large drop in the magnetic field at the moment the 0.04A current was introduced to the system. No other sensor detected this drop, and the reason for this drop is not known. All sensors, except sensor 4 on the test beam, show a small sudden increase in their response when the 0.04A current was first introduced. Furthermore, all sensors show significant fluctuations, that follow a cyclic 24-hour pattern.

In order to correct the raw data with regard to the residual magnetic field of the steel and individual
sensor variability, the raw data were subtracted by their individual average value for the initial current-less case. This procedure centers the first 24 hours of the signal around zero and allows us to discern if a change in the field can be observed when different current levels are applied. Figure 9.4 shows the zeroed field values with respect to the average value for the initial current-less 48 hour period.

The daily noise cycles are still seen in the data in figure 9.4. In the reference beam, the near sensors fluctuate about zero. In the test beam, however, three of the test sensors and the companion sensor show an overall increase in value with time. The increase in the companion sensor is not expected, and could be related to the imposed field or sensor variability. Based on the passive sensing results reported in chapter 7, the expected behavior for the sensors on the test beam is an increase in the field when the anodic current is applied, followed by a drop when the applied current is removed. An increase is seen in most of the sensors of the test beam upon the application of the current at 48 hours. However, subsequent drops and rises are not seen. This implies that once corrosion is induced by an imposed current, removal of the imposed current may not stop corrosion completely.

The gradiometric representation of the same data, shown in figure 9.5, lower the influence of the daily cycles in the signals. Gradiometric results are obtained by subtraction of near sensor data from companion sensor magnetic field data for each test location and time. This presentation of data is influenced significantly by the behavior of the companion sensor itself. As a result, the gradiometric results present different trends than that of the zeroed data in figure 9.4. The gradiometric data indicate a large increase in field value for the reference beam after application of the first current step. In the test beam, sensor 4 shows the largest increase in field while sensors 1 and 3 actually show a decrease over time, which cannot be interpreted using the model developed in chapter 7.
Figure 9.4: Zeroed magnetic data for beam sample set 1 without chloride ions in the mixture (left) and with chloride ions in the mixture (right). Evolution of magnetic field over time for different applied current levels is shown. Results have been zeroed with respect to their own average magnetic field value for the initial 48 hours with no imposed current.

Figure 9.5: Gradiometric representation of magnetic field data for beam sample set 1 without chloride ions in the mixture (left) and with chloride ions in the mixture (right). Evolution of magnetic field over time for different current levels is shown. Gradiometric results have been obtained by subtraction with companion magnetic field data for each test location and time.
9.2.2 Active magnetic sensing

Active magnetic sensing was carried out after the completion of the passive magnetic tests. Active data followed the imposed current sequence prescribed in table 9.3. Figure 9.6 shows the active spectral response at location a, over a coated section of bar. No corrosion is expected at this location for either beam. The percent change in the spectral amplitude for both beams is in general negative, and shows no particular connection to the applied current sequence. The percent change of the signal is calculated by $PC(\%) = \frac{[MSA(Oe) - BSA(Oe)]}{BSA(Oe)} \times 100$; where $MSA$ is the measured spectral amplitude for the different imposed current levels and $BSA$ is the base spectral amplitude with incident field present but without an imposed current.

Figure 9.6: Percent change of spectral amplitude for sample set 1 for different current levels with respect to values without applied current. Effect of excitation frequency is shown. Results for beam without chloride ions in the mixture are shown on the left and with chloride ions in the mixture on the right. Active magnetic field data were taken at location a in figure 9.1.

Figure 9.7 shows the active spectral response at location b, over exposed reinforcement. Corrosion is expected at this location. Data for the reference beam is in general negative and no apparent relationship to applied current level and sequence is noticeable. Results for the test beam show a decrease for excitation frequencies below 50kHz. The responses at the individual excitation frequencies appear unrelated to the imposed current levels and sequence.

Figure 9.8 shows the change in spectral amplitude for measurements carried out at the center of the beam. The data again show no consistent connection to applied current amplitude and sequence.

9.2.3 Visual inspection

At the conclusion of the tests series the reinforcing bars were carefully extracted and cleaned, and the locations of the sensors were marked on the bar. Figure 9.9 shows the concrete sample set after the reinforcing
Figure 9.7: Percent change of spectral amplitude for sample set 1 for different current levels with respect to values without applied current. Effect of excitation frequency is shown. Results for beam without chloride ions in the mixture are shown on the left and with chloride ions in the mixture on the right. Active magnetic field data were taken at location $b$ in figure 9.1.

Figure 9.8: Percent change of spectral amplitude for sample set 1 for different current levels with respect to values without applied current. Effect of excitation frequency is shown. Results for beam without chloride ions in the mixture are shown on the left and with chloride ions in the mixture on the right. Active magnetic field data were taken at location $c$ in figure 9.1.
bars were removed. As expected, the test beam with chloride ions in the mixture exhibited significant staining and cracking due to corrosion. The reference beam did not exhibit staining and cracking.

The extracted reinforcing bars were polished, weighed and examined visually. The anodic reinforcing bar extracted from the reference beam exhibited no corrosion. The bottom surface of the reinforcing bar from the test beam did exhibit significant and widespread corrosion. The top surface of the same bar did show some corrosion, but not to the same extent as the bottom surface. The corrosion was mostly uniformly spread across the surface. Some pitting was noticed throughout the bar surface, particularly close to the locations where sensors 1, 2 and 4 were placed. Figures 9.10 and 9.11 show the upper and bottom surfaces of the extracted reinforcing bars. Figure 9.12 shows the upper surface of the polished reinforcing bar from the test beam, where the highest concentration of pitting is observed at location c. It is interesting to note that the passive magnetic field over location c showed the highest values; as indicated by sensor 2 response in 9.4.

Figure 9.9: Concrete specimens from sample set 1 after the removal of anodic reinforcing bars. The top specimen is the reference beam without chloride ions and the bottom one is the test beam with chloride ions in the mixture.

The mass loss was calculated and directly compared to the predicted values from Faraday’s law (equation 6.2). The predicted mass loss was 4.3 grams, but the actual mass loss was 4.8 grams; this difference is 12%. Faraday’s law underestimates the corrosion loss by a significant amount in this case. This would suggest that once corrosion is induced by an externally applied anodic current, it does not cease completely when the current is removed. Interestingly, the zeroed magnetic field data (figure 9.4) showed an increase in the field when the anodic current was initially imposed, however no subsequent drops were observed when the applied current was removed.
Figure 9.10: Upper surfaces of extracted reinforcing bars sample set 1. The top bar is from the beam without chloride ions in the mixture and the bottom one with chloride ions in the mixture.

Figure 9.11: Lower surfaces of extracted reinforcing bars sample set 1. The top bar is from the beam without chloride ions in the mixture and the bottom one with chloride ions in the mixture.

Figure 9.12: Polished upper surface of extracted reinforcing bar from test beam. Test locations indicated by letters. Pitting indicated by circle.
9.3 Test results: sample set 2

9.3.1 Passive magnetic sensing

The tests for sample set 2 were designed to investigate the effect of sequentially increasing imposed current levels. The sensor placement is shown in figure 9.1. The imposed current level was increased in 0.01A steps up to 0.03A, as described in table 9.2. Based on the passive sensing results presented in chapter 7, the expected behavior of the passively sensed magnetic field is an increase in the magnitude of the field with increasing applied current.

Figure 9.13 shows the raw magnetic field data for the test and reference beams. All sensors again show fluctuation that follows a 24 hour cycle. This is particularly noticeable in the reference beam data. In the reference beam, data from sensors 1 and 2 increase with time, whereas the companion sensor fluctuates about zero. In the test beam, data from sensor 2 increase gradually with time. Data from sensor 3 show a small sudden decrease in the response when the 0.01A current is introduced. Sensor 4 was damaged during the course of the tests and its results are not shown.

Figure 9.13: Raw magnetic field data for beam sample set 2 for reference (left) and test (right) beams. Evolution of magnetic field over time for different applied current levels is shown.

As with sample set 1, the raw data were subtracted by their individual average valued for the current-less case to correct for the residual magnetic field and individual sensor variability. This procedure centers the first 24 hours of data around zero and allows us to discern if a change in the field is observed at different applied current levels. Figure 9.14 shows the zeroed field values with respect to the average value for the initial current-less 24 hour period. For the reference beam, the companion sensor detects daily fluctuations but remains about zero. The two sensors near the steel reinforcement, however, gradually increase over time. Although no corrosion occurs here, the response is similar to what we would expect near active corrosion. The test beam shows mixed results. Data from the companion sensor and sensor 1 fluctuate about zero.
Data from sensor 2 increases over time and sensor 3 decreases over time.

Based on the passive sensing schemes developed for A36 steel in chapter 7 (section 7.4.5) results for the test beam suggest that active corrosion occurs nearby sensor 2, at location \( c \). Sensor 1 predicts negligible corrosion. The negative results from sensor 3 cannot be interpreted. The companion sensor fluctuates about zero, implying that no significant distinction in the external field was observed.

The average values of the zeroed field for each imposed constant anodic current level period were calculated and are shown in figure 9.15. These average values are used in the equation developed for corrosion rate for A36 steel as a function of averaged zeroed magnetic field \( R(mm/y) = 4.7 * MF(Oe) + 0.19 \). Based on the equation, the predicted corrosion rate at location \( b \) is 0.23\( mm/y \) after 48 hours. However, the expected corrosion rate for an imposed current of 0.01A is 1.45\( mm/y \) for the same period using Faraday’s law (equation 6.2). The corrosion rates expected from applied current are much larger than that predicted based on the measured magnetic field.

24 hour noise cycles are still noticeable in the data in figure 9.14. A gradiometric representation of the same data reduces these daily fluctuations for the reference beam. The ‘gradiometric’ representation helps to clearly identify the effect of the imposed current levels as daily steps, as shown in figure 9.16 in the reference beam. These steps in magnetic field are observed even though corrosion is not expected to occur in the reference beam. The test beam data show similar behavior to the “zeroed” representation, shown in figure 9.14. It appears that the gradiometric representation does not contribute to the understanding of corrosion because it depends on the measurements of the companion sensor, which is not directly related to the corrosion process itself.
Figure 9.15: Average change of magnetic field at different imposed current levels with respect to base noise measurements for sample set 2. Average change for reference (left) and test (right) beams is shown.

Figure 9.16: Gradiometric representation of magnetic field data for beam sample set 2 without chloride ions in the mixture (left) and with chloride ions in the mixture (right). Evolution of magnetic field over time for different current levels is shown. Gradiometric results have been obtained by subtraction with companion magnetic field data for each test location and time.
9.3.2 Active magnetic sensing

Active magnetic sensing was carried out at the center of the beams (location c). The imposed current sequence is detailed in table 9.3. The obtained data in figure 9.17 show no particular connection between the applied current sequence and the active spectral response in neither the reference nor the test beam. The percent change of the signal is calculated by \( PC(\%) = \frac{MSA(Oe) - BSA(Oe)}{BSA(Oe)} \times 100; \) where \( MSA \) is the measured spectral amplitude for the different imposed current levels and \( BSA \) is the base spectral amplitude with incident field present, but without an imposed current.

![Graph showing percent change of spectral amplitude for different current levels.](image)

Figure 9.17: Percent change of spectral amplitude for sample set 2 for different current levels with respect to values without applied current. Effect of excitation frequency is shown.

9.3.3 Visual inspection

Upon completion of magnetic sensing tests, the concrete specimens were opened and the reinforcing bars were extracted and cleaned. The locations of the sensors were marked on the bar. Figure 9.18 shows concrete sample set 2 after the removal of the reinforcing bars. In the bottom of the figure, the test beam shows significant staining and cracking from the corrosion of the reinforcement, whereas the reference beam did not exhibit staining or cracking.

The extracted reinforcing bars were polished, their actual mass loss was recorded, and they were examined visually. The reinforcing bar from the reference beam exhibited no visible mass loss or corrosion. The reinforcing bar extracted from the test beam did show extensive corrosion on the bottom surface and lesser amounts of localized corrosion on the upper surface. Pitting was visible at a few locations along the upper surface, particularly at location c, where sensor 2 was placed. Figures 9.19 and 9.20 show the upper and lower surfaces of the extracted reinforcing bars. Figure 9.21 shows the polished upper surface of the reinforcing bar from the test beam, where pitting is observed nearby location c. This observation supports with the observed magnetic behavior from figure 9.14, where the signal from sensor 2 gradually increased with time.
and predicted indicating the highest corrosion rates of the sensed locations.

The mass loss was directly measured and compared to predicted values from Faraday’s law (equation 6.2). The expected mass loss was 4.23 grams and the actual mass lost was 4.30 grams. The difference between predicted, by means of Faraday’s law, and measured mass loss for the reinforcing bar was only 2%.

9.4 Test results: sample set 3

9.4.1 Passive magnetic sensing

For sample set 3, the passive sensing was carried out with a single set of sensors, which were moved to collect data at eight different positions. The sensor set was comprised of two surface sensors and a companion sensor, as shown in figure 9.2. Ten time signals were acquired at each each test location and time. Each time signal was comprised of 8192 points gathered with a 10kHz sampling rate. Figure 9.22 shows the evolution of the magnetic field over a period of one day for the companion sensor and figure 9.23 shows similar data for the near surface sensors. As previously noted with the other test sample sets, there is fluctuation over the day at each test location, but significant spatial variation in the magnetic field, along the length of the bar, dominates the response.

Once anodic current is applied to the system, relative measurements at each location may be carried out. In this case, data were zeroed by subtracting the average value at each measurement test location by the initial value (prior to the application of current) at each location. By using this signal processing
Figure 9.19: Upper surfaces of extracted reinforcing bars sample set 2. The top bar is from the beam without chloride ions in the mixture and the bottom one with chloride ions in the mixture.

Figure 9.20: Lower surfaces of extracted reinforcing bars sample set 2. The top bar is from the beam without chloride ions in the mixture and the bottom one with chloride ions in the mixture.
Figure 9.21: Polished upper surface of extracted reinforcing bar from test beam. Areas were pitting was observed have been circled.

Figure 9.22: Average magnetic field data from companion sensors of beams in sample set 3 without chloride ions (left) and with chloride ions (right) in the mixture across different test locations. Data were collected for one day before current was introduced in the system.

Figure 9.23: Average magnetic field data from near sensors of beams in sample set 3 without chloride ions (left) and with chloride ions (right) in the mixture across different test locations. Data were collected for one day before current was introduced in the system.
scheme, the disrupting effects of spatial variability of the magnetic field are reduced. Figure 9.24 shows the results for an imposed current of 0.03A. The companion sensor from the test beam (right) experiences little variation with respect to the base magnetic field data at test locations c to f, which are over the exposed portion of the bar (refer to figure 9.2). The two near surface sensors at the same locations experience a much larger increase. This implies that the magnetic field from the induced corrosion is detected by the near surface sensors and not by the companion sensor. Results from the reference beam (left) show similar changes between the companion and the near surface sensors, suggesting that the imposed anodic current does not generate a corrosion magnetic field in this specimen.

Figure 9.24: Zeroed magnetic field measured along reinforcing bars at a given time and for a fixed current level (0.03A) for sample set 3. Results were zeroed with their own average magnetic field value with no imposed current. The response from the beam without chloride ions in the mixture is shown on the left and with chloride ions in the mixture is shown on the right.

Daily averages of zeroed magnetic field at each location were calculated for different imposed current levels. Figure 9.25 shows the zeroed daily field averages for the companion sensors, and figure 9.26 shows the zeroed daily magnetic averages for one of the near sensors. Based on the passive sensing experiments reported in chapter 7, the expected behavior for the test beam is incremental increases in the field over locations of exposed bar as each successive anodic current level is imposed. However, the near surface sensors show expected behavior at only one location (f) for the test beam that is near exposed bar. Otherwise, the locations over exposed bar (c to f) show roughly equivalent behavior. Locations a and h are at the edge of the beams where the bar is coated and no corrosion is expected there. The high values at these locations could be related to the positioning of the sensors, since they were not always parallel to the reinforcing bar at the beam edges.

Based on the passive sensing schemes presented in chapter 7, the corrosion rate in the test beam set locations c through f can be predicted. Table 9.4 shows the expected corrosion rate based on Faraday’s law (equation 6.2) and the predicted corrosion rates at these locations (c through f) obtained by applying the
Figure 9.25: Zeroed daily average of magnetic field for companion sensor from sample set 3. The response from the beam without chloride ions in the mixture is shown on the left and with chloride ions in the mixture on the right. Results have been zeroed with respect to their average daily magnetic field value with no imposed current.

Figure 9.26: Zeroed daily average of magnetic field for near sensor from sample set 3. The response from the beam without chloride ions in the mixture is shown on the left and with chloride ions in the mixture on the right. Results have been zeroed with respect to their average daily magnetic field value with no imposed current.
equation that relates corrosion rates to measured magnetic field for A36 steel \( R(\text{mm/y}) = 4.7 \times MF(\text{Oe}) + 0.19 \). The values show that the predictions from magnetic field greatly underestimate the actual corrosion rate generated by the imposed anodic currents.

Table 9.4: Comparison between expected (equation 6.2) and predicted corrosion rates at different locations for the test beam.

<table>
<thead>
<tr>
<th>Imposed anodic current (A)</th>
<th>Expected corrosion rate (mm/y)</th>
<th>Predicted corrosion rate at “c” (mm/y)</th>
<th>Predicted corrosion rate at “d” (mm/y)</th>
<th>Predicted corrosion rate at “e” (mm/y)</th>
<th>Predicted corrosion rate at “f” (mm/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>2.89</td>
<td>0.69</td>
<td>0.44</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td>0.03</td>
<td>4.34</td>
<td>0.58</td>
<td>0.55</td>
<td>0.56</td>
<td>0.40</td>
</tr>
<tr>
<td>0.035</td>
<td>5.07</td>
<td>0.47</td>
<td>0.38</td>
<td>0.25</td>
<td>0.52</td>
</tr>
</tbody>
</table>

The data in figures 9.25 and 9.26 show that there is great variability from location to location, even after the data have been zeroed. A gradiometric representation of the data, where the reference magnetic data from the companion sensors is subtracted from the magnetic field data from the near sensor, is shown in figure 9.27. However, the expected behavior with increasing applied current is not seen, and there appears to be no significant distinction between the behavior of reference and test beams.

Figure 9.27: Zeroed gradiometric representation of daily average magnetic field data for sample set 3. The response from the beam without chloride ions in the mixture is shown on the left and with chloride ions in the mixture on the right. Results have been zeroed with respect to their daily average magnetic field value with no imposed current. Then gradiometric results have been obtained by subtraction with companion zeroed daily average magnetic data.

### 9.4.2 Active magnetic sensing

After the passive tests were completed, active magnetic testing was carried out at locations b, d, and e. Corrosion is not expected to occur at location b. A reference measurement was taken without an imposed
current, followed by a 0.04A imposed current. Then a second cycle was applied using a 0.05A applied current, as described in table 9.3. After the cycles, the percent change in spectral amplitude was calculated. The percent change of the signal is calculated by $PC(\%) = \frac{MSA(Oe) - BSA(Oe)}{BSA(Oe)} \times 100$; where $MSA$ is the measured spectral amplitude for the different imposed current levels and $BSA$ is the base spectral amplitude with incident field present, but without an imposed current. Figure 9.28 shows that no particular connection was observed for either reference or test beams at the reference location $b$. But results from the two locations over the exposed bar, shown in figures 9.29 and 9.30, do not show expected trends either.

Figure 9.28: Percent change of spectral amplitude for different current levels with respect to values without applied current. Effect of excitation frequency is shown. Results for beam without chloride ions in the mixture are shown on the left and with chloride ions in the mixture on the right. Active magnetic field data were taken at location $b$ on figure 9.2, which is over the coated region of the bar.

Figure 9.29: Percent change of spectral amplitude for different current levels with respect to values without applied current. Effect of excitation frequency is shown. Results for beam without chloride ions in the mixture are shown on the left and with chloride ions in the mixture on the right. Active magnetic field data were taken at location $d$ on figure 9.2, which is over an exposed region of the bar.
9.4.3 Visual inspection

Reinforcing bars from test sample set 3 were extracted, cleaned and visually inspected after the conclusion of the tests. As with the previous sample sets, the concrete surface of the test beam showed significant staining and cracking, as shown in figure 9.31 while that of the reference beam did not. The reinforcing bar from the test beam showed minor, sporadic corrosion on the upper surface and extensive corrosion on the bottom surface, as shown in figures 9.32 and 9.33. The anodic bar from the reference beam showed no evidence of corrosion, as seen in those same images. The mass loss was directly measured and compared to predicted values from Faraday’s law (equation 6.2). The expected mass loss was 2.21 grams and the actual mass lost was 2.24 grams. The difference between predicted, by means of Faraday’s law, and measured mass loss for the reinforcing bar was only 1%.

Only locations locations c, d, e, and f were over uncoated bar in the test beam and therefore exhibited corrosion. It appears that the corrosion rates predicted from the magnetic field (table 9.4) are not influenced by the local pitting at locations d and e. This lack of sensitivity may be caused by the moving sensor set employed on these beams. Pitting was observed in the polished bar at the two center locations (d and e), as indicated in figure 9.34. Results reported in chapter 7 demonstrate the sensitivity of the passive sensing configuration to sensor movement and position.

9.5 Conclusions

The developed passive and active sensing schemes have been applied to three sets of reinforced concrete specimens subjected to external anodic currents. Passive sensing was carried out with either multiple fixed
Figure 9.31: Concrete specimens from sample set 3 after the removal of anodic reinforcing bars. The top specimen is the beam without chloride ions and the bottom one with chloride ions in the mixture.

Figure 9.32: Upper surfaces of extracted reinforcing bars sample set 3. The top bar is from the beam without chloride ions in the mixture and the bottom one with chloride ions in the mixture. Sensing locations are indicated by letters.
Figure 9.33: Lower surfaces of extracted reinforcing bars sample set 3. The top bar is from the beam without chloride ions in the mixture and the bottom one with chloride ions in the mixture.

Figure 9.34: Polished upper surface of extracted reinforcing bar from test beam. Areas were pitting was observed have been circled.
sensor locations (test samples 1 and 2) or with a single set of sensors moved across multiple locations on the specimens (test sample 3). The sensor to anodic reinforcement separation distance was kept as small as possible, less than 5mm. However this separation distance is still larger than used to illustrate the principle in aqueous environments.

The applied anodic currents did initiate controlled corrosion in the test beams where the bar was exposed (uncoated). No corrosion was observed in the reference beam and in the coated portions of bar in the test beam. The actual amount of corrosion was higher than predicted by Faraday’s law in the case of on and off cycles of applied anodic current. Accurate estimates of corrosion loss were obtained using Faraday’s law for sequences of consistently increasing current levels.

Raw passive sensing data showed minimal sensitivity to corrosion caused by applied current levels. Daily ambient noise and local residual magnetic fields obscure the measurements. Signal zeroing helps eliminate these disruptions. The data from companion sensors are also useful to help interpret the observed field. Gradiometric presentation of the data do not add much additional insight.

Data from active magnetic measurements do not show clear connection to the corrosion in the samples. Data were acquired at different locations and for different current levels, but no distinction was observed between beams with and without chloride ions. Furthermore, no clear distinction between different current levels was observed in the active data.

Visual inspection showed that most corrosion takes place on the lower surface of the reinforcing bar, away from the top surface. This may be caused by greater access of chloride ions to the bottom surface for this particular sample geometry and because currents come from the cathodes. Unfortunately, these locations where the highest corrosion was observed were likely not sensed with the sensing configuration.

Application of the equations developed in chapter 7 to estimate corrosion rates based on passive magnetic field data resulted in much lower corrosion rate estimates than those obtained directly from the imposed anodic current. Differences between predicted and actual corrosion in steel could be due to the sensor separation distance (the field rapidly drops with increasing separation distance) or to different field-rate behavior for corrosion in aqueous solutions and that in situ. For the case of fixed sensors (sample sets 1 and 2), magnetic field data indicated higher corrosion rates at particular locations that coincide with regions of higher pitting concentration.

Future measurements should seek to reduce the sensor to sample separation distance and employ embedded and fixed sensors in close contact to the corroding structures. Access to all surfaces of the bar would be optimal.
Chapter 10

Summary, conclusions, and recommendations

Non-destructive evaluation and sensing methods that directly and accurately monitor corrosion within the civil infrastructure are needed. Traditional corrosion monitoring techniques and sensors have limitations: the corrosion process itself is not monitored directly, they may not be applied to coated bars or at large cover depths, or a direct electrical connection to the metal is required. Magnetic sensing approaches were explored as practical and sensitive alternatives to the traditional methods. Passive and active magnetic testing configurations, using GMR sensor sets, were first applied to aluminum and steel samples in controlled aqueous solutions that promote specific rates of corrosion. The methods were then applied to steel reinforced concrete samples whose corrosion rates are controlled by impressed anodic currents. An approach based on magnetic sensing has potential to overcome the limitations of exiting corrosion characterization methods. GMR sensors offer a practical approach to employ magnetic sensing for corrosion detection. However issues such as disruptions due to ambient noise and residual magnetic fields in the material must be overcome.

Based on the results presented in this thesis, the following conclusions and findings can be drawn:

1. Impressed anodic currents can be used to achieve controlled, fast, and accurate corrosion of steel in prismatic concrete specimens. The procedure is predictable and controllable within a wide range of imposed currents, and does not require surface ponding if sufficient amounts of chloride ions are added to the concrete mixture. Impressed current density levels should be above 200 $\mu A/cm^2$ and sodium chloride addition above 5% by mass.

2. GMR sensors employed in a passive sensing scheme can detect magnetic fields set up by corrosion currents in A36 steel and 2024 aluminum. A more remarkable result is that the amplitude of the emitted magnetic field, based on the average amplitude of the time signal, is related to the corrosion rate of the respective metals. Developed relationships between the measured corrosion rate and the zeroed magnetic field measurements can be used to predict the corrosion rates for specific materials, at a fixed location. However, corrosion induced magnetic field drops rapidly with increasing separation distance between the sensor and the test material. At distances larger than 1mm the magnetic field
reaches base noise levels, for the corrosion levels and sensors studied here.

3. Frequency and PSD domain analyses did not provide additional insight to the corrosion process, since the magnetic field spectral energy owing to corrosion is concentrated at the very low frequencies, essentially represented by DC current processes.

4. Active magnetic testing was carried out to overcome the distance offset limitations associated with passive testing. Although some distinction between corroding and non-corroding states can be observed, consistent data and meaningful relationships between the active magnetic response and corrosion rate could not be established.

5. Raw passive sensing data showed limited sensitivity to corrosion in steel reinforced concrete samples caused by applied current levels. Daily ambient noise and local residual magnetic fields obscure the measurements. For the case of fixed sensors, magnetic field data indicated higher magnetic field values at particular locations that coincide with regions of concentrated pitting attack. However the predicted corrosion rates based on passive sensing underestimate the actual corrosion of steel. The differences could be due to larger separation distances, or different field-rate behavior for corrosion in aqueous solutions and that in situ. Active magnetic data showed high scatter and no relationship with corrosion rate was observed.

Based on the findings summarized in these conclusions, an application of passive magnetic sensing for infrastructure corrosion characterization is envisioned. The small sensor spacing needed for measurements limits the range at which passive magnetic sensing can be applied. Essentially the sensor should be attached almost directly to the metal. Sensors should be protected from the environment in a non-conducting and non-ferromagnetic casing. A thin polymer casing would be the best option. The casing should completely enclose the GMR sensors. An array of sensor sets is recommended for redundancy because of the inherent data variability. Each sensor set should be comprised of one sensor that monitors the metal and another remote sensor to monitor the magnetic field of the environment. Sensors must be firmly fixed at one location to minimize disruptions from sensor movement.

Sensors should be able to export the information they gather. Two options are possible: a physical connection (hardwire) or a wireless communication configuration. The latter option seems feasible as recent developments in technology have greatly improved performance and reduced the size and power consumption of wireless antennas. GMR sensors are easily powered since their power consumption is low and they have a wide range of operating potentials. To make them more viable, a combination of batteries and solar cells could be used.
Data should be gathered at the same time of day at the fixed locations to minimize the effects of daily cyclic variability in ambient field. Several time domain signals should be taken each time (at least ten) and averaged to correct for data and sensor variability. The time signals should be acquired with at least a 10kHz sampling rate. The amplitude change in the measured magnetic field time signal with respect to a known base magnetic value, for instance the initial value when the sensor is first installed, should be used to predict and monitor corrosion. A steady increase in the field over an extended period could indicate localized corrosion. If the sensors are placed in close contact (<1mm) to the sample and a relationship between corrosion rate and magnetic field has been developed for that particular metal, the measurements can be used to predict corrosion rates.

Sensors should be located at critical points in a given structure. An example of such location would be the midspan point of a girder under a bridge deck. Bridge decks are susceptible to corrosion since they have two moisture fronts and deicing salts rupture the passivity of the reinforcing steel. Figure 10.1 shows a precast segmental bridge that could be susceptible to corrosion. Another example of an application is in post-tensioned, unbonded tendons within concrete elements. These tendons are generally protected with grout to avoid corrosion. However, at long distances from the injection point of the grout, improper grouting and a loss in protection may occur. Figure 10.2 illustrates the grouting procedure in a concrete member and the location where lack of grouting may cause corrosion. Figure 10.3 shows an ungrouted portion of a concrete tendon. Corrosion of tendons may cause catastrophic failure of the structure.

![Figure 10.1: Precast segmental bridge. A critical location where corrosion could be catastrophic is shown with a red circle [59].](image)
Figure 10.2: Grouting details for a concrete member. Location for possible grouting problems is shown with a red circle [60].

Figure 10.3: Voids in grouted tendon ducts of a post-tensioned highway bridge [61].
Chapter 11

References


