

IMPERIAL COLLEGE LONDON

**CURRENT DEFLECTION NDE FOR PIPE
INSPECTION AND MONITORING**

by

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For my parents

Abstract

The detection of corrosion on insulated and/or coated pipes in the oil and gas industry remains a challenge. Routine inspection, which is commonly achieved with in-line tools known as “pigs”, is not possible where there is any risk of the pig becoming stuck. There are thousands of kilometers of pipe worldwide deemed “unpiggable” whose safety must be ensured using Non-Destructive Evaluation (NDE) external to the pipe if potentially catastrophic failure is to be avoided.

Many NDE techniques lack sufficient sensitivity due to the coating thickness producing a high standoff distance between the pipe and the sensor and therefore require costly and time-consuming removal of the coating. A method capable of detecting and/or monitoring of defects (e.g. one-third-wall depth corrosion) while leaving the insulation/coating intact would be highly attractive. This thesis documents the development of a technique in which a low-frequency AC current is directly injected into the pipe at distant locations, and perturbations in the magnetic field caused by “current deflection” around defects are measured using solid-state magnetic sensors. Two methods of applying this novel technique were investigated. Firstly, scanning the sensors to measure perturbations in the field and screen for defects, and secondly, permanently installing sensors outside the pipe for Structural Health Monitoring (SHM).

A Finite Element (FE) model has been developed and used to investigate the practical challenges that are faced by the technique and how these may be overcome. The sensitivity of the technique for defect detection by external pipe scanning in a practical scenario has then been evaluated using a model-assisted Probability of Detection (POD) framework that combines the measurements of the signal from an undamaged pipe with synthetic damage profiles and contributions from general corrosion and sensor misalignment. The results indicate that good performance is expected for damage detection by scanning above a typical insulation thickness with just a few amps of injected current.

A similar framework has then been used to evaluate the sensitivity of the technique as an SHM solution which suggests excellent corrosion detection performance with the permanent installation of inexpensive magnetic sensors. The technique has potential advantages over competing methods in both scanning and monitoring modes and there are many opportunities for future development.



I hereby declare that this thesis and the work reported herein was composed by
and originated entirely from me. Information derived from the published and
unpublished work of others has been acknowledged in the text and references are
given in the list of sources.

A handwritten signature in black ink that reads 'Rollo Jarvis'.

Rollo Jarvis (2017)

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Nomenclature

Constants

μ_0	Magnetic permeability of free-space.
ϵ_0	Electrical permittivity of free-space.

Variables

δ	Electromagnetic skin-depth.
s	Sensor separation in gradiometer (baseline distance).
A	Minimum peak area for detection.
κ	Minimum pole separation for detection.
σ	Electrical conductivity.
p	Pitch for permanently installed sensor array.
μ_r	Relative magnetic permeability.
Δ	Standoff distance.
ω	Angular frequency.
f	Frequency.
$\mathbf{D}$	Electrical displacement field.
$\mathbf{E}$	Electrical field strength.
$\mathbf{B}$	Magnetic flux density.
$\mathbf{H}$	Magnetic field strength.
$\mathbf{J}$	Current density.
$\mathbf{m}$	Magnetic dipole moment.
ψ	Magnetic scalar potential.
d	Maximum defect depth.
T	Wall thickness.
β	Orientation in cylindrical co-ordinate system.

Acronyms

AC	Alternating Current.
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ACFM	Alternating Current Field Method.
ACPD	Alternating Current Potential Drop.
AMR	Anisotropic Magnetoresistance.
ANSI	American National Standards Institute.
API	American Petroleum Institute.
ASTM	American Society of.
AUC	Area Under Curve.
BS	British Standard.
CUI	Corrosion Under Insulation.
DC	Direct Current.
DCPD	Direct Current Potential Drop.
EC	Eddy Current.
EM	Electromagnetic.
EMAT	Electromagnetic Acoustic Transducer.
EOC	Environmental Operating Condition.
ERW	Electric Resistance Welded.
FE	Finite Element.
FN	False Negative.
FP	False Positive.
FSM	Field Signature Method.
FWHM	Full Width at Half Maximum.
GMR	Giant Magnetoresistance.
ILI	In Line Inspection.
IMU	Inertial Measurement Unit.
LPF	Low-Pass Filter.
MAPOD	Model Assisted Probability of Detection.
MBN	Magnetic Barkhausen Noise.
MFL	Magnetic Flux Leakage.
MMM	Magneto-Mechanical Memory.
MPI	Magnetic Particle Inspection.
MR	Magnetoresistive.
MRI	Magnetic Response Imaging.
MTM	Magnetic Tomography Method.

NDE	Non-Destructive Evaluation.
NDT	Non-Destructive Testing.
OD	Outer Diameter.
PD	Potential Drop.
PEC	Pulsed Eddy Current.
PFA	Probability of False Alarm.
PMR	Pulsed Magnetic Reluctance.
POD	Probability of Detection.
PSD	Phase-Sensitive Detection.
RCNDE	Research Centre for Non-Destructive Evaluation.
RMS	Root Mean Square.
ROC	Receiver Operating Characteristics.
ROV	Remotely Operated Vehicle.
RPMI	Rotating Permanent Magnetic Inspection.
SCC	Stress Corrosion Cracking.
SHM	Structural Health Monitoring.
SLOFEC	Saturated Low Frequency Eddy Current.
SNR	Signal to Noise Ratio.
TMR	Tunnelling Magnetoresistance.
TN	True Negative.
TP	True Positive.
UT	Ultrasonic Thickness.

1 | Introduction

BP plc. is one of the largest energy companies worldwide, producing over 14 million tonnes of petrochemicals per year and operating in over 70 countries. The business model spans the entire supply chain from oil and gas exploration and extraction to manufacturing, trading, transporting, and marketing the products. BP's renewable energy business is also the largest among its oil and gas peers. BP operates thousands of kilometres of pipelines which transport the extracted oil and gas between facilities. Ensuring the structural integrity of this infrastructure is essential to prevent environmental and financial loss, and even loss of life that could follow a pipe failure.

1.1 Industrial Motivation

Petrochemical pipes can be broadly categorised into either “pipelines” which carry hydrocarbons between facilities and are typically a single conduit, or “piping” which describes all pipes contained within a processing facility. Piping is typically smaller in diameter than pipelines, and can include multiple pipes in close proximity, on inaccessible racks, or buried for sections. Non-Destructive Evaluation (NDE) should be applied to both types of pipe in order to find and evaluate defects that have the potential to compromise their service lifetime.

Corrosion has been established as the major cause of pipeline failure (Brondel et al. 1994) and the most common way of screening for corrosion is with the use of so-called “smart pigs” - tools that are passed through the body of the pipe containing sensors that are able to provide a direct indication of the wall condition of the pipe (Quarini et al. 2007). The infrastructure of many pipelines and nearly all facility piping does not support the use of a pig due to the potential for it to become stuck at sharp bends or diameter changes. Other reasons for a pipe to be “unpiggable”

include the inability to launch or retrieve the device, low pressure or turbulent flow unsuitable for propelling the device, the presence of features such as valves, or internal coatings. In such cases, the application of an NDE technique external to the pipe is required (Burkhardt, Goyen, et al. 2008).

Pipes are often coated and/or clad for corrosion resistance, insulation and protective purposes (Sloan 2001), and many applicable NDE techniques require the removal of this coating and cladding in order to achieve a satisfactory sensitivity to defects. It is also desirable to perform NDE when the component being tested is in service to prevent any loss in production of oil or gas. Within the Research Centre for Non-Destructive Evaluation (RCNDE) (*UK Research Centre in NDE* 2017), a consortium of British universities and industrial partners, it was identified that there are few techniques that could meet these requirements for in-service defect detection while maintaining the pipe coating, insulation and/or cladding intact. A literature review was therefore performed which analysed the potential for development of any of these techniques. The review revealed that a number of NDE methods had inherent attractive properties, and there was scope to develop a new hybrid technique with capabilities suited for application coated/insulated pipes.

The technique, similar to the Alternating Current Field Method (ACFM) and Direct Current Potential Drop (DCPD), was termed a “current deflection” method. It had showed promising results based upon the previous activities of RCNDE members (Nagy 2012a); however, its relative performance over existing NDE methods was unknown, and the suitability for deployment in the petrochemical industry was uncertain. The potential for permanently installing a relatively large number of magnetic sensors had also recently been made possible by recent advances in high-sensitivity, low-cost magnetic sensing technologies, so there was significant interest in exploring the possibility of operating the current deflection method as a Structural Health Monitoring (SHM) solution. In a parallel project in collaboration with the University of Warwick, research was conducted on an NDE technique that claims to exploit a relationship between stress and magnetisation known as the Magnetomechanical Memory method (MMM). Although this research does not form part of this thesis, it informed the review of other techniques, and journal articles documenting the work are reproduced in the appendix of this thesis. The author contributed the FE modelling sections of these research articles and aided with the processing of the

raw measurement data.

1.2 Aims and Objectives

1. To explore the potential electromagnetic current deflection technique for NDE of unpiggable pipes, analysing its capabilities for use in NDE via defect screening by scanning and in Structural Health Monitoring (SHM) using permanently installed sensors.
2. To develop a methodology for analysing the performance of the technique, in both scanning and monitoring modes of operation, and to provide an estimate of the sensitivity.
3. To understand the limitations of the technique and the reasons for these.
4. To determine whether or not the technique has significant strengths in comparison to existing methods and if so, to determine the next steps in the development of the method.

1.3 Thesis Outline

The thesis is structured as follows.

- Chapter 2 provides an outline of currently available NDE techniques for the inspection and monitoring of difficult-to-inspect pipes, focussing mostly on electromagnetic techniques. The fundamentals of the electromagnetic theory that underpin this research are also introduced.
- Chapter 3 introduces the current deflection technique that is the core research of this thesis. The methodology for laboratory experiments and Finite Element (FE) models of the method are introduced and validation of the model is presented.
- Chapter 4 explores a number of the potential challenges that must be overcome if implementing the current deflection technique into the field.

- Chapter 5 introduces a flexible framework for analysing the performance of the current deflection method used in scanning mode, and presents example Receiver Operating Characteristics (ROC) for the technique.
- Chapter 6 outlines a framework to provide performance analysis of the technique used for SHM and gives an estimate of the sensitivity in a practical setting.
- Chapter 7 concludes the main findings of the thesis and the contributions from academic and industrial standpoints.

2 | Inspection and Monitoring of Unpiggable Pipes: A Review of Literature

In order to determine the focus of the key research questions for the development of the technique at the subject of this thesis, it is first necessary to assess the gaps in the capabilities of existing NDE for unpiggable pipelines. This was realised by performing a comprehensive literature review which is summarised in this chapter. A greater emphasis has been placed on the descriptions of electromagnetic NDE because this thesis focusses on the development of an electromagnetic NDE technique.

This chapter is categorised based upon the underlying physics on which the NDE is based. In the first category, “Magnetic Methods”, techniques that are based purely upon magnetic theory with no electrical currents are discussed. These include techniques based upon leakage of a magnetic flux inside the material at the location of a defect; techniques that rely on a complex interaction between stress and magnetisation, and also on microscopic changes in the magnetic structure of a material during magnetisation.

The second category “Electromagnetic Methods” concerns techniques based upon the theory of electromagnetic induction. To preface this section, a brief discussion of the most important concepts of electromagnetism from an NDE standpoint is given. Of particular importance is the “skin effect” which describes the frequency dependence of current distribution in a conductor. Although the induction and sensing mechanisms vary between techniques, defect detection is fundamentally enabled because a flaw will disturb the flow of current in the conductor. The first set of NDE methods discussed are called “Eddy Current” (EC) techniques, the most

well-established of the electromagnetic methods which are based on the induction of localised fields within the sample. The alternating current field method is then described, which stems from eddy current testing but instead induces a more uniform field in the sample. Also, techniques that directly inject a current into the sample and measure variations in the induced field are discussed (potential drop and NoPig), as well as an emerging technology - magnetic response imaging.

The final section discusses non-electromagnetic methods that are available for NDE of unpiggable pipes. Acknowledgement of the capabilities and weaknesses of these techniques are important when guiding the development of the electromagnetic method explored within this thesis.

2.1 Magnetic NDE Methods

2.1.1 Magnetic Particle Inspection and Magnetic Flux Leakage

One of the most widely used magnetic NDE methods is Magnetic Particle Inspection (MPI). The technique relies on the difference in magnetic permeability of the material and surrounding medium. The sample being tested must first be brought to a level of magnetisation so that it exists in the region in the upper-right or lower-left parts of its magnetisation curve. This is where $\frac{dB}{dH}$ is decreasing near the point of magnetic saturation and is indicated by the black dot and the shaded areas on Fig 2.1. Magnetic saturation ensures that the presence of a defect causes the internal magnetic flux to leak out of the material and spread out due to the lower permeability of the surrounding medium (it can not support as much magnetic field) (Shi et al. 2015; Sposito 2009).

The “leakage flux” can be detected by various methods to indicate the location of a defect. Fluorescent magnetic particles suspended in a solution can be applied to the material to aid visual identification of flaws (MPI inspection) (Brondel et al. 1994). Alternatively, the leakage flux can be detected using magnetic sensors, in which case the method is termed Magnetic Flux Leakage (MFL). MFL is commonly deployed on In-Line Inspection (ILI) tools, and the need to magnetically saturate the pipe wall means that only a small standoff (the distance between the sensor and

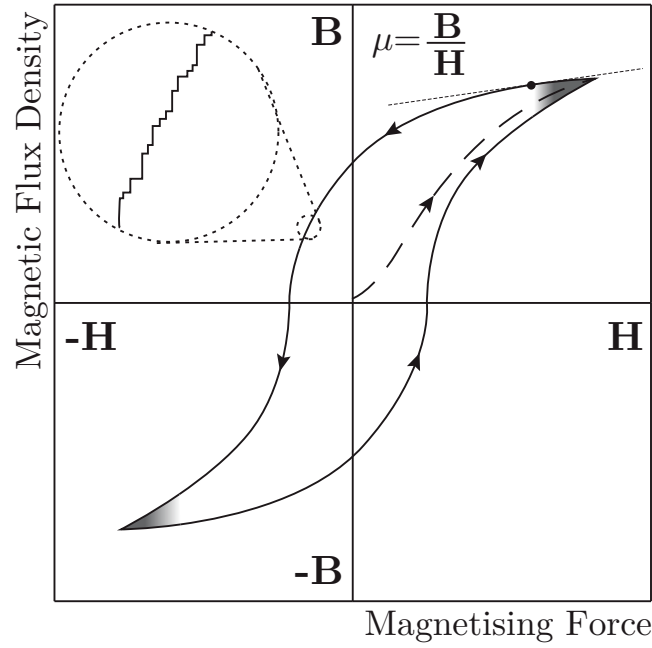


Figure 2.1: Hysteresis curve of a ferromagnetic material. The region reaching magnetic saturation is shaded in grey, where the magnetic permeability μ approaches unity. Cutaway shows a zoom of the hysteresis curve showing Barkhausen effect.

the sample) can be tolerated. Although testing is not limited to surface-breaking defects, sensitivity is reduced in thick-walled pipes due to the difficulty of achieving magnetic saturation (Shi et al. 2015). Conversely, MPI must be performed on bare metal and is only sensitive to surface-breaking and near-surface cracks due to the need for visual inspection of the fluorescent magnetic particles. The techniques are most sensitive to defects that lie in the plane orthogonal to that of the magnetic flux (circumferentially oriented defects in pipelines). The detection of narrow axially oriented defects often requires an orthogonal rotation of the magnetic flux which can be practically challenging (Shi et al. 2015). As with some of the other techniques explored in this chapter, the sizing and characterisation of defects requires comparison to a model. Although there have been many laboratory studies of MFL, its use in practice is limited owing to the much more challenging industrial conditions (Shi et al. 2015).

MFL has been proposed for use in traditionally unpiggable pipes via articulated ILI tools with collapsible diameters (Beugen 2009; Foster-miller et al. 2004; Kim et al. 2013); however, their use in industry is unproven and restrictions for access still apply. Pulsed MFL has been suggested as an alternative MFL method that is tolerant to a greater standoff (Wu et al. 2017). In this method, the MFL probe

is driven by a pulse which allows information from different thicknesses to be extracted due to the electromagnetic skin-effect (Wu et al. 2017). Pulsed Magnetic Reluctance (PMR) is a complementary technique that has been designed for use together with pulsed MFL to detect and size sub-surface defects in ferromagnetic material, although further research is required before industrial deployment (Wilson et al. 2007).

Within the rail industry, MFL has been used for the inspection of rail heads by using two contact brushes to inject a large amount ($\sim$ kA) of low-voltage direct current into the rail, and detecting the leakage flux from the induced magnetic field with a search coil (Clark et al. 2009; Harcourt et al. 1935). The technique was not successful in detecting transverse fissures that were aligned parallel to the induced field, and the high amplitude current could interfere with the railway signalling (*Rail Inspection* 2017).

Magnetic Flux Exclusion

In the early 1980's BP and Harwell NDT centre began developing a magnetic NDE technique capable of finding half-wall depth pitting corrosion in 6 mm thick storage tanks in petrochemical plants (Saunderson 1988). Due to the size of the tanks and the localised nature of the target defects, which appear on the blind side of the tank, ultrasonic thickness inspection was prohibitively time consuming. Eddy currents were unable to penetrate to the far side of the tank unless the frequency was so low that the inspection became very slow. Floor scanners have been produced that use a permanent DC magnetic field to bring the ferromagnetic tank floor close to magnetic saturation. An array of magnetic sensors is then used to detect regions in which there is wall thinning caused by corrosion which results in the magnetic field within the plate to leak out and register as a signal. Although this technique is referred to as Magnetic Flux Exclusion, its working principle is identical to MFL (Hobbs 1997).

2.1.2 Barkhausen Noise

During the hysteresis cycle of a ferromagnetic material, the magnetic domain walls undergo a random sequence of discontinuous rearrangements. Before a domain wall can reorient with the external magnetic field, it must overcome local obstacles at

pinning sites such as dislocations or inhomogeneities. When the domain has sufficient energy, it will suddenly reorient to a new position. These rearrangements give rise to small, sudden changes in the bulk magnetisation that are known as Magnetic Barkhausen Noise (MBN), and appear as steps in the hysteresis curve shown in Fig. 2.1 (Stefanita 2008). The stress distribution and microstructure (e.g. dislocation distribution) have influence on the MBN, therefore forming the basis for an NDE technique. The signal can be measured by detecting MBN using magnetic sensors (typically simple search coils) that are either positioned above the test piece, or encircling it. MBN typically originates from only the top 30 μm of the material.

Although MBN is not an effective method of detecting corrosion on pipes, it can be complementary to MFL by aiding the interpretation of the signals. The stress affects the MBN through various factors, which can be difficult to separate. Barkhausen testing requires highly skilled and experienced operators to interpret the complex signals. It can also only operate effectively at low standoff.

2.1.3 Magnetomechanical Memory Method

The Magneto-Mechanical Memory (MMM) method, also referred to in some literature as Metal Magnetic Memory method is a passive technique in that it requires no external fields or currents. The technique relies on the measurement of perturbations in the Earth's magnetic field that may appear due to multiple stress cycles via a phenomenon known as the magnetomechanical effect (Dubov 2007, 2016; Jiles 1999; Suárez-Ántola et al. 2014).

Wang et al. have claimed to have developed a linear model that describes the relationship between stress concentrations and the magnetic signals measured in MMM (Wang et al. 2010); however, Jiles notes the difficulty of creating an accurate model of the magnetomechanical effect due to difficulty of modelling hysteresis in ferromagnets, particularly in the demagnetising effects due to finite geometries which makes it difficult to distinguish whether a signal is due to geometrical effects or a change of sample properties (Jiles 1988, 1998). Without an accurate model, false calls would be a significant problem. Augustyniak concludes that it is impossible to form a bidirectional correlation between the local material stress and magnetic field level as the magnetic field depends on a number of inseparable factors (Augustyniak et al. 2015). Other published reports have found the technique to

be unreliable (Arkulis et al. 2009). The author was involved in a parallel RCNDE project with Warwick University which studied MMM in more detail. The research paper resulting from this project can be seen in the appendix of this thesis (Z. Li, Dixon, Cawley, Jarvis, Nagy, and Cabeza 2017).

2.1.4 Magnetic Tomography Method

The Magnetic Tomography Method (MTM), also occasionally referred to as Stress Concentration Tomography (Spier Hunter Limited 2014), is a passive NDE method claiming detectability of defects at a significant distance from the pipe by measuring magnetic field anomalies due to regions of high mechanical stress, although the sensitivity is low (Liao et al. 2011; Mirzoev et al. 2016). This phenomenon is described by the magnetoelastic effect and the magnetomechanical effect, similar to MMM. The claimed applications of MMM include pipeline, rail and boiler inspection, whereas MTM solely describes the technique of remotely scanning buried pipelines from ground-level, or using a Remotely Operated Vehicle (ROV) in the case of subsea pipelines (Kolesnikov 2014).

There is very limited peer-reviewed literature surrounding MTM. The vast majority of publications are in the form of marketing leaflets, websites and presentations. For this reason, there has not been a thorough analysis of the theory which underlies the technique, although a conference paper by Liao et al. confirms that the method relies on the magnetomechanical effect (Liao et al. 2011). There are multiple reports that the technique has a high false call rate and an inability to size or characterise defects (Mirzoev et al. 2016).

A field test has been completed by the company Transkor-K comparing ILI with MTM performed for TNK-BP in 2009 on 2 BP pipelines from the Samotlor oilfield (Bradley 2009). In a test of oil pipeline BPS 32-BPS 24, MTM had a Probability of Detection (POD) of 11% and Probability of False Alarm (PFA) of 18.6% which is deemed unacceptable. The uncertainty in the defect locations required over 500 m of unnecessary excavation. A similar test on pipeline BPS14-BCCP produced a PoD of 45% and PFA of 85%. It is clear from these field studies that the accuracy and capabilities of MTM is far over-sold and, in its current form, it is not a replacement for in-line inspection. A recent study that the author collaborated on highlighted that the large false call rate is likely due to the presence of ferromagnetic objects in

the path of the pipeline (Z. Li, Jarvis, et al. 2017). The interested reader is referred to the appendix for the complete research article.

2.2 Electromagnetic Methods

The techniques discussed in this section are based upon the physics of electromagnetic induction. The fundamental equations to describe electromagnetism were formulated by James Clerk Maxwell. Written in their differential form and in magnetic materials, they are Ampère’s law:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (2.1)$$

where $\mathbf{H}$ is the magnetic field, $\mathbf{J}$ is the current density and $\mathbf{D}$ is the electrical displacement field; Faraday’s law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.2)$$

where $\mathbf{E}$ is the electric field which is related to the electrical displacement field by the constitutive equation $\mathbf{D} = \varepsilon \mathbf{E}$ where ε is the electric permittivity, and the current density by $\mathbf{J} = \sigma \mathbf{E}$ where σ is the electrical conductivity. $\mathbf{B}$ is the magnetic flux density which, in conducting materials, is related to the magnetic field by $\mathbf{B} = \mu \mathbf{H}$ where μ is the magnetic permeability that can be expressed as the product of the relative permeability μ_r and the permeability of free-space μ_0 . Gauss’ law for electric charges states

$$\nabla \cdot \mathbf{D} = q \quad (2.3)$$

where q is the charge density and finally Gauss’ law for magnetic monopoles:

$$\nabla \cdot \mathbf{B} = 0 \quad (2.4)$$

Faraday’s law describes how a time-varying magnetic field will always be accompanied by a spatially varying, non-conservative electric field, and vice versa. It also follows that a changing magnetic field will *induce* an electric current in a nearby conductor known as an “eddy current”. According to Lenz’s law, the direction of

this current flow is such that its corresponding magnetic field acts to oppose the change in magnetic flux that produced it. The time derivative in Faraday's law tells us that the amplitude of the eddy current is proportional to the rate of change of flux, so electromagnetic induction is more effective as the frequency of the field is increased.

In practice we frequently consider sinusoidally varying currents, so it is useful to consider the time-harmonic solutions of Maxwell's equations which explain electromagnetic wave propagation. The magnetic and electric fields can be written using complex wave notation as $\mathbf{H} = \mathbf{H}_0 e^{i\omega t}$ and $\mathbf{E} = \mathbf{E}_0 e^{i\omega t}$ with angular frequency ω and complex amplitude $\mathbf{H}_0$ and $\mathbf{E}_0$. These can then be substituted into equations 2.1 and 2.2 then rearranged to give the general electromagnetic wave equations:

$$(\nabla^2 + k^2)\mathbf{E} = 0 \quad (2.5)$$

$$(\nabla^2 + k^2)\mathbf{H} = 0 \quad (2.6)$$

where $k^2 = -i\omega\mu(\sigma + i\omega\varepsilon)$. In conducting materials at all frequencies relevant to electromagnetic NDE, σ is generally much greater than $\omega\varepsilon$, therefore the wavenumber is complex and has real and imaginary parts with magnitude $k = \sqrt{-i\omega\mu\sigma}$. Considering a plane wave propagating into a conductor in the z direction, the solutions to the wave equations 2.5 and 2.6 are

$$\mathbf{E} = E_0 e^{-kz} e^{i(kz - \omega t)} \mathbf{e}_x \quad (2.7)$$

$$\mathbf{H} = H_0 e^{-kz} e^{i(kz - \omega t)} \mathbf{e}_y \quad (2.8)$$

These waves are orthogonal to one another and transversely polarised with respect to the propagation direction. It is apparent that the amplitude of the wave decays exponentially as it propagates through the conductor. The skin depth, δ can then be defined as

$$\delta = \frac{1}{k} = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (2.9)$$

where $f = \frac{\omega}{2\pi}$. The skin depth denotes the distance into a conductor for which the amplitude of the propagating wave reduces by a factor of $\frac{1}{e}$ or $\sim 37\%$. Due to the dependence on σ and μ , δ is much smaller for highly conducting and magnetically

permeable materials that can support higher amplitude eddy currents and a greater induced flux to oppose the external flux change that produced them.

2.2.1 Eddy-Current Testing

Eddy current testing is perhaps the most widely used of all the electromagnetic NDE techniques. Eddy currents are induced in a conducting material when there is a change in flux density in the material and these currents flow in a direction which acts to reduce the change or motion that causes them. The secondary magnetic field produced by eddy currents therefore opposes the primary magnetic field, and the range of the primary magnetic field is reduced with respect to the undisturbed case. The region in the range of the primary magnetic field is known as the “near-field”. The electromagnetic perturbation here also causes a diffuse electromagnetic wave to propagate (especially in geometries that act as wave guides like pipes) that can interact with defects that are out of range of the primary magnetic field. This region is labelled the “remote-field”.

The frequency of operation determines the depth of sensitivity to defects according to the electromagnetic skin effect. There are a number of configurations of eddy current techniques that interact with either the near-field or the remote-field and use a single-frequency, a multi-frequency or a pulsed input. Each of these will be discussed briefly in terms of their relevance to the NDE of unpiggable pipes. As well as defect detection, eddy current techniques can also be used for thickness gauging of metals or coatings; conductivity or permeability measurements or texture, hardness and residual stress measurements. Eddy current testing is non-contact and therefore alleviates the problems associated with coupled techniques namely the need for a smooth surface and good coupling in the case of piezoelectric ultrasonic testing.

Near-Field Eddy Current Testing

Near-field eddy current testing describes an excitation in a primary probe coil that is brought close to a conducting material so that eddy currents are induced. The technique relies on defects in the conductor changing the eddy current distribution which therefore affects the electrical impedance of the primary coil. The impedance can be monitored on an oscilloscope or screen and characteristic patterns allow the operator to locate and size defects. The primary coil in near-field eddy current

probes is typically driven at 100 Hz–MHz which limits the current distribution to a layer at the surface of the material due to the skin effect meaning the technique is most effective at detecting surface breaking defects. The probe excitation can either be at a single frequency, or multiple frequencies can be investigated in a sweep to probe deeper into the material, or to optimise the test to measure conductivity or permeability variations.

Near-field eddy current probes are sometimes used in ILI tools; however, there are potential issues when testing pipes externally. The majority of petrochemical pipes are ferromagnetic, which makes them significantly more difficult to test than non-magnetic materials due to the magnetic permeability variations affecting the signal. The thermal and mechanical history can cause strong inhomogeneity in the magnetic permeability of the pipe so, for materials with very high permeability, it is sometimes favourable to bring them to magnetic saturation such that the relative permeability falls to unity (Sposito 2009). Although the technique is non-contact, the sensitivity will be too low at the large standoffs associated with typical pipe coating/insulation thickness. For these reasons, conventional near-field eddy current testing cannot realistically be used as an NDE method to inspect pipes outside of insulation.

Pulsed Eddy Current Testing

The principles of operation in Pulsed Eddy Current (PEC) testing remain the same as previously described, however a step current voltage pulse is used to excite the primary coil rather than an alternating current. Due to Fourier theory, the magnetic field response to the excitation pulse contains information at many different frequencies which is useful due to the skin effect dictating that penetration is frequency dependent. It is therefore possible to use this frequency information to learn more from the sample being tested. The signal response is plotted in the time domain which allows depth gauging of defects as indications closest to the primary coil will be seen earliest in time. A reference signal is obtained and subtracted from the received signal to mitigate uncertainties and ensure that changes in the total signal are solely from dimensional changes, defects and conductivity variations. PEC testing can obtain information from multiple frequencies in a much shorter time than performing the equivalent individual EC tests at different frequencies (Crouse

2014); however, multiple single frequency tests combined with phase-sensitive detection offers the best signal to noise ratio at the cost of increased test time (Nagy 2011).

There have been recent attempts to adapt PEC techniques for inspection of unpiggable pipelines. Collapsible ILI tools have been developed that are able to pass through traditionally unpiggable regions of pipe (Plotnikov et al. 2008). External application is also possible while leaving the coating and cladding intact so long as the nature of the pipe wall and cladding is known adequately (Cheng 2012). Due to the reduced power consumption of a short pulse in comparison to the equivalent sinusoidal signal with the same large excitation current, PEC can support higher excitation pulses that allow testing at a much greater standoff than conventional probes. Certain cladding types such as ferromagnetic galvanised steel make measurement difficult (Cheng 2012). It is also only possible to ascertain the wall thickness averaged over the probe footprint, which is typically tens of mm in diameter. Li et. al determined that improved performance to subsurface degradation can be realised by measuring the gradient of the magnetic field using a pair of magnetoresistive sensors rather than measuring the net field (Y. Li et al. 2016).

Remote Field Eddy Current Testing

Remote Field Eddy Current (RFEC) inspection is most applicable to the testing of pipelines as relatively long lengths of conductor can be tested from a single location. Low frequency (<100 Hz) currents are used to ensure full penetration of the pipe wall. The schematic diagram in Fig. 2.2 shows that eddy currents flow from the inner pipe wall at the excitation coil and then predominately along the outer surface of pipe with their amplitude decaying exponentially (Atherton 1995; Nagy 2011).

A detector coil or an array of solid state sensors is placed in the remote field zone which is typically axially separated from the excitation coil by more than two pipe diameters. Changes in the signal (amplitude and phase) received in this remote field zone indicate the presence of a defect somewhere along this distance. Wall thickness loss can be determined due to its approximately linear relationship with the phase shift, although accuracy is limited to the correctness of calibration with respect to reference pipes (Nagy 2011). The technique is primarily implemented on magnetic pigs which run through the body of pipelines collecting large amounts of

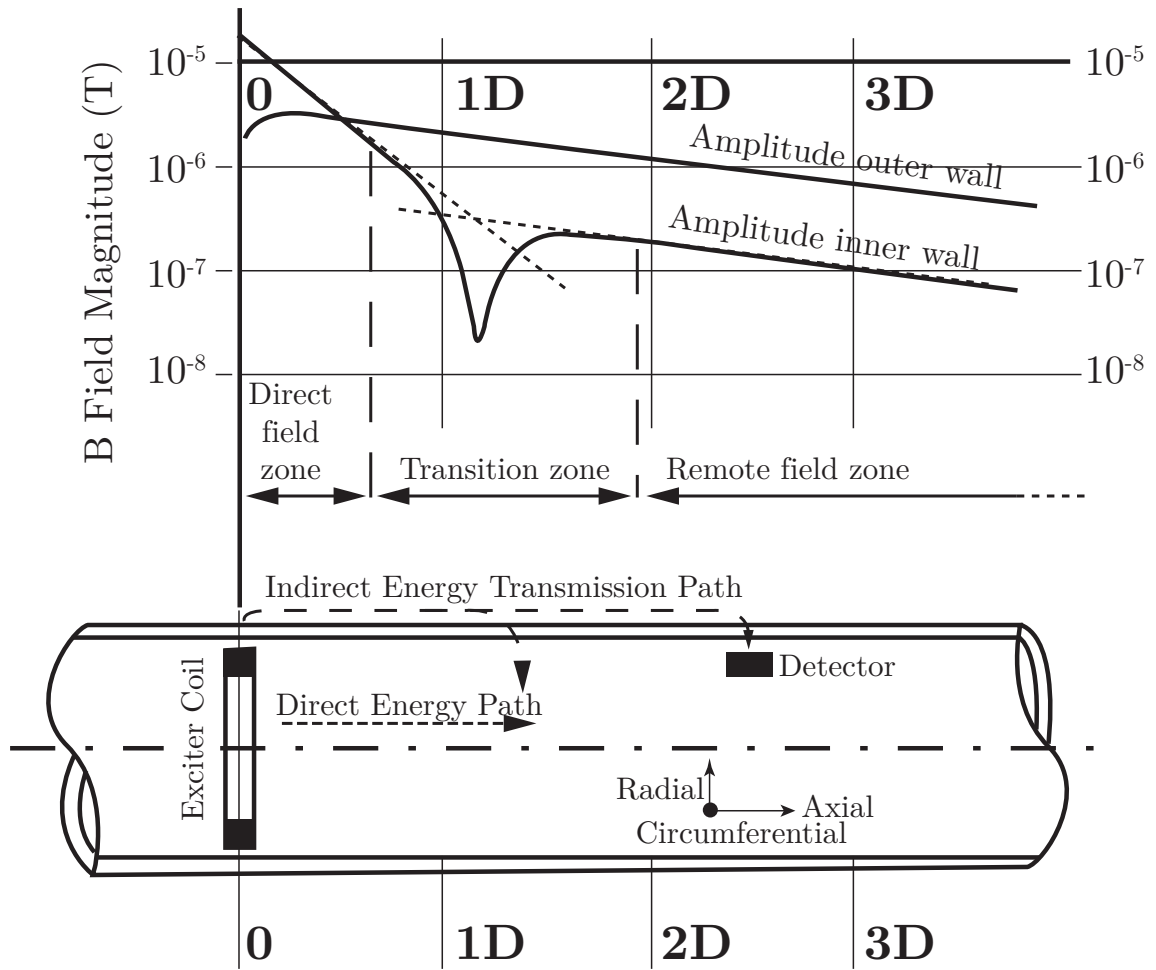


Figure 2.2: Schematic of the remote field eddy current method. The energy paths are shown and the profiles of the magnetic field inside and outside the pipe that are used to indicate the near and far field operating zones. D = pipe diameter. (Adapted from Atherton 1995 with permission).

data at time. Disadvantages of this technique are its relative difficulty in detecting axially orientated cracks which do not perturb the axially flowing remote current to a significant degree (Atherton 1995). A higher power is required in relation to conventional EC techniques owing to the lack of sensitivity due to the signal being attenuated after travelling a large distance.

RFEC has also been applied to the testing of traditionally unpiggable pipelines. Teitsma et al. planned to develop the technique by creating an internal RFEC device with sensitivity comparable to that of MFL pigs, whose diameter was significantly less than the inner wall diameter of the pipe thereby avoiding the risk of becoming trapped (Teitsma 2004). Similar efforts have been attempted by other researchers, who demonstrated good performance for the detection of metal loss defects in tra-

ditionally unpiggable pipes with prototype systems (Burkhardt, Goyen, et al. 2008; Laursen et al. 2010); these, however, still require internal access to the pipe.

Saturated Low Frequency Eddy Current Method

The Saturated Low Frequency Eddy Current (SLOFEC) method aims to improve the detection capability of MFL by using active eddy current sensors in place of conventional Hall-effect sensors, resulting in approximately double the upper wall thickness limit of MFL (Bönisch 2000). Furthermore, phase information from the sense coil can be used to determine the defect type. SLOFEC requires a DC magnetic field to saturate the pipe so that induced eddy currents can penetrate to the inner surface of the material. An increase in standoff results in a reduction of the amplitude of the eddy currents and the magnitude of the DC field present in the sample. For this reason, if a significant standoff (>30 mm) is to be tolerated, the size and power requirements of the testing equipment quickly becomes prohibitively large (Bönisch 2000; Raad et al. 2002).

Rotating Permanent Magnetic Inspection

A new eddy-current technique has been designed with the inspection of unpiggable pipes in mind. The Rotating Permanent Magnetic Inspection (RPMT) technique describes a rotating permanent magnet which induces an eddy current that flows within the pipe (Nestleroth and Davis 2007; Nestleroth, Davis, and Flamberg 2006). Metal loss anomalies are then detected by measuring perturbations in the induced magnetic field from the eddy current flow using an array of hall-effect sensors inside the pipe. A lock-in amplifier is used to measure at the angular frequency of the magnet rotation which is typically 5 Hz. The sensors are separated from the rotating magnet by more than one pipe diameter, so the measured field is predominantly the induced field from the eddy currents and not the primary field from the rotating magnets.

The diameter of the rotating magnet configuration can be small with respect to the pipe bore, which potentially allows the construction of a flexible ILI tool that is unrestricted by obstructions affecting traditional pigs. As with many of the techniques designed for ILI of unpiggable pipes, future development of the technique is required before a commercial system is made available, and not all restrictions

are removed (e.g. the need to launch/trap the tool).

2.2.2 Alternating Current Field Method

The Alternating Current Field Method (ACFM) was initially developed as a non-contact potential drop method that allowed the detection and sizing of surface breaking cracks by making an electric current flow in the surface of the sample and measuring current deflection around defects by monitoring changes in the induced magnetic field (Lewis et al. 1988; Lugg 2012). During the initial development of the technique, the current was introduced by direct injection; however, electromagnetic induction of a high-frequency current is now far more common (Nagy 2012a). The high frequency of the current (typically around 20 kHz) limits it to a thin layer at the conductor surface and therefore ACFM generally only provides sensitivity to surface-breaking defects. The technique can be applied outside of a coating up to 10 mm thick (LeTessier et al. 2002), is fast and does not require instrument calibration before use (Nagy 2012b).

A visualisation of the current distribution on the surface of a conductor is shown in Fig. 2.3a. If a flaw is present whose orientation is perpendicular to the current flow, then the current will be forced to flow around it. This change in the current distribution will modify the induced magnetic field surrounding the defect. Figure 2.3b shows the horizontal or x component of the induced magnetic flux density measured during a scan across the defect at some small standoff distance above the plate. This component maps the current density distribution, so maxima in the signal appear at the edges of the defect, and a minima above the defect centre. Away from the defect, the magnetic flux density tends to a baseline value of B_{x0} . The out-of-plane magnetic flux density response is shown in Fig. 2.3c. A bipolar signal is produced due to the rotation of the current around the defect, which tends to zero as the distance from the defect is increased and crosses zero at the defect centre due to symmetry. In ACFM scans B_x is often plotted against B_z to produce a “butterfly plot” as shown in Fig. 2.3d, named after the shape it forms. This is advantageous as it ensures that the measurement is independent of the probe speed.

If a thin crack-like defect is oriented parallel to the direction of the current flow, there will be very little current deflection; however, a measurable signal is often still received due to the leakage of the magnetic flux in the sample at the edges

of the defect. This effect only occurs in ferromagnetic materials as they are able to support a significant magnetic flux density (Lugg 2004). For larger volumetric defects, or cracks at an angle to the current flow, the received signal will be part due to current deflection and part due to flux leakage. As these operation modes give opposite polarity signals, there are cases where destructive interference can reduce the received signal so, to avoid missed defects, it is recommended to scan in orthogonal directions.

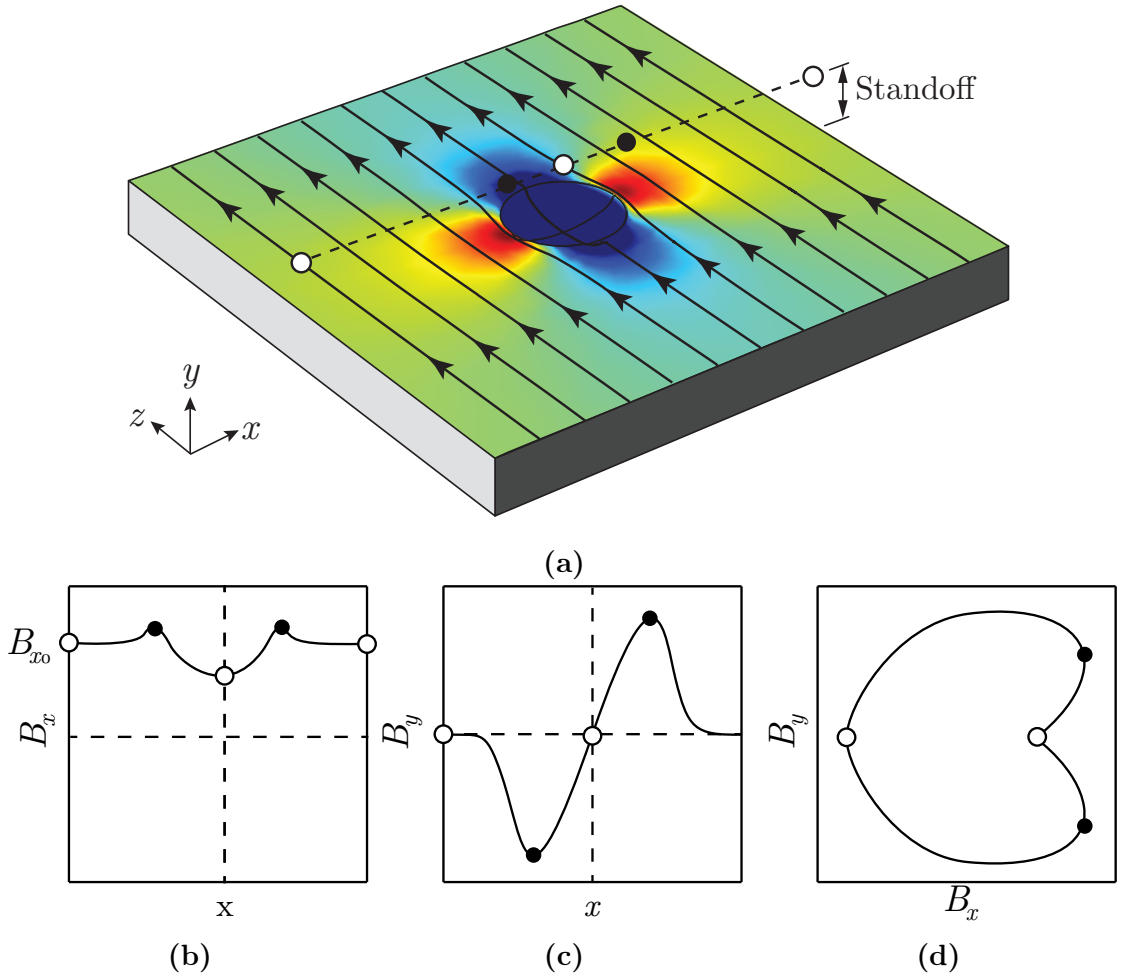


Figure 2.3: (a) Current density distribution on a conducting block with a semi-ellipsoidal defect. Black arrows show direction of the current flow. (b) B_x (c) B_y and (d) butterfly plot measured along the dotted line in (a) that bisects the defect and contains the solid and open markers for reference.

ACFM can be applied to pipe inspection following the same concepts shown in Fig. 2.3 and modifying the coordinate system from Cartesian to cylindrical. The crack sizing capabilities of ACFM follow from the understanding of the measured signals by using theoretical models. The limited similarities between mathematical

models and real-world defects leads to significant uncertainty in the categorisation of defects (Lugg and Topp 2006; Sposito 2009), however it has been shown that the technique is as accurate as MPI for detection, furthermore it can provide defect depth information to $\pm 15\%$ accuracy (Lugg 2012).

The significant advantage of ACFM in comparison to potential drop methods is that it is non-contact and can be used without the need to remove paint or coating. It is also capable of both scanning and monitoring (by storing soft records of defect data and looking for changes of the signal over time) (Energy Workforce 2014; Laenen et al. 2007). More recently, the development of ACFM arrays has allowed more rapid inspection of larger areas (Lugg and Topp 2006). Lugg notes that the development of algorithms describing the ACFM signals produced from Stress Corrosion Cracking (SCC) would greatly improve the ability of ACFM to classify the severity of SCC (Lugg and Topp 2006). There has been progress in the modelling of ACFM signals to improve sizing capabilities. A model based inversion method has been developed which sizes long cracks in ferrous metals. A de-convolution algorithm was also developed which corrects for signals being measured at an unknown standoff (Amineh et al. 2008).

There are a number of limitations of ACFM when considering its application to the inspection of unpiggable pipes outside of insulation. The technique is typically applied at a low standoff in order to maintain sufficient sensitivity while having an inductively coupled current in the conductor, so thick insulation and coating would still need to be removed. Also, the high frequencies of current being used restrict the detection capability to solely surface breaking defects (LeTessier et al. 2002); geometric variations can lead to false alarms; and the large sensor size can cause limitations to access (Nagy 2012b).

2.2.3 Potential Drop Techniques

Potential Drop (PD) NDE is often used to size cracks (Sposito 2009). Two pairs of electrode probes are used, one for current input and output and the other to measure the potential drop, as shown in Figure 2.4 (Saka et al. 2006). The technique can be categorised according to the type of current injected by one of the probe pairs.

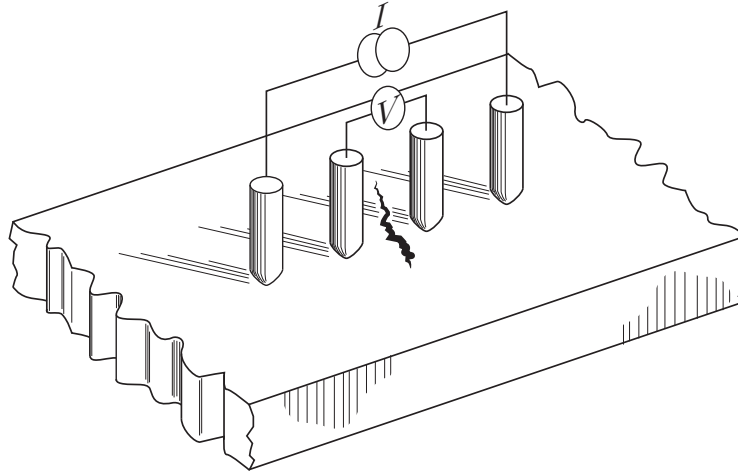


Figure 2.4: A potential probe configuration for potential drop measurements.

Direct Current Potential Drop

For this technique, a direct current is fed between the injection electrodes and the potential drop is measured with the other pair. The injection electrodes must be a sufficient distance away from the sensing electrodes in order to allow the current to spread uniformly through the sample before reaching the defect. When there is metal loss between the probes, the cross sectional area carrying the current decreases which therefore increases the resistance and alters the measured potential drop. Changes in conductivity also affect the signal. A baseline signal recorded in a defect-free area of the sample is used to eliminate changes in the signal originating from factors not of interest such as changes in temperature or fluctuations in the current (Sposito 2009).

Alternating Current Potential Drop

The electromagnetic skin effect can be exploited in order to increase the detection performance of surface breaking defects. A low-frequency current that can penetrate deep into the conductor will be largely unperturbed by the presence of a surface-breaking defect in comparison to a high-frequency current that is forced to flow around the defect. A greater potential drop and greater sensitivity is therefore achieved in comparison to DCPD. In turn, a lower amplitude current is permitted, often less than 1 A (Sposito 2009). The obvious drawback is that the high-frequency current is unperturbed by sub-surface flaws, so care must be taken when selecting the appropriate NDE solution. Using a low-frequency current combined with phase-

sensitive detection enables increased performance while maintaining sensitivity to sub-surface flaws; however, it is important to use a low enough frequency to ensure that the skin depth is greater than the minimum flaw depth (Corcoran et al. 2016).

Potential drop techniques are unsuitable for scanning purposes as the contact electrodes would need to move over the surface of the conductor which could cause damage. Their main application is found in monitoring defect growth over time. The requirement of potential drop techniques to be physically coupled to the pipe severely limits their application in hard-to-reach pipes with coatings that cannot easily be removed.

Field Signature Method

The Field Signature Method (FSM) is a modification of potential drop methods that uses an array of probes, and a reference sample to compensate for temperature effects. The technique claims increased sensitivity over PD and has been used to monitor internal erosion, corrosion and cracking (Wold et al. 2007). Recently, the ability to characterise pitting has been improved (Gan et al. 2016). Galvanic contact with the conductor is required for both PD and FSM, hence insulation must be removed and the methods are not suitable for scanning. FSM is also expensive to implement (Santos et al. 2013).

2.2.4 NoPig

The “NoPig” method is an above ground inspection method aimed at identifying corrosion on difficult-to-inspect buried pipelines carrying an injected electric current. The technique was TÜV approved in 2005 and has been deployed in the field, particularly in Germany and the Netherlands (Krivoi 2007). The method relies on the fact that the magnetic flux density profile surrounding a pipe with metal loss is frequency dependent due to the electromagnetic skin effect and stray magnetic flux leakage (Krivoi 2008).

An AC current between a few Hz and a few hundred Hz and of the order of 10 A is passed through the pipe between two injection points that have potential to be a few kilometers apart. Where there is a defect in the pipe, some of the induced magnetic flux from the current can no longer be contained within the steel pipe walls so it instead flows out of the pipe and deforms the induced external magnetic field. The

horizontal (azimuthal) component of the magnetic field is recorded at 1 m intervals above the ground using sensors capable of measuring sub-nanotesla variations. The current amplitude is also measured to determine the existence of “coating holidays” (discontinuities in the coating) where current would leave the pipe. Figure 2.5 shows a schematic diagram of the NoPig technique.

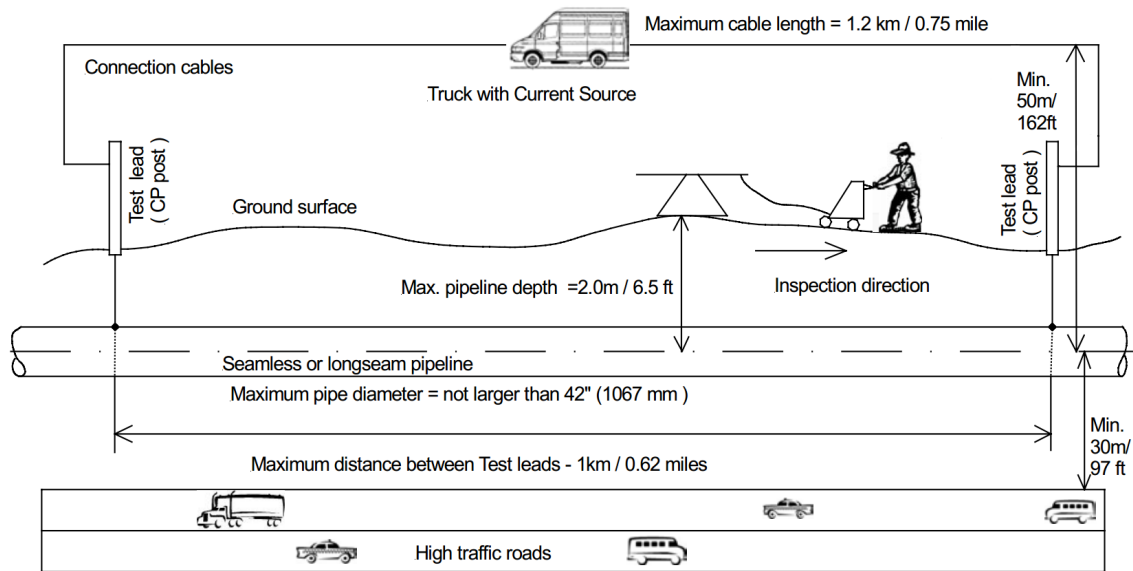


Figure 2.5: Schematic diagram of the NoPig method. (Reproduced from Krivoi 2007).

The significance of using AC current is that at higher frequencies (hundreds of Hz), the current is restricted to only the pipe outer surface due to the electromagnetic skin effect, whereas at low frequencies it flows through the entire wall thickness. In the case of a defect-free pipe, the magnetic field lines are identical to those induced by a thin wire carrying the same magnitude of current and running along the pipe axis - referred to as the “virtual current axis”. The current distribution within the pipe will change at locations with metal loss, which will alter the distribution of the induced magnetic field. The measured location of the virtual current axis will therefore shift, and indicate the presence of a defect. If the defect is located on the pipe inner wall, only the low-frequency magnetic field will be affected because of the skin effect. Conversely, if the outer wall has metal loss, the virtual current axis will be perturbed for all frequencies. Measuring the amplitude of the magnetic field can therefore reveal the presence of defects, and the frequency response of the field can indicate their location on the pipe (Krivoi 2007).

The claimed minimum detectable defect has dimensions of 50 mm×50 mm and a

metal loss of 50% and a standoff of 1.5 m or less. For depths between 1.5 m and 2 m, this is increased to 150 mm×50 mm. No information about the defect morphology can be inferred (Achterbosch et al. 2003). The amplitude of the magnetic field decreases with distance from the current source, so pipes deeper than 2 m are not considered inspectable. The distance between the sensor and the pipe is so large that the technique is only sensitive to relatively large defects, and sensitivity can be greatly affected by external influences such as busy roads, stray currents, adjacent pipes and metal objects in the vicinity of the line (Achterbosch et al. 2003). The technique being researched in this thesis is similar to the NoPig method; however, the standoff is much lower which helps to limit these weaknesses. One aim of the current research is to investigate the relationship between standoff and sensitivity.

2.2.5 Magnetic Response Imaging

“Magnetic Response Imaging” uses sets of coils wrapped around the pipe outside of insulation and non-metallic cladding to measure the magnetic response of the steel (Singer et al. 2013). An alternating current activates drive coils which create a magnetic field that acts to align and oscillate the magnetic domains in the steel. This in turn induces a detectable current in the sense coils (Singer 2013). In regions of the pipe with corrosion damage or wall loss there are fewer magnetic domains, therefore a lower response will be registered in the sense coils in comparison to defect-free regions of the pipe. The electromagnetic skin effect can be exploited to increase the sensitivity to either surface-breaking defects or inner-wall deterioration by changing the excitation frequency (Singer 2013).

A linear trend has been observed between the signal loss and the mass loss fraction of the pipe, allowing the severity of the corrosion to be estimated (Singer et al. 2013). Claimed advantages of the technique are that it can monitor insulated pipes, can be used subsea and underground, and can measure metal loss up to 0.5% of the cross-section (Singer 2013; Singer et al. 2013). The technique may also be employed in scanning mode by mounting the sense and drive coils on a semi-circular tube and moving this along the length of the pipe (Singer 2013). Temperature variations affecting the magnetic response are corrected by monitoring the temperature near the pipe with sensors, this temperature calibration typically takes between a day and a week before taking measurements. Calibration of the technique is performed by

comparison to a reference pipe which is new and has a known wall thickness (Singer 2013).

The technique claims to invert the magnetic signal to retrieve the mass-loss fraction of the pipe; however, it is unclear how factors other than metal loss such as material composition variation, residual stresses, or features that may give a similar indication as corrosion could influence the measured signal. The claimed sensitivity is also uncertain due to a lack of any published data or field trials.

2.3 Non-electromagnetic Methods

2.3.1 Ultrasonic Thickness Gauging

Ultrasonic transducers allow the wall thickness of a component to be measured very accurately. The transducer excites a wave pulse which propagates through the metal and reflects off the back wall. Using the known sound speed in the metal, the time to receive the echo can be measured and used to infer the wall thickness. Piezoelectric transducers require good coupling between the transducer and the test piece, therefore they often demand that the surface is prepared. Electromagnetic Acoustic Transducers (EMAT) initiate the ultrasound in the material, so are able to tolerate unprepared or even thinly coated surfaces, and high temperatures; however, their sensitivity is often low (Burrows et al. 2014). Permanently installed sensors allow frequent readings to be taken which enables the rate of wall thinning to be obtained accurately (Honarvar et al. 2013).

With respect to the testing of insulated pipes, the coating and insulation must first be removed to allow the transducer to be placed in direct contact with the metal into which the ultrasonic waves will propagate. Some pipes allow for this by having removable inspection plugs; however, as the thickness measurement is localised to the transducer location, corrosion can easily be missed. Furthermore, the plugs can allow water ingress which may promote corrosion growth (Santhosh Lukose 2010).

2.3.2 Ultrasonic Guided Waves

The geometry of a pipe as a waveguide can be exploited to propagate different ultrasonic “guided” wave modes over a long distance (>50 m) from the location of the

transducer array (Alleyne et al. 2004; Cawley et al. 2003; Lowe et al. 1998). Ultrasonic guided waves are therefore well-suited to the inspection of pipes that do not support ILI, and are able to detect corrosion removing 5% of the pipe wall thickness. There is a requirement for good coupling with the pipe which means that thick or viscous coatings must be removed at the transduction site. Furthermore, the sensitivity near to large pipe features such as flange joints is reduced due to strong wave reflections, and the interpretation of the signal is operator dependent, particularly in complex lines. The test range is also reduced for buried pipes predominantly due to energy leakage into the soil (Leinov et al. 2016).

2.3.3 Radiography

Radiography has been successfully applied to the in-service detection of corrosion under insulation in pipelines (Edalati et al. 2006; Guo et al. 2011). Through-transmission radiography requires access to both sides of the pipe, and for large diameter pipes, either gamma ray or high energy X-rays must be used in order to propagate over such a large distance between source and receiver (Haith 2017; Ong et al. 1997; Zscherpel et al. 2006). Back-scatter radiography may be used when there is access to only one side of the pipe although the scattered radiation is diffuse (non-imaging) and of a low intensity (Ong et al. 1997). The use of radiography also has health and safety implications and rigorous standards must be met before its use is justified (*EN 16407 Parts 1 and 2: Newly published European standards for the in-service digital and film radiography of pipes* n.d.).

2.3.4 Microwave

In a manner similar to ultrasonic guided wave methods, the pipe and insulation can be used as a coaxial waveguide for the propagation of microwaves. Development of a NDE technique based upon this principle determined that water in the insulation layer that occupies more than 5 % cross sectional area can be detected with good accuracy. The detection of water is generally a good indication that corrosion under insulation is present (Jones et al. 2012); however, significant damage that is present under dry insulation could potentially be missed. A prototype system has been developed but further research is required before the technique is implemented into

industry.

2.4 Summary of Existing NDE

This literature review has explored the available techniques for the inspection and monitoring of unpiggable pipes, outlining the basic theory underpinning their functionality and identifying their strengths and weaknesses. Generally, there are a number of significant weaknesses in current techniques. A number of methods are only efficient for pipeline inspection when operating on internal pigs (eddy current techniques, MFL) and although in some cases the pigs have been adapted to travel through conventionally unpiggable lengths of pipe, access requirements still exist and the production of the pig is generally very costly (Burkhardt, Crouch, et al. 2006; Burkhardt, Goyen, et al. 2008; Kim et al. 2013; Plotnikov et al. 2008).

In the cases where techniques may be applied for external inspection or monitoring, the removal of the thick insulation coating is often a necessity (potential drop techniques, eddy currents, ultrasonic thickness gauging, ACFM, MBN, MPI). Guided wave techniques are attractive, but still require partial insulation removal and skilled operators. The techniques that claim functionality at large (>10 mm) standoff often require bulky equipment (SLOFEC) or have poor sensitivity or high false-call risk (MRI, MTM, MMM, NoPig). Finally, the techniques which use a high frequency current are unable to detect internal defects (ACFM, ACPD, eddy currents). PEC is well developed for CUI inspection, but works only on ferromagnetic pipes through non-ferromagnetic coating. It also has potential to miss small-diameter pitting defects due to the probe-averaging effect. The other techniques explored have safety implications (radiography) or are under-developed (microwave).

This chapter has highlighted the potential for a technique that is able to inspect or monitor for damage occurring anywhere throughout the wall thickness of an insulated and coated pipe with good sensitivity and low false-call risk. This technique is described in detail in the following chapter.

3 | Current Deflection NDE

As demonstrated in the previous chapter, there are few currently available NDE methods for the inspection or monitoring of unpiggable pipes for corrosion damage while leaving the coating and insulation intact. ACFM is attractive as it provides good detection capability; however, the induction of a high-frequency current limits detection to surface-breaking defects, and also the sensitivity is reduced at high standoff. NoPig can measure internal and external defects, but has relatively poor sensitivity due again to the high standoff. In this chapter, a novel approach based upon similar principles as these NDE methods is introduced which aims to circumvent their relative weaknesses to achieve a good sensitivity to damage occurring anywhere throughout the wall thickness when measuring external to pipe insulation.

In the first section, the underlying principles and the operating configuration of the technique will be discussed, including the current injection method and the sensing configurations. Later, a Finite Element (FE) model is introduced which is used to predict magnetic field perturbations from current deflection and investigate the behaviour of the current deflection signal. Experimental demonstration of the technique in scanning mode is presented for different defect geometries in different pipe types. The results are then used to validate the FE model. This chapter partly comprises work that has been published in the journal *NDT & E International* and permission has been obtained by *Elsevier* to reuse text and figures where appropriate (Jarvis et al. 2016).

3.1 Principles of Method

In the discussion of ACFM in the previous chapter, it was explained that a defect in a conducting sample causes perturbations in the induced magnetic field surrounding the sample. Furthermore, if the sample is ferromagnetic, some leakage of the

magnetic flux will occur at the defect location (Lugg 2004). As the magnitude of the induced current is proportional to the rate of change magnetic flux in the coil, ACFM operates at a high-frequency; however, this limits the induced current to the surface of the conductor. If the current were physically injected into the sample (as in the NoPig technique) rather than being induced, its amplitude would be independent of the frequency therefore the skin-depth could be controlled in order to inspect either the surface layer of the conductor or the entire wall thickness.

The principles of low-frequency current deflection, and the resulting perturbations in the components of the magnetic flux density from a corrosion-like defect are illustrated in Fig. 3.1. In Fig. 3.1a, flow-lines of the current density, $\mathbf{J}$, are plotted which show a general flow in the y direction, except near the defect where the current is deflected. The large J_y induces a strong B_x (Fig. 3.1b) with a local minimum centred over the defect where J_y is weakest, and peaks above the defect edges perpendicular to the current flow. The quadripolar profile of B_y (Fig. 3.1c) results from deflection of the current in the x direction around the defect. The bipolar profile of B_z (Fig. 3.1d) is a result of the clockwise and counter-clockwise rotation of the current as it deflects around the defect. The local maxima and minima in each component of $\mathbf{B}$ approximately mark the boundary of the defect, although they spread apart as the standoff is increased due to diffusion of the field. The current deflection principles are identical when the conductor is a pipe rather than a plate. In this case, the x , y and z components become θ , r , and z .

Figure 3.2a shows the distribution of the magnitude of the current density in a cross section of a 6" pipe (wall thickness $T = 7.1$ mm) between two distant electrodes attached to the outer wall of the pipe used to inject a 100 Hz, 2 A current. The variation in magnitude of the current density across the pipe wall is shown in Fig. 3.2 for various frequencies. Alternating current is concentrated to a layer at the pipe surface of thickness δ (equation 2.9, page 34) which is small at high frequencies. When $\delta > T$, the current is distributed uniformly throughout the wall thickness and is limited only by the conductor geometry. At low (quasi-DC) frequencies the current can therefore be perturbed by defects occurring at any location throughout the wall thickness. The current behaves as quasi-DC in the frequency range

$$f < \frac{1}{\sigma \pi \mu T^2} \quad (3.1)$$

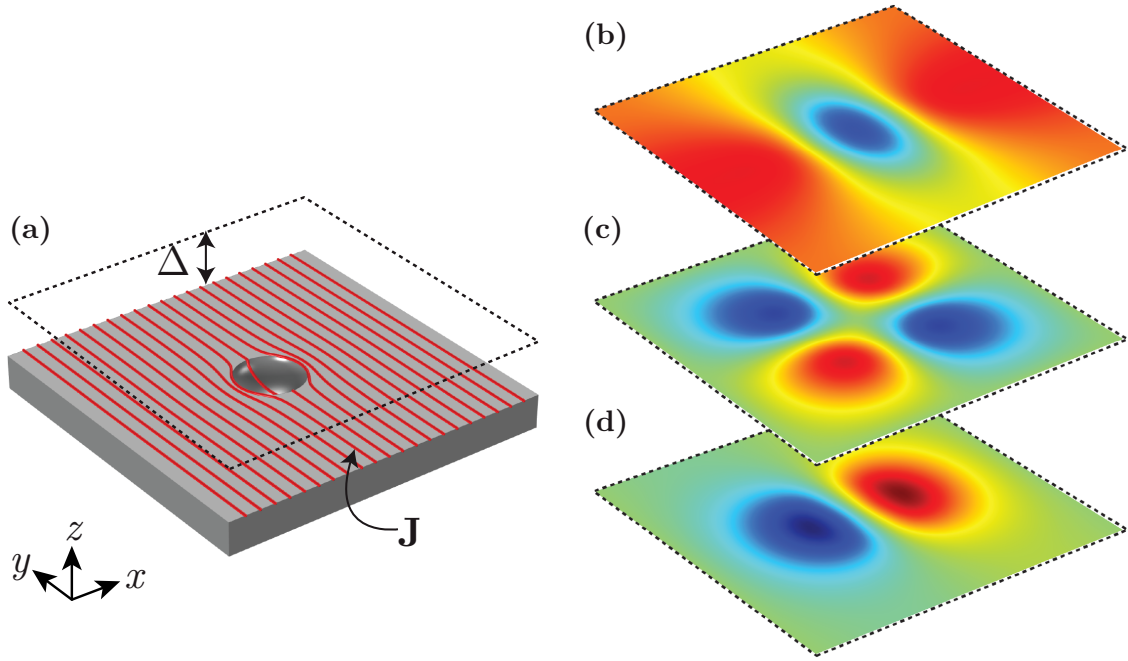
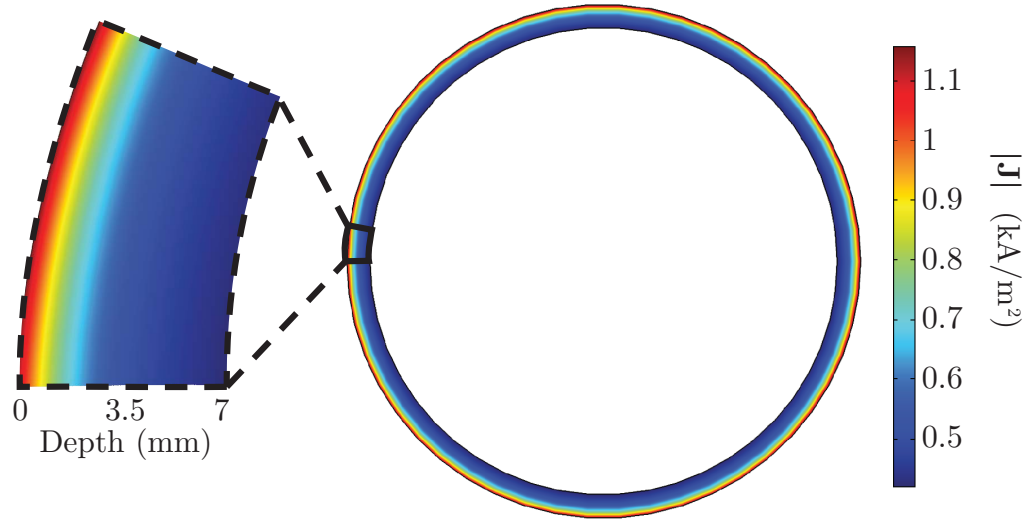


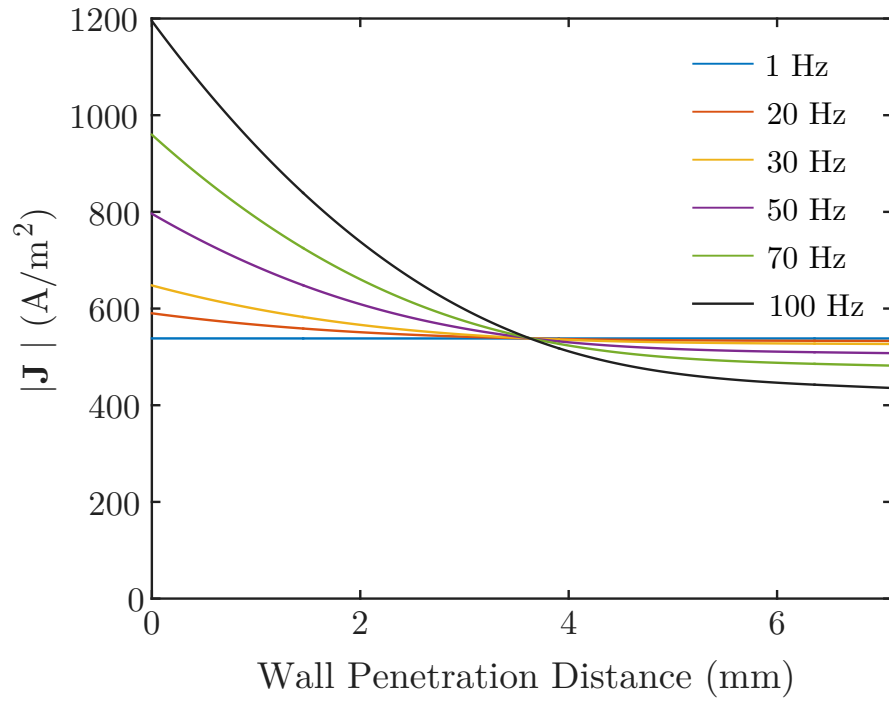
Figure 3.1: (a) Current density contours are shown on the surface of a current carrying plate with a semi-ellipsoidal defect (current flow is in $\hat{y}$). The (b) x , (c) y and (d) z components of the magnetic flux density are shown at a surface above the conductor, separated by the standoff distance. Red = high intensity, blue = low intensity. (Reproduced from Jarvis et al. 2017a with permission from Elsevier.)

which is generally below 10 Hz for carbon steel pipes less than 10 mm thick, or a few kHz for non-magnetic pipes. The magnetic permeability, μ , tends to be strongly inhomogeneous in ferromagnetic materials so a current frequency must be chosen such that δ is much larger than the thickness of the conductor. This ensures that the measured perturbations in the induced magnetic field are caused only by geometry changes in the conductor and variations due to the magnetic properties of the material are suppressed.

The perturbations in the magnetic field that arise from quasi-DC current deflection are small in comparison to the geomagnetic field ($\sim 50 \mu\text{T}$); however, by using an alternating rather than direct current, phase-sensitive detection becomes possible which can effectively eliminate DC bias, drift and other low-frequency noise sources and greatly improve the sensitivity. An NDE method is enabled by using magnetic sensors to either scan for, or monitor for changes in the induced magnetic field surrounding a pipe due to current deflection around defects. This chapter focusses on the possible configurations for the technique when operating in the scanning mode.



(a)



(b)

Figure 3.2: (a) Current density distribution across the cross section of a 6" carbon steel ($\mu_r = 100$) pipe carrying a 100 Hz current. (b) Current density variation throughout the pipe wall at different frequencies.

3.2 Finite Element Model of Current Deflection in a Pipe

In order to reduce the need for time-consuming and expensive experimentation, a model must be created in order to investigate the many factors that influence the induced magnetic field distribution surrounding a conductor containing a defect. Previous researchers have derived models to find the magnetic perturbation due to current deflection around different defect geometries by analytically solving Maxwell's equations, although the use of thin-skin assumptions that only consider surface current flow mean that the solutions are restricted to high-frequency cases and to simple geometries (Lewis 1991; McKirdy et al. 1993; Michael et al. 1991). For irregular geometries that far better match realistic defects, no closed-form analytical solutions to Maxwell's equations exist; however, with recent advances in computational efficiency, it is now possible to overcome this restriction by creating 3D numerical models that discretise the geometry into many small "finite elements". Maxwell's equations can be formulated as a set of partial differential equations and the approximate solution to these equations can be found at a number of discrete node points in the model (the vertices of the finite elements) by minimising an error function. As the exact solution rarely exists, there is some error associated with the results of FE models therefore it is extremely important to validate their output using equivalent experimental studies. The validation of the FE models discussed in this section is presented later in the chapter in section 3.3.4.

An FE model was created using COMSOL[®] to investigate how various factors influence the current deflection signal. A steady-state solver was used. This allows the time-derivatives to be eliminated which greatly reduces the computational complexity of the problem; however, the solution is only relevant for the low-frequency quasi-DC case. The intricacies of the FE solver are out of the scope of this thesis, although the interested reader is referred to (COMSOL AB 2017) for a detailed overview. The model, shown schematically in Fig. 3.3, contains a 6" schedule-40 ($T = 7.1 \text{ mm}$) pipe surrounded by a large air domain. A current was made to flow within the pipe by applying a 2 A terminal to the cross section at one end of the model, and a ground terminal to the opposite end, translating to an average current density of $\mathbf{J} = \mathbf{J} \cdot \hat{e}_z = \sim 550 \text{ A m}^{-2} \cdot \hat{e}_z$ within the pipe. The solution to the magnetic

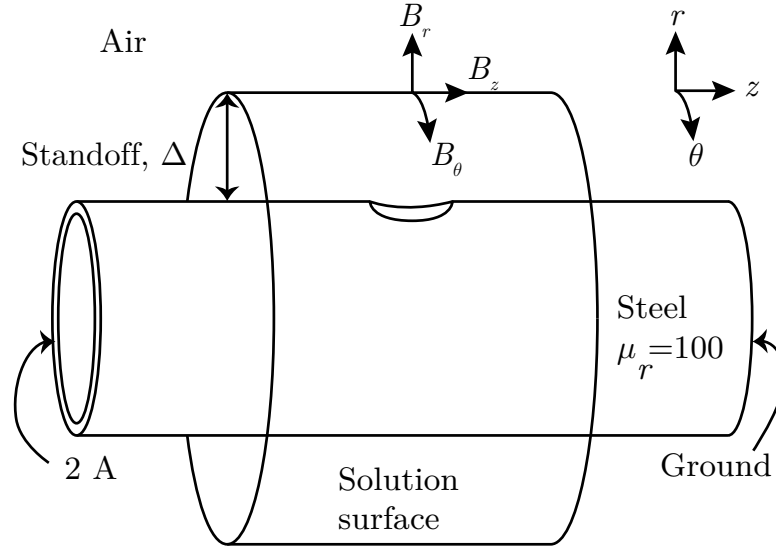


Figure 3.3: FE model schematic. The stationary solver was used to find a DC solution on the surface shown outside 6" schedule-40 pipe, $T = 7.1$ mm. One possible defect geometry is shown at the top of the pipe.

flux density was extracted on a cylindrical surface coaxial with the pipe, and at a standoff distance Δ from the pipe nominal outer radius. The magnetic and material properties of the pipe could be varied to investigate ferromagnetic or non-magnetic materials. Where appropriate, symmetry boundary conditions were exploited to reduce computational time.

An adaptive tetrahedral mesh was used where the maximum element size was small (generally 5 mm) in the pipe domain, and in the air domain at low standoff, so that the current and field perturbations could be well resolved. A larger maximum element size was tolerated at increased standoff distances where the spatial gradient of the field was reduced (e.g. 20 mm at $\Delta = 100$ mm). The automatic meshing algorithm in COMSOL[®] reduces the element size near areas of complex geometry (especially at sharp corners that would cause strong current deflection) where the change in the magnetic field and current is expected to be greatest, as shown in Fig. 3.4. A convergence study was completed which determined that the most important meshing parameter is the minimum element size. The value used should be dependent on the defect geometry but, for the defects considered in this research, convergence is generally reached at 1.5 mm. For the studies in this thesis, a minimum element size of 0.5 mm was selected as a good compromise between solution time and result accuracy, unless otherwise stated.

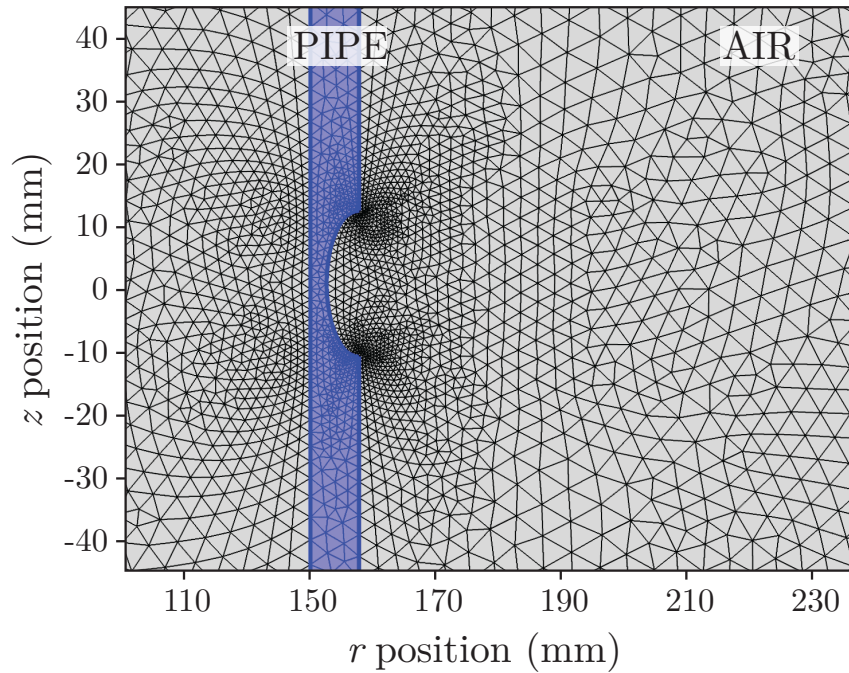


Figure 3.4: Example of adaptive meshing algorithm with a maximum finite element size of 5 mm and minimum size of 0.5 mm. The triangular element size in this 2D model is reduced in areas where the gradient of $\mathbf{B}$, $\mathbf{J}$ etc. are expected to be greatest.

3.2.1 Effect of Defect Geometry

The current deflection signals were predicted for a number of defect geometries. Concave defects of maximum depth $\frac{T}{3}$ and diameter of $3T$ were chosen to represent corrosion patches on both the inner and the outer wall of a carbon steel pipe where the relative magnetic permeability was set to $\mu_r = 100$. This geometry was selected as it is a standard size used by BP for investigation of new NDE. Due to the curvature of the pipe, the inner wall concave defect had a slightly larger volume in order to maintain the same curvature and maximum depth as the outer wall concave defect. Flat-bottomed slots of the same depth, a width of 1 mm and a length of $3T$ were chosen to represent cracks. The extreme cases of the slot oriented along the pipe axis and along its circumference were modelled. The defect geometries are shown schematically in Fig. 3.5.

The spatial distributions of the perturbation in the magnetic flux density caused by current deflection around the outer wall concave defect at a standoff distance of $\Delta = 10$ mm are shown in Fig. 3.6. The defect is centred below the origin of the diagrams. Figure 3.6a shows B_r , which exhibits a bipolar profile due to the clockwise and anticlockwise rotation of the current around either side of the defect.

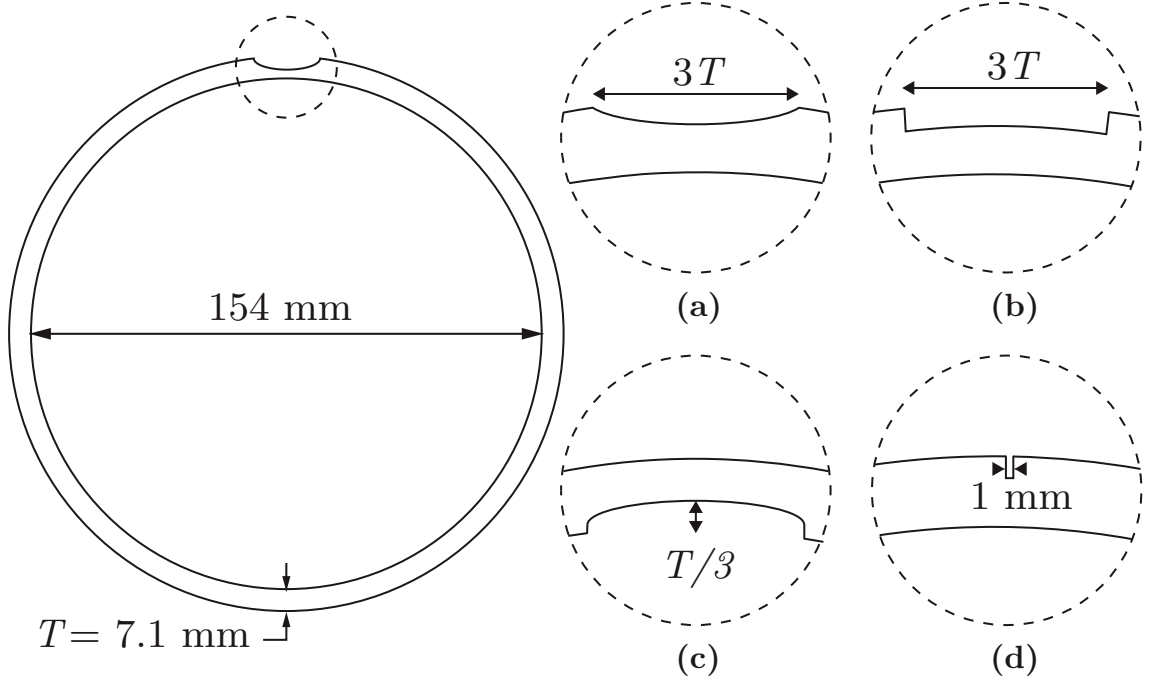


Figure 3.5: Cross sectional slice through the centre of the pipe showing the different defect geometries used for FE studies. (a) Outer concave defect; (b) outer circumferential slot (1 mm width); (c) inner concave defect; (d) outer axial slot ($3T$ length). Inner slots were modelled but are not pictured.

The peaks are azimuthally separated by a distance greater than the defect width. The axial component, shown in Fig. 3.6b, is quadripolar due to the change in the current direction as it avoids the defect. The azimuthal component in Fig. 3.6c has a local minimum centred over the defect due to the wall loss reducing the total current at this location. The current density is highest just outside the defect on the line $z = 0$, which leads to two maxima in B_θ . The average value of B_θ is a few microtesla due to the directionality of $\mathbf{J}$.

The spatial distributions were calculated for the other defect geometries and the peak-to-peak values of each component of $\mathbf{B}$ are shown in Table 3.1. It can be seen that when the defect is located on the outer wall, the resulting field perturbation is larger in magnitude than for the same inner wall defect. This is largely due to the increased distance between the defect and the sensor and the reduction of leakage flux due to the presence of additional ferromagnetic steel between the inner wall defect and sensor. The amplitude decreases in all cases at the higher standoff distance.

The slot geometry produces a smaller current deflection signal than the concave

Table 3.1: Peak-to-peak of magnetic flux density components due to current deflection around internal (I) and external (E) concave and slot defect geometries predicted at $\Delta = 10$ mm and $\Delta = 25$ mm above the surface of a 6" pipe carrying 2 A current.

Defect Geometry	I/E	Δ (mm)	Peak-peak (nT)		
			B_r	B_z	B_θ
$3T \times 3T \times \frac{T}{3}$	E	10	83.2	53.1	118.6
$3T \times 3T \times \frac{T}{3}$	I	10	56.0	34.9	80.1
$3T \times 3T \times \frac{T}{3}$	E	25	18.4	13.4	28.5
$3T \times 3T \times \frac{T}{3}$	I	25	15.2	12.7	25.3
$3T \times \frac{T}{3}$ slot (θ aligned)	E	10	40.9	23.7	55.8
$3T \times \frac{T}{3}$ slot (θ aligned)	I	10	23.4	15.3	40.1
$3T \times \frac{T}{3}$ slot (θ aligned)	E	25	8.5	7.0	15.2
$3T \times \frac{T}{3}$ slot (θ aligned)	I	25	6.0	5.1	11.8
$3T \times \frac{T}{3}$ slot (z aligned)	E	10	15.4	12.2	32.0
$3T \times \frac{T}{3}$ slot (z aligned)	I	10	14.2	11.0	28.5
$3T \times \frac{T}{3}$ slot (z aligned)	E	25	3.3	3.7	8.2
$3T \times \frac{T}{3}$ slot (z aligned)	I	25	2.9	3.9	7.6

defect regardless of its orientation; however, when the slot is aligned perpendicular to the undisturbed current axis, the perturbation is much greater than when it is parallel to the direction of current flow. This is due to the circumferential slot deflecting a larger amount of current than the axial slot. The signal from the slot lying parallel to the current axis originates almost entirely from magnetic flux leakage, and is over an order of magnitude lower than the concave defect signal when it is aligned along z , indicating the weakness of the technique in locating cracks oriented parallel to the current flow.

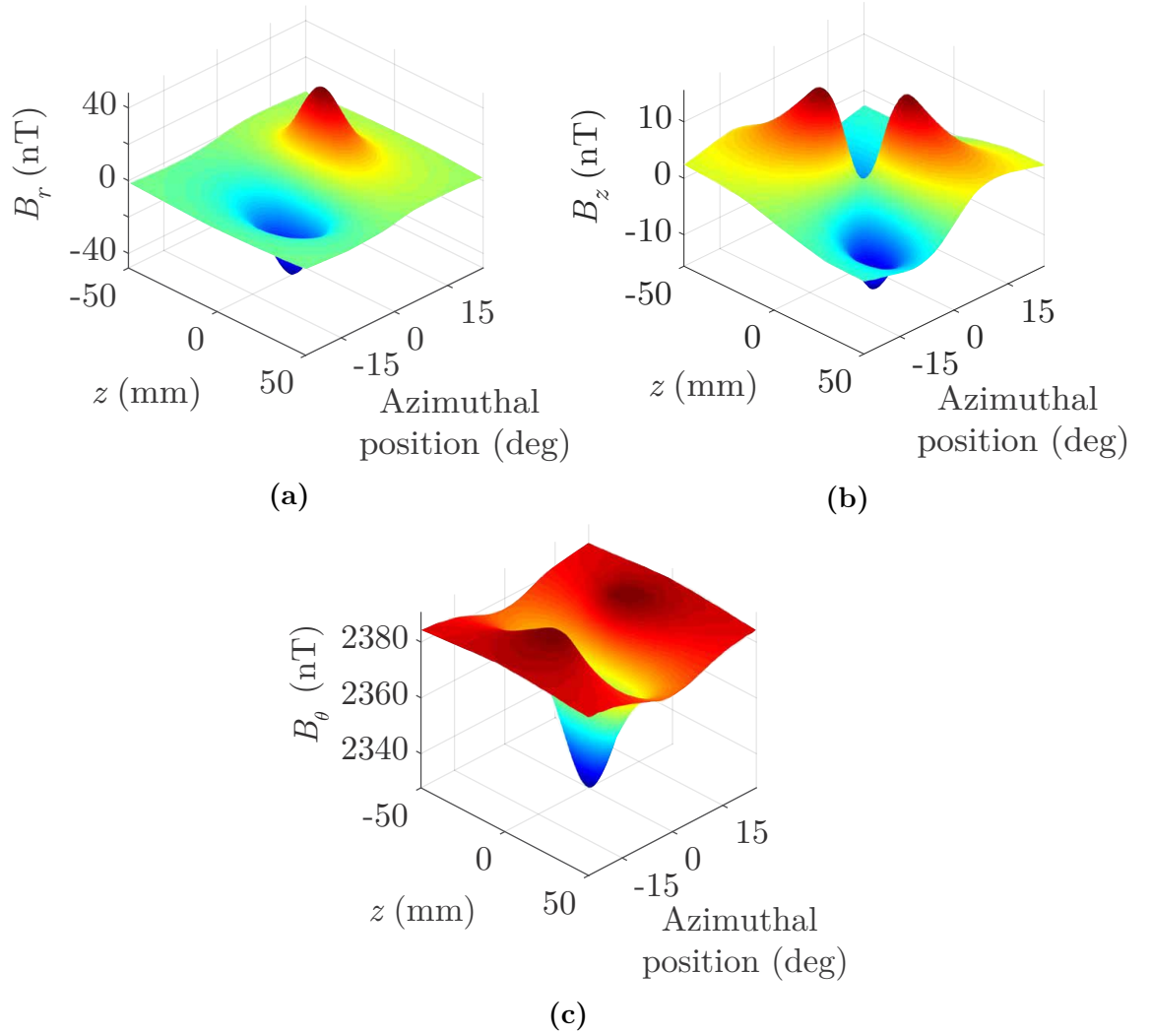


Figure 3.6: FE prediction of spatial distributions of the (a) radial; (b) axial and (c) azimuthal components of the magnetic flux density arising from current deflection from a $3T \times 3T \times \frac{T}{3}$ defect at 10 mm standoff.

3.2.2 Effect of Standoff

The peak-to-peak values of the perturbations in the magnetic flux density due to the deflection of a 2 A current around a semi-ellipsoidal half-wall-depth defect were predicted for various standoff distances. These perturbations in B_r and B_θ are plotted on a circumferential scan path axially aligned with the defect centre in Fig. 3.7. B_z has not been plotted as the symmetry of the signal means that there is no perturbation on this path (see Fig. 3.6b).

Figure 3.7a shows how the peak-to-peak value of the perturbation in B_r reduces in amplitude as the standoff increases. The average value of B_r is always zero. In Fig. 3.7b, it can be seen that the peak-to-peak value of the perturbations in B_θ similarly reduce in amplitude as standoff is increased. The average value of B_θ also decreases with $\frac{1}{\Delta}$ (in the case of a pipe), suggesting that the instability in standoff expected during a practical scan may make measurements of small changes in B_θ difficult.

Figure 3.8a plots the peak-to-peak magnetic flux density on a decibel scale normalised to the values closest to the pipe surface for clarity. The peak-to-peak of each component of $\mathbf{B}$ behaves similarly, falling rapidly with increasing standoff and decreasing by 20 dB relative to the signal at the pipe surface in the first 18 mm. As the standoff is increased further, the signal drops by a lesser extent, losing an additional 20 dB over the next 40 mm. As the standoff becomes large in comparison to the defect size, the defect behaves as a magnetic dipole which loses amplitude with the cube of the standoff distance (note that this behaviour is not observed within the standoff limit of Fig. 3.8a). With 2 A current in the pipe the absolute values at 1 mm standoff are 1228 nT, 448 nT and 681 nT in the radial, axial and azimuthal components respectively, dropping to 30 nT, 19 nT and 37 nT at 25 mm standoff. Figure 3.8b shows how the spatial extent of the signal increases approximately linearly with standoff. The data fits a linear regression with an average R-squared value of 0.997. This suggests that fewer sensors could be used at higher standoff due to the more diffuse signal provided the loss in signal amplitude could be compensated for.

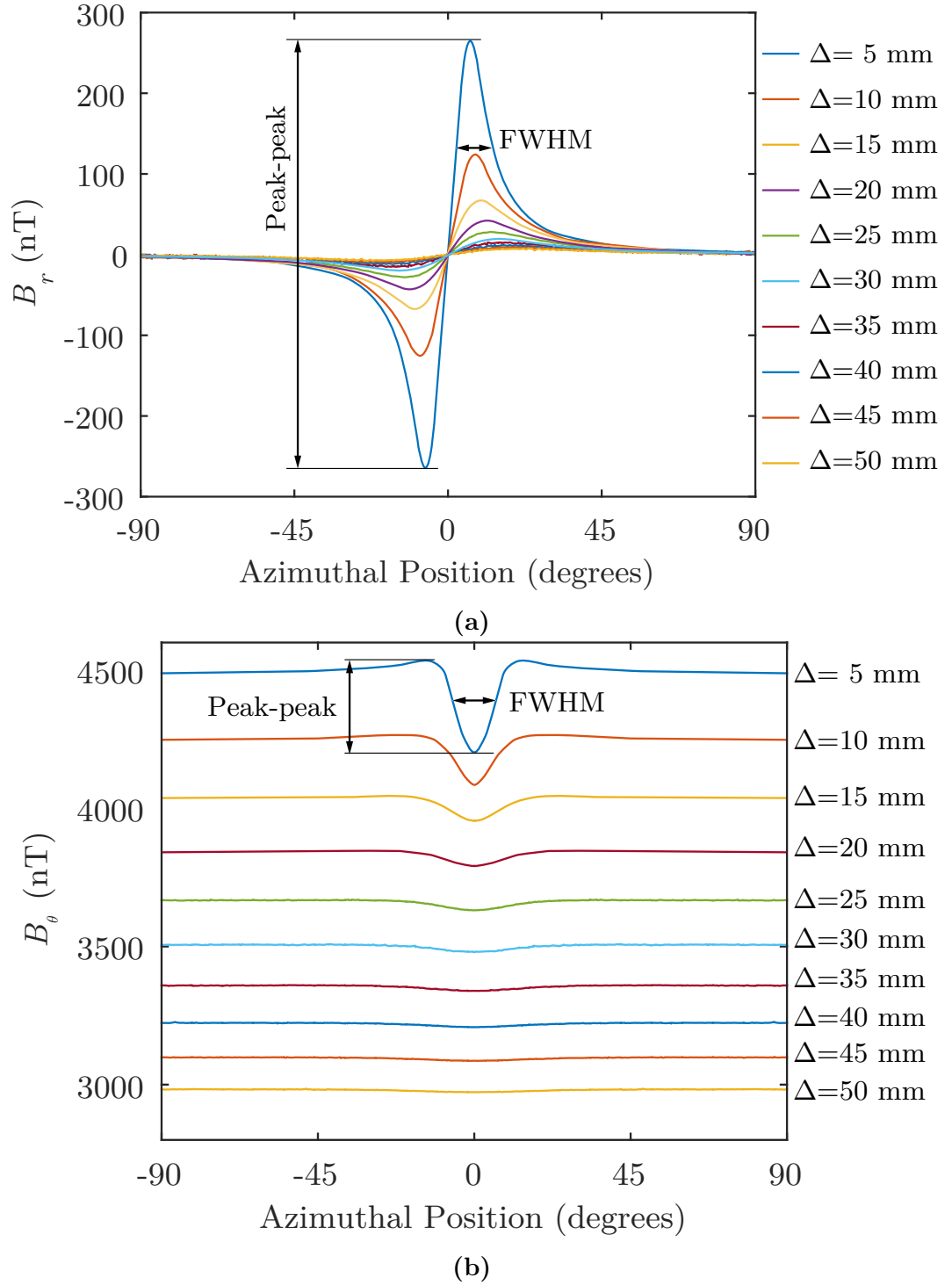


Figure 3.7: (a) Radial and (b) azimuthal components of the magnetic flux density predicted on a circumferential scan path at various standoff distance above a pipe containing a $3T \times 3T \times \frac{T}{2}$ outer wall defect.

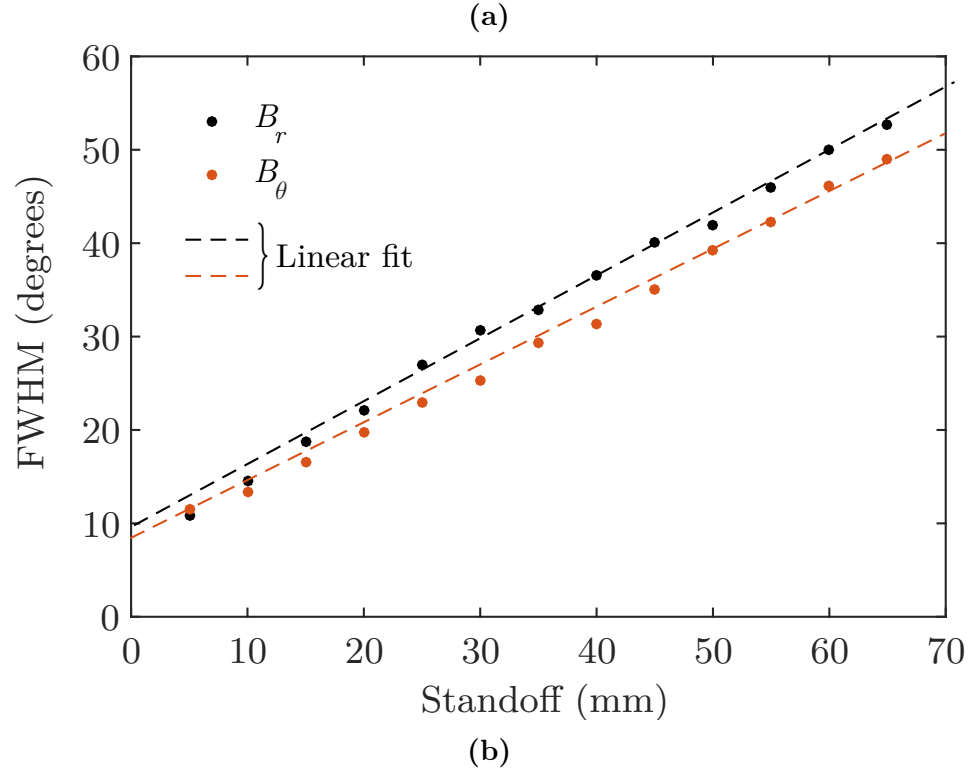
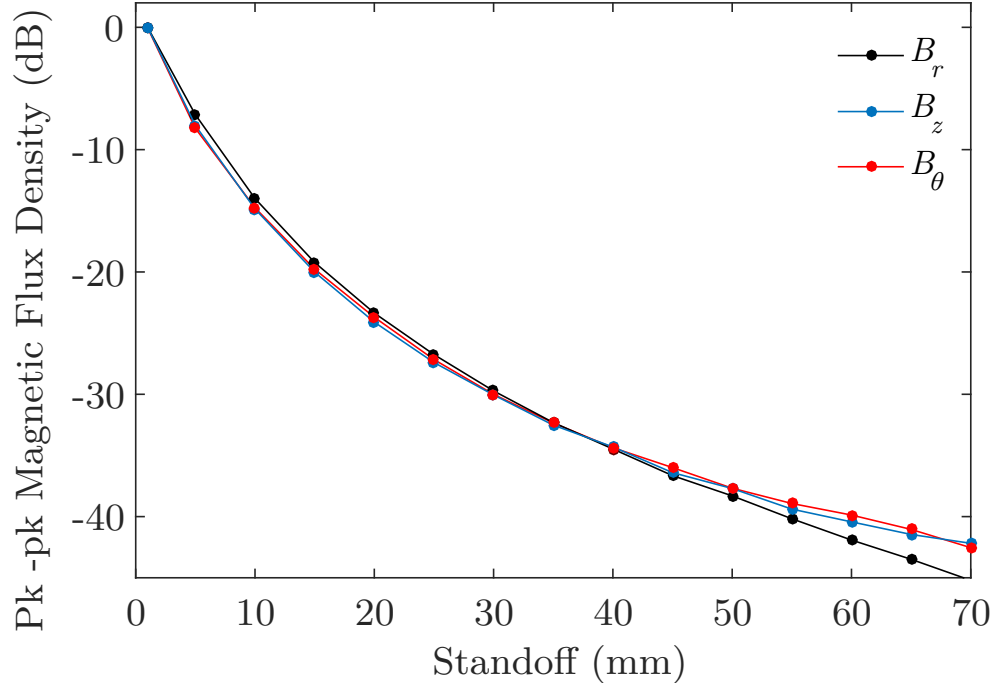


Figure 3.8: (a) The peak-to-peak and (b) the FWHM (as defined in Fig. 3.7) in the components of the magnetic flux density varying with standoff for a $3T \times 3T \times \frac{T}{2}$ defect.

3.3 Experimental Measurement of Current Deflection

Experimental measurement of current deflection serves multiple purposes:

- Validation of the FE model
- Investigation into practical challenges of current deflection (e.g. magnetic sensors, environmental variations, material property variations etc.)
- Demonstration of the technique

This section will briefly discuss the considerations and decisions that were made when designing the experiments. Following this, a demonstration of the stability and repeatability of the measurements is presented. Finally, experimental validation of the FE models for various scenarios are shown.

3.3.1 Sensor Choice

A literature review was completed which explored all possible magnetic sensor types. The chosen sensor must have sensitivity to low (nanotesla) field levels; be able to resist harsh industrial environments; and be small, cheap and low cost. It must also be capable of measuring the vector components of $\mathbf{B}$ rather than purely its magnitude. After careful comparison of all sensor types, it was concluded that Magnetoresistive (MR) sensors offered the best overall performance.

MR sensors exploit a material property in which the electrical resistance is dependent on the externally applied field. There exist different types of MR sensor based on different magnetoresistance mechanisms. Ordinary, Anisotropic (AMR), Giant (GMR) or Tunnelling (TMR) sensors exhibit progressively greater resistance changes with the applied field change. A study by Stutzke et al. compared the noise density of a number of commercially available magnetoresistive sensors. It was determined that although the sensitivity of GMR and TMR sensors is generally greater than AMR, their more complex multi-layer structure introduces a higher intrinsic noise, resulting in poorer detectability for low-field strengths, especially at low frequencies (Stutzke et al. 2005). A number of AMR sensors were reviewed before AFF755B by Sensitec was chosen (Sensitec MagnetoResistive Sensors 2011).

This sensor, along with Honeywell HMC1001 (which was recently discontinued) offer the best noise performance (Fúra et al. 2016; Vyhnánek et al. 2013) and have been used previously in industrial applications, including NDE (Jogschies et al. 2015). As MR sensor technology continues to advance, it will be beneficial to review sensor options periodically. For the testing of very thick samples, it may be beneficial to investigate the use of fluxgate sensors which exhibit lower noise density and higher sensitivity than AMRs with a trade-off of higher cost, size and power-requirement.

A Stanford Research SR830 lock-in amplifier was used to measure the noise density of the sensors in the unshielded laboratory environment over the useful frequency range (DC–100 Hz). The result is plotted with a logarithmic frequency scale in Fig. 3.9.

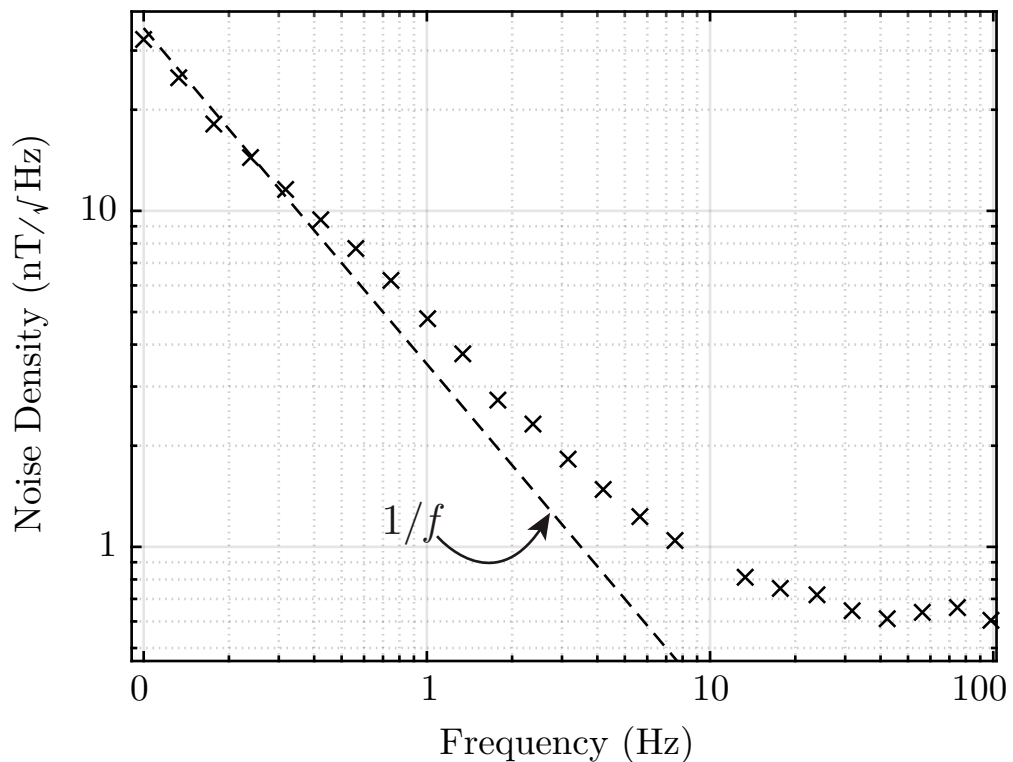


Figure 3.9: Noise density of AFF755B sensors measured using lock-in amplifier below 100 Hz.

The spectral noise density of the unshielded sensors was between 1 to 2 times greater than the value reported in the data sheet throughout the tested frequency range. The same performance was recorded for multiple sensors so it could be possible that the purchased batch had worse performance than the manufacturers test sensor. Furthermore, environmental magnetic noise could have negatively affected

the unshielded sensors noise performance. The noise could be reduced with a high quality pre-amplifier, although the lock-in amplifier alone was sufficient to complete the measurements presented in this thesis. The noise density increases as the frequency is reduced. This is primarily due to “flicker noise” which has $\frac{1}{f^n}$ characteristic, where n is approximately unity (see Fig. 3.9). The data revealed that, over the tested frequency range, there were no isolated regions of significant electromagnetic noise in the laboratory environment. It was important to avoid operating at 50 Hz and its harmonics due to significant magnetic interference from the mains (line) frequency. These results suggest nanotesla fields could be resolved with a few seconds averaging time when measuring below 100 Hz. The sensitivity value provided in the data sheet was used to convert the sensor voltage to a magnetic flux density. Calibration with a reference magnetic field found this value to be accurate.

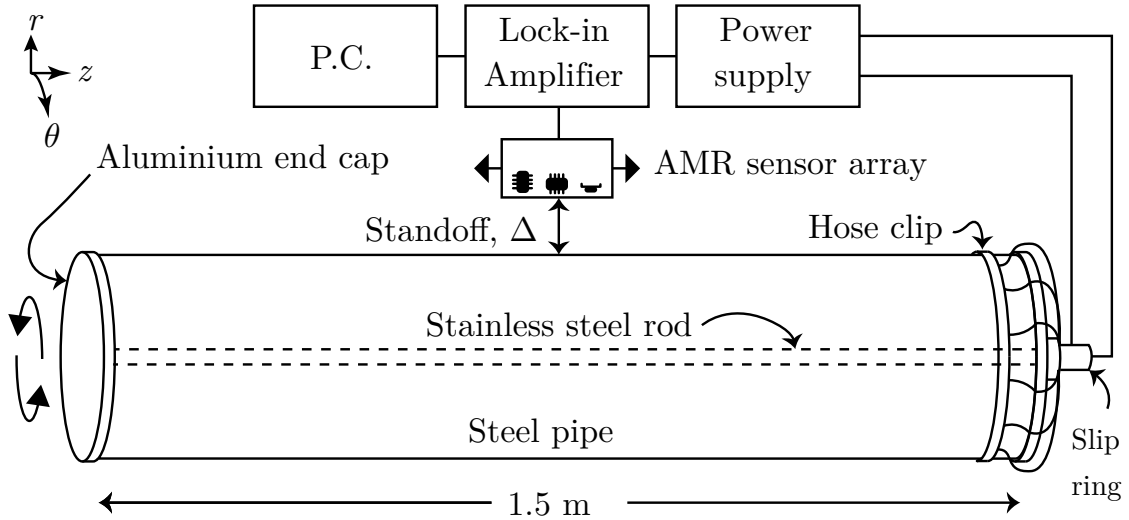


Figure 3.10: Schematic diagram of pipe automated scanning rig. Pipe rotation and array position are controlled by stepper motors. Current injection shown using hose clip.

3.3.2 Pipe Scanning System

The components of the magnetic field surrounding a current carrying pipe were measured using an array of three AMR sensors, one oriented in each of the radial, axial and azimuthal directions with respect to the pipe. The differential signal from each sensor was read using a Stanford Research SR830 lock-in amplifier using phase-sensitive detection. This sensing mechanism is crucial as it is the only way to measure small magnetic fields without spatial variations in the large geomagnetic field swamping the signal, or interference due to spurious magnetic signals such as the 50 Hz mains frequency. This is achieved by multiplying the input signal with a reference signal and integrating over some averaging time (Stanford Research Systems 2011). 1.5 m lengths of 6-inch pipe were selected for testing. Initial experiments were performed on an austenitic steel (grade 302) pipe, and subsequent experiments on a carbon steel pipe. Both longitudinally seam-welded and seamless pipes were tested. A schematic diagram of the experiment is shown in Fig 3.10.

The sensors were multiplexed and read in turn using a LABVIEW interface. Before each experiment, a flip-pulse was applied to an integrated set/reset coil inside the sensor chips to ensure the optimization of the sensor performance by reorienting the magnetic domains in the AMR film and correcting for magnetic hysteresis (Schneider et al. 1999). The reference signal from the lock-in amplifier allowed a Kepco 36-6D bipolar operational power supply to draw a current of 2 A (RMS) that

flowed within the pipe at the frequency of interest. In earlier experiments, the current injection was achieved via 12 wires evenly spaced around the circumference of the pipe and clamped down onto the metal using a hose clip in order to decrease contact resistance, as shown in the schematic diagram in Fig. 3.10. Multiple injection points were necessary to allow uniform spread of the injected current over the whole cross section of the relatively short length of pipe. This was later improved upon by injecting the current directly into the end cap, which was connected to the pipe via 18 springs evenly spaced around the circumference. These changes were implemented to reduce the edge effects in the magnetic field that occur from the current spreading out from the injection points. As the maximum length of pipe tested was 1.5 m, this was necessary as the edge effects limit the region of the test pipe that would be representative of a practical test in which current would be injected remotely from the sensing location. It is important to note that in an industrial setting, such a complex injection would not be necessary because the edge effects could be accounted for by increasing the spacing between injection points.

The injection wires were fed through a slip-ring to ensure that they did not tangle following multiple pipe rotations. A stainless steel rod was held in tension at the pipe axis between aluminium end caps, which allowed the current injection and retrieval points to be at the same end of the pipe, negating the need for long trailing wires to complete the current loop. The rod also suppresses the large azimuthal field component which reduces the risk of interference due to sensor misalignment. This will be discussed further in later chapters.

The position of the sensors relative to the pipe was controlled by a pitch and height adjustable plastic array holder with a sliding mechanism to adjust the standoff distance. Non-ferromagnetic material was used wherever possible in order to avoid flux concentration of the induced magnetic field from the injected current. During initial experiments, the sensor array was positioned manually; but this was later automated due to the time taken to complete a measurement. The sensor array holder was fixed to an aluminium linear actuator which was capable of moving the array along the entire length of the pipe. The rotation of the pipe was facilitated by a worm drive connected to a stepper motor. Figure 3.11 shows photographs of the scanning frame before and after the improvements had been made.

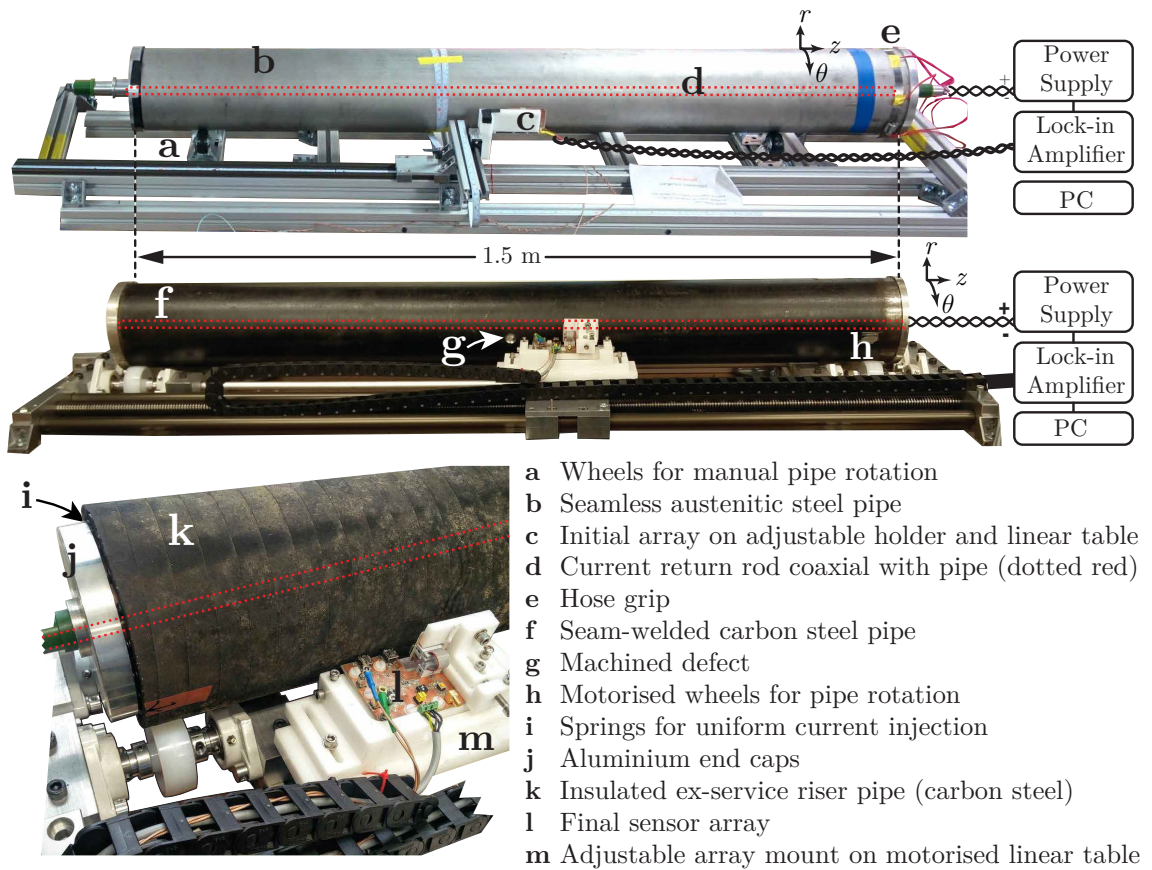


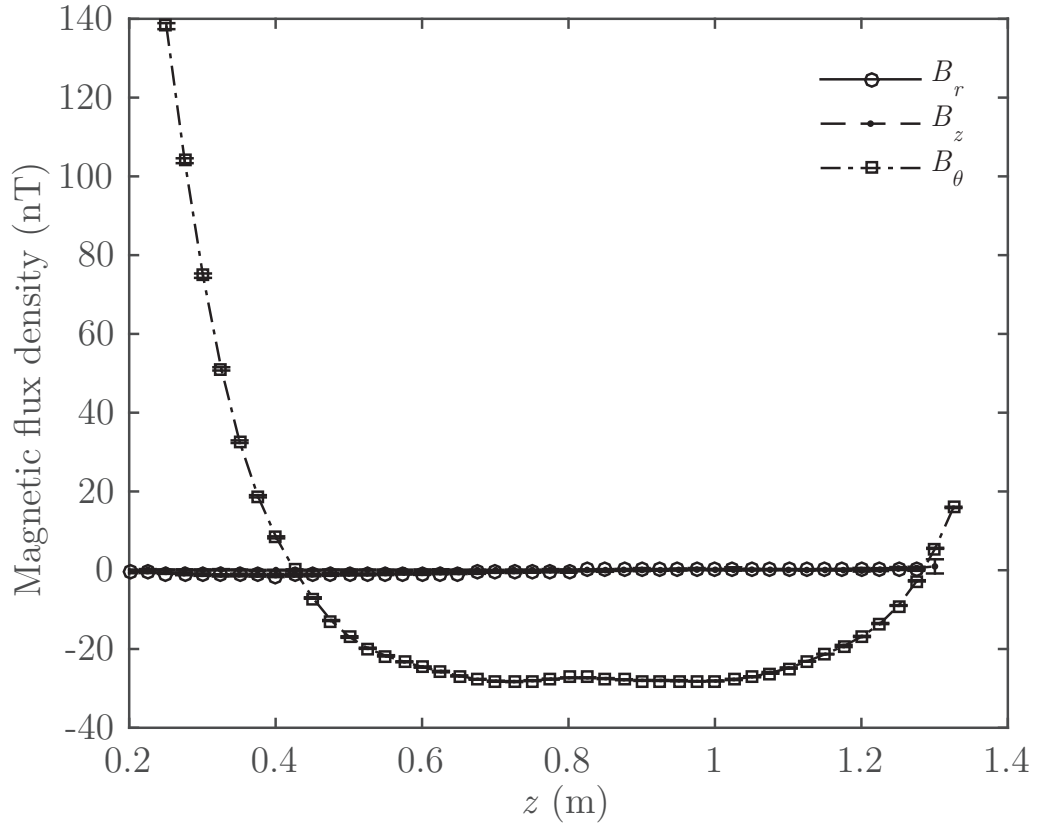
Figure 3.11: Photographs of scanning system. Top: Initial system with manual positioning. Middle: Final automated system. Bottom: Photograph showing end caps and sensor array. The testing of different pipe types is shown.

3.3.3 Stability and Repeatability of Measurements

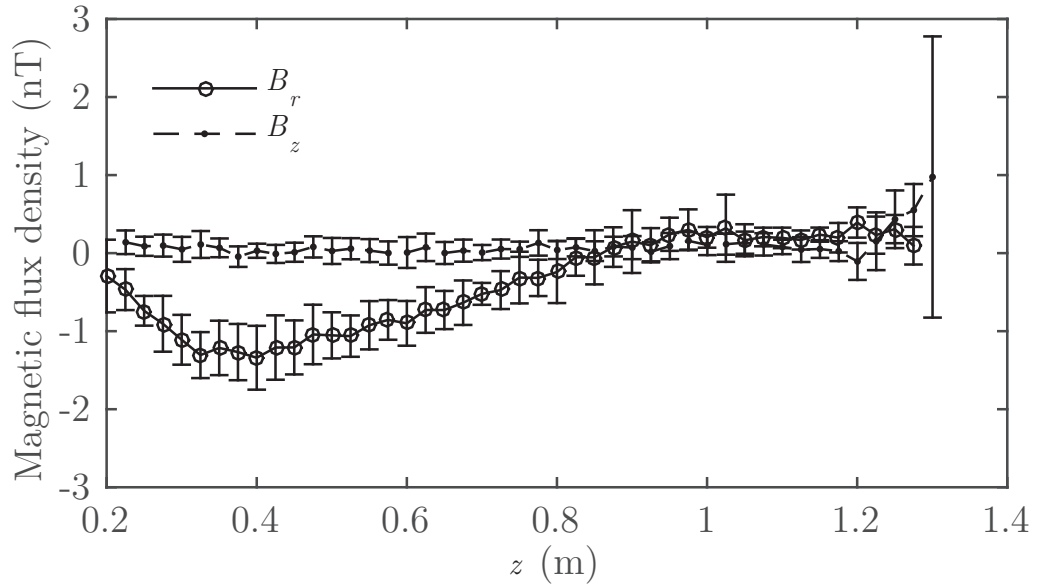
In order to assess the suitability of AMR sensors for the measurement of the magnetic flux density signals, the temporal and spatial stability of the measured signal was quantified. Fifteen scans were completed with an overall scan length of 1 m at 10 mm standoff distance from a longitudinally seam-welded carbon steel pipe with a spatial resolution of 25 mm. The scans were taken on a line diametrically opposite from the longitudinal weld. The pipe carried a 2 A current at 150 mV and 5 Hz. The mean of all fifteen scans is shown in Fig. 3.12. The standard deviation was calculated to be 282 pT, 198 pT and 205 pT for the radial, axial and azimuthal components respectively across the whole scan length. The radial and axial components stay close to zero along the length of the pipe due to the lack of any defects to perturb the current, with mean values of -400 ± 88 pT and 99 ± 26 pT respectively, where the uncertainty is the standard error of the mean (Altman et al. 2005). The azimuthal component exhibits large gradients towards the edges of the pipe due to edge effects and settles to a value of -28 nT towards the centre of the pipe. A misalignment between the axes of the pipe and the rod used for the return current path is likely to be the reason that the azimuthal component is not reduced to zero away from the pipe ends.

At this standoff, the solution to Ampère's law for an infinite cylinder carrying 2 A of current yields a value of the induced magnetic flux density of 4.2 μ T in the azimuthal component (the radial and axial components are identically zero), thus the addition of the rod for the return current path has reduced the azimuthal flux density by more than two orders of magnitude at the pipe centre. This large azimuthal component is largely unimportant as it is the more stable axial and radial components that will likely be used for defect detection and monitoring, and this method of suppression of the azimuthal component is clearly not possible in the field.

To investigate the temporal stability of the signal, each component of $\mathbf{B}$ was measured every three minutes over the course of a week with an averaging time of 25 s. A 2 A current was maintained in the pipe and the modulation frequencies chosen were 1 Hz, 5 Hz and 25 Hz. It is important that measurements can be taken at such low frequencies to ensure that the measured magnetic signal is due only to the current distribution as restricted by the pipe geometry and not the electromag-



(a)



(b)

Figure 3.12: (a) Mean and standard deviation (error bars) of 15 repeated scans of the magnetic flux density components performed at 10 mm standoff from a 6" pipe carrying 2 A current at 5 Hz. Pipe ends are located at $z = 0$ m and $z = 1.5$ m. Average standard deviations are 282 pT, 198 pT and 205 pT for B_r , B_z , and B_θ respectively across the whole scan length. (b) is the same data without B_θ plotted and with the vertical scale adjusted for clarity.

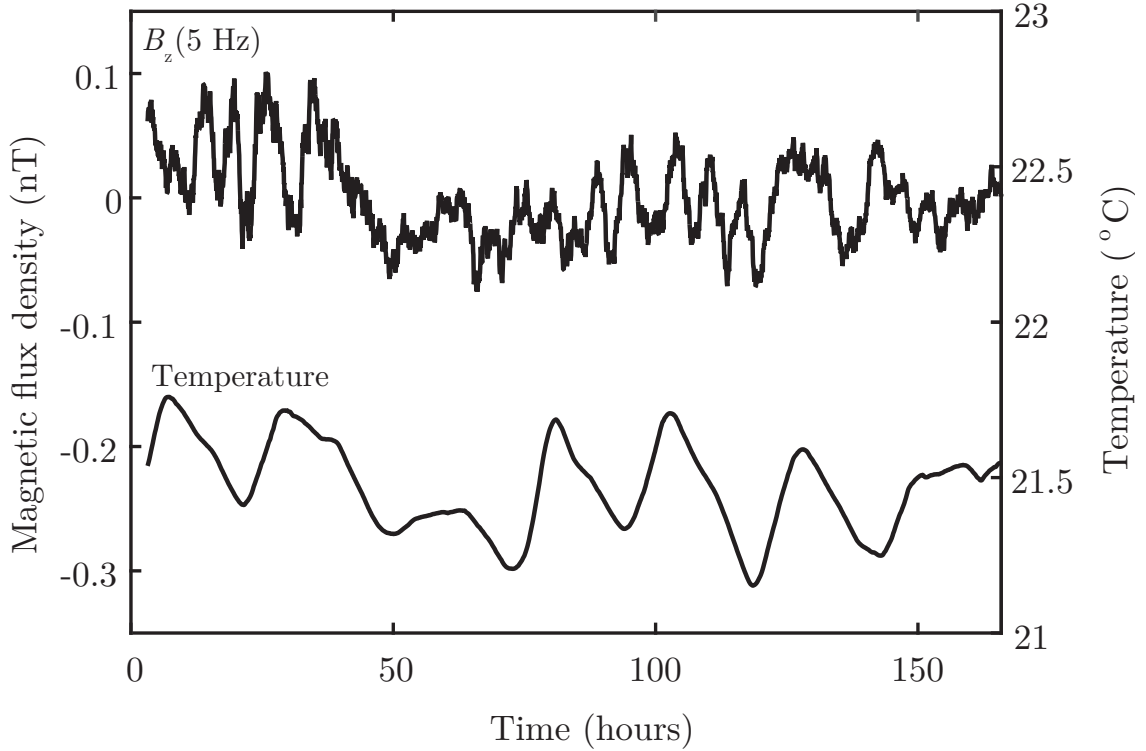


Figure 3.13: Stability of magnetic signal over a week, measuring B_z halfway along the pipe at 10 mm standoff with 2 A, 5Hz current in pipe. Temperature measured independently using a thermocouple.

netic skin effect. The results are shown in Fig. 3.13. As the profiles from all the measurements were similar, only the 5 Hz signal from the radially oriented sensor has been plotted for clarity. The temperature was monitored with a thermocouple positioned near the sensor.

There was a small temperature variation of 2 °C during the daily cycles. Over the course of the week, a decreasing trend can be noted on both the magnetic flux and temperature measurements. The sensor measurement was not temperature compensated as the range in the magnetic flux density over the entire week was significantly less than 1 nT; however, when utilising AMR sensors in the field where large temperature variations are common, temperature correction is possible through the use of a coil integrated within the chip. Some additional higher frequency noise is present on the magnetic measurements yet crucially they do not stray far from zero as expected from the measurement of a defect-free pipe. The mean of the radial sensor was -18 ± 550 pT, -80 ± 180 pT and -25 ± 270 pT at 1 Hz, 5 Hz and 25 Hz respectively where the uncertainty is the standard deviation. The noise density of the sensors was measured as 1.37, 0.46 and 0.32 nT/ $\sqrt{\text{Hz}}$ at 1 Hz, 5 Hz and 200 Hz

respectively.

The lack of any significant drift in the measurement implies that the use of a flip-pulse through the set/reset coil which is sometimes required to reset hysteresis in MR sensors is not a requirement in the laboratory environment. In further tests it was revealed that the use of the flip-pulse was only necessitated when a strong permanent magnet was brought close to the sensor; the sensors were not saturated by the induced fields from a 2 A current in the standoff range of interest. In an industrial environment it is likely that a flip-pulse in the set/reset coil would be utilized periodically to reset the magnetic domain orientation in the sensor and to correct for a drifting offset voltage with temperature as variations are likely to be more severe than in the lab.

3.3.4 Model Validation

Flat-Bottomed Slots in Austenitic Steel

Measurements of current deflection from flat bottomed slots milled into the outer surface of a 1.5 m long 6-inch schedule-40 austenitic steel pipe were taken in order to validate the FE model. A $\frac{T}{2}$ maximum depth slot was positioned half way along the pipe, and $\frac{T}{4}$ and $\frac{3T}{4}$ slots were located 0.4 m from either end and circumferentially separated by 120° in order to minimise the interaction between the signals. Each component of $\mathbf{B}$ was measured for a 1.1 m length at the pipe centre at 15 mm intervals and around the entire circumference in 10° increments. Each sensor was averaged for 25 s and the current frequency was 25 Hz (resulting in a skin depth of ~ 83 mm) which is low enough to ensure quasi-DC operation in non-magnetic austenitic steel. The magnetic flux density profiles in a section of the scan around the deepest defect are shown in Fig. 3.14a–c. The data were cubically interpolated to a finer spatial resolution of every 1° and every 2.5 mm. The characteristic perturbations of current deflection are exhibited in these measurements, as in the FE predictions in Fig. 3.6. It can be seen in Fig. 3.14c that there is some asymmetry about the defect centre in the azimuthal direction. This is probably due to changes from the uniform pipe geometry due to manufacturing tolerances in the wall thickness.

A circumferential scan centred above the deepest slot at 10 mm standoff (illustrated in Fig 3.15) was compared to the identical defect geometry recreated in

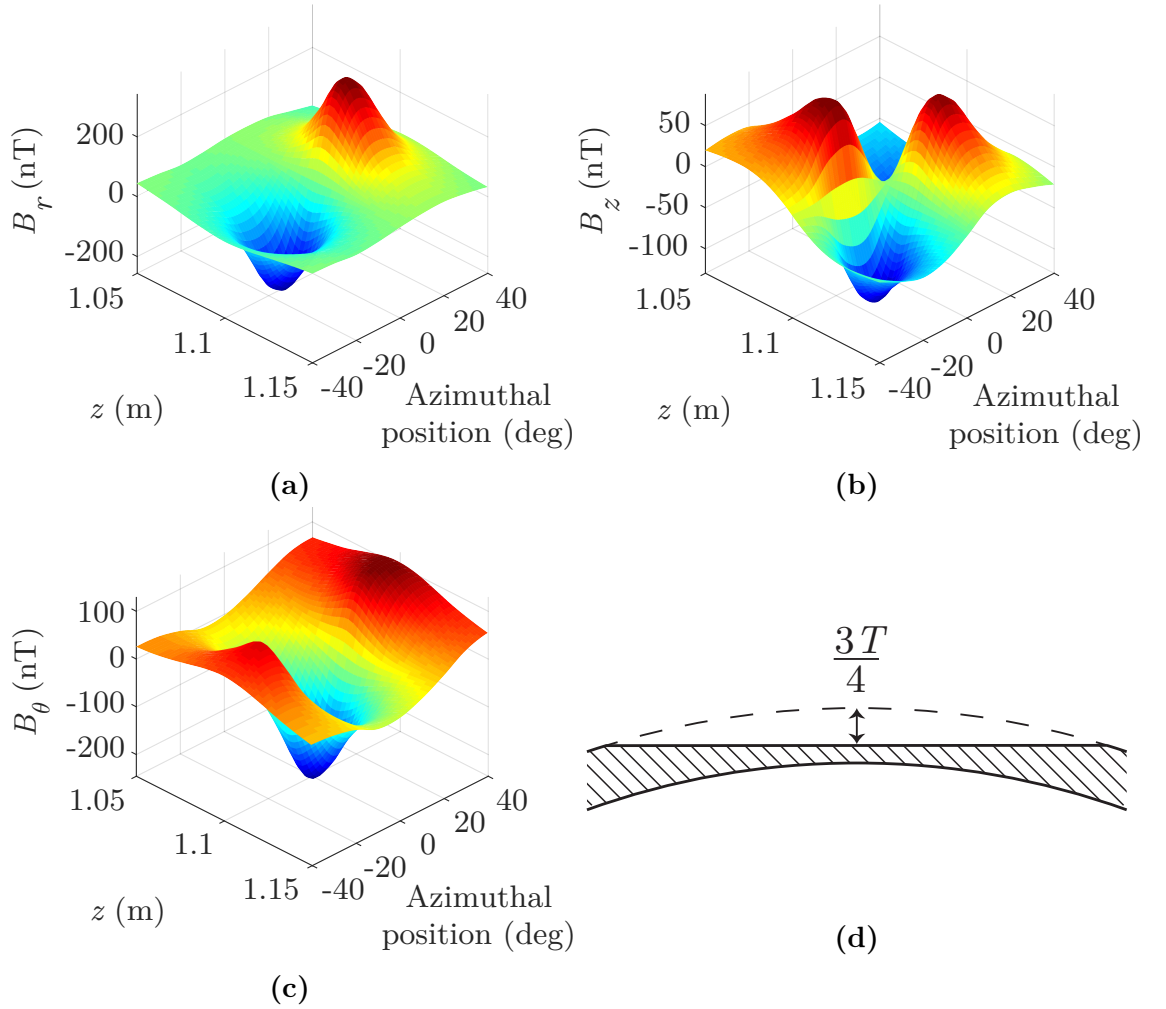


Figure 3.14: Spatial distributions of the (a) radial; (b) axial and (c) azimuthal components of the magnetic flux density arising from current deflection from a flat bottomed slot (shown schematically in (d)) measured at 10 mm standoff from the pipe.

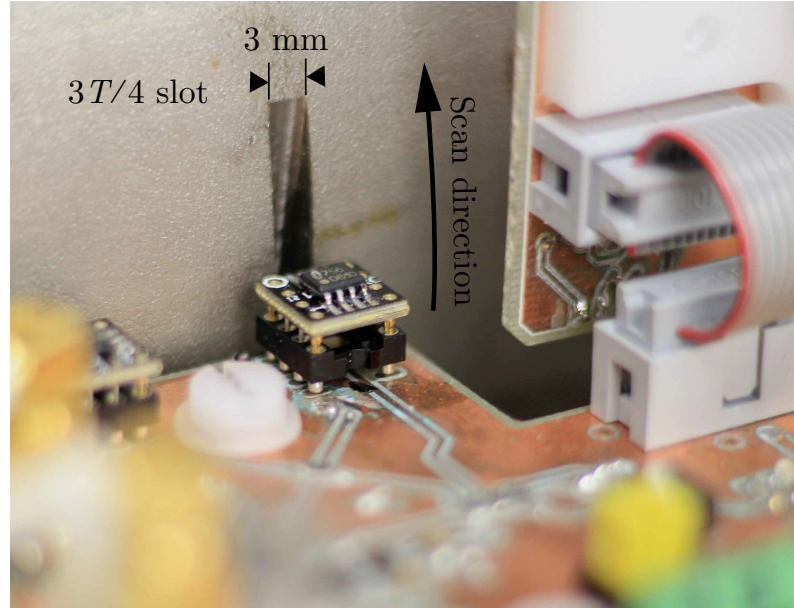


Figure 3.15: Photograph of sensor positioned outside of a $3\text{ mm} \times \frac{3T}{4}$ slot at $\Delta = 10\text{ mm}$ showing circumferential scan direction.

FE. In order to correct for the slight variations in wall thickness within the specified manufacturing tolerances, the baseline was established by taking an additional circumferential scan offset axially by a distance of 50 mm where the defect signal is diminished but the perturbations in B_r caused by the nominal wall thickness changes (which vary slowly along the pipe axis) remain. The baseline corrected measurement of B_r over the circumferential scan is plotted in comparison to the FE prediction in Fig. 3.16. The FE data is plotted as a dashed line. There is an excellent agreement between the measurement and the FE data, both exhibiting peak-to-peak amplitudes of 605 nT.

Semi-Ellipsoidal Bowls in Carbon Steel

The model was well validated for the wide flat bottomed slots in the previous experiment; however, this geometry differs from the standard of a $3T$ diameter semi-ellipsoidal defect that is usually set by BP to investigate new NDE techniques for corrosion inspection. Furthermore, the previous non-magnetic pipe had a relative magnetic permeability close to unity, which permitted a current up to a few kilohertz to behave as quasi-DC. Validation is required for ferromagnetic pipes which demand a much lower frequency current, and which may have magnetic property variations that have potential to interfere with the signal. To serve this purpose, a

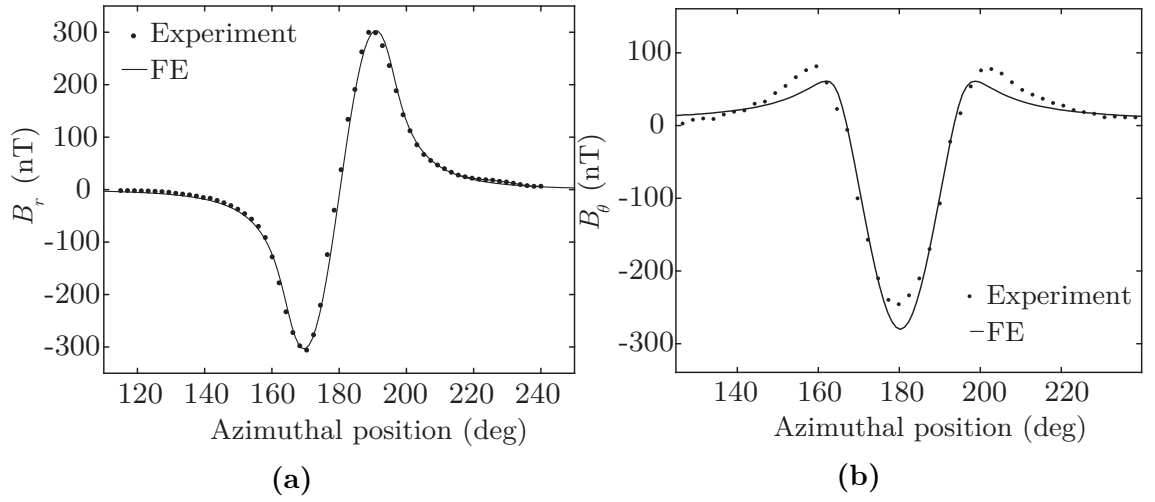


Figure 3.16: Comparison of FE prediction (solid line) with a baseline corrected measurement (dots) of the (a) radial and (b) azimuthal components of the magnetic flux density at 10 mm standoff.

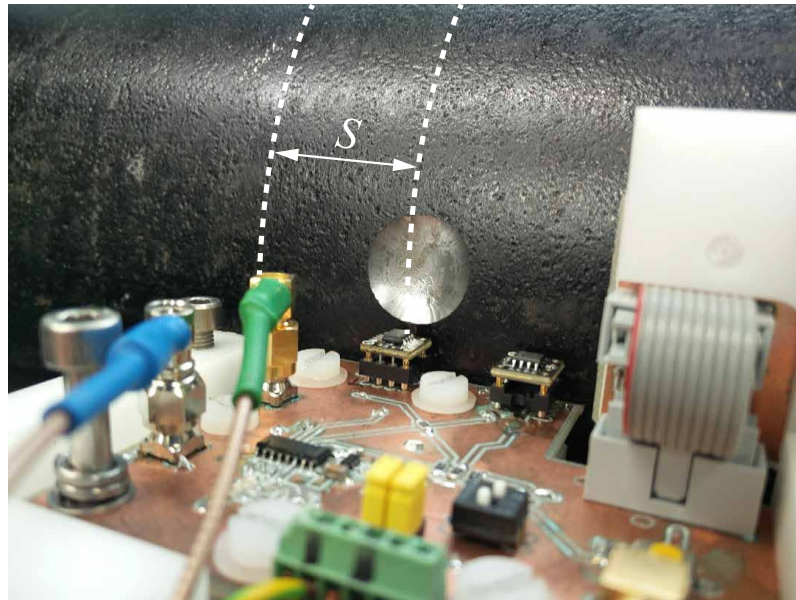


Figure 3.17: Photograph of the sensor positioned outside a $3T \times 3T \times \frac{T}{2}$ defect in a carbon steel pipe. Dashed line shows scan paths directly over the defect and offset by an axial distance s .

154 mm nominal bore (6") schedule-40, 7.1 mm wall thickness longitudinally seam-welded carbon steel pipe had a $3T \times 3T \times \frac{T}{2}$ semi-ellipsoidal defect milled into the outer surface, as shown in Fig. 3.17.

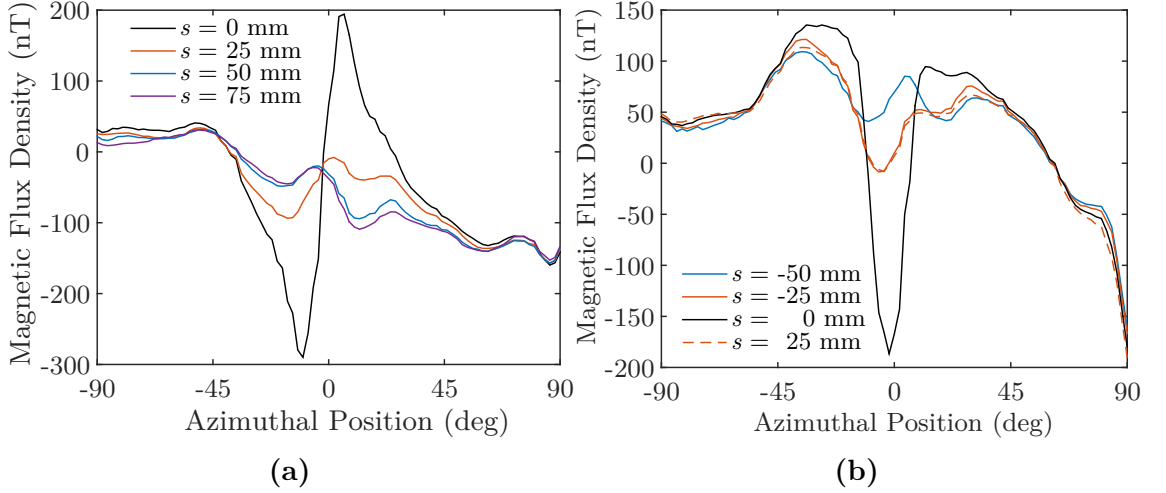


Figure 3.18: Circumferential scans of (a) B_r and (b) B_θ around a $3T \times 3T \times \frac{T}{2}$ semi-ellipsoidal defect at $\Delta = 10$ mm and axial offset s .

Figure 3.18 shows circumferential scans of B_r and B_θ at a lift-off distance of 10 mm. The different data sets show scans that are axially offset from the defect centre by a distance s , as shown in Fig. 3.17. The perturbation due to the defect (closest to 0°) is clearly greatest for the scans directly aligned with the defect. As the offset is increased, the defect perturbation reduces yet the general profile of B_r or B_θ away from the defect remains similar. In Fig 3.18b, the scans at $s = -25$ mm and $s = 25$ mm are very similar, suggesting that this baseline signal does not vary rapidly (over tens of mm) with axial position. This is similarly confirmed in Fig 3.18a where the signals away from the defect at $s = 50$ mm and 75 mm show very little variation.

As the FE model predicts only the perturbation due to the defect, a 1D first-order gradiometer was synthetically formed by subtracting the circumferential scan measured using a single sensor positioned axially in-line with the defect from the scan measured when the sensor was axially offset by a distance s . After forming the gradiometer, the radial signal becomes

$$\frac{\partial B_r}{\partial z} s \approx B_r(r, \theta, z) - B_r(r, \theta, z + s) \quad (3.2)$$

The resulting profile leaves just the defect perturbation, which is compared to a

FE prediction in Fig. 3.19. There is good agreement between the gradiometric measurement and FE. The differential sensing method is effective at suppressing variations in magnetic flux density that vary slowly along the pipe axis and spurious magnetic signals originating far from the pipe, at the expense of slightly reduced sensitivity to the primary field originating from current deflection from the defect. The peak-to-peak amplitude of the measurement perturbation is around 10 % lower than the FE because the defect signal has not fully decayed at the axial offset distance s .

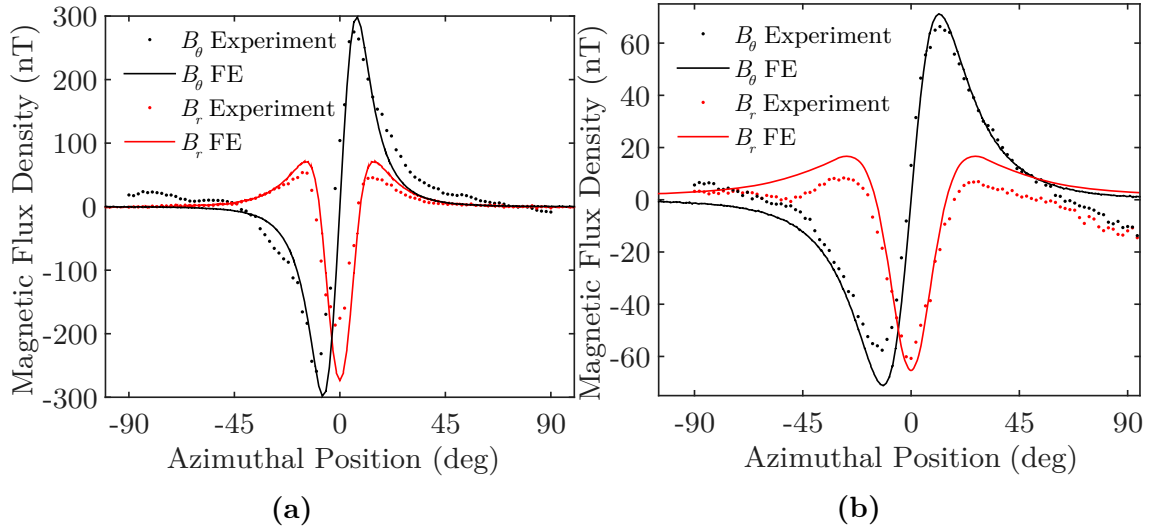


Figure 3.19: Circumferential scans of B_r and B_θ around a $3T \times 3T \times \frac{T}{2}$ bowl using a 1st order gradiometer at (a) $\Delta = 10$ mm, $s = 50$ mm and (b) $\Delta = 25$ mm, $s = 100$ mm.

At the increased standoff of 25 mm (Fig 3.19b), the primary field due to current deflection diffuses and reduces in amplitude. These data provide validation of the FE model, and indicate how the sensitivity to defects can be increased with differential sensor configurations, which will be explored further in the following chapter. The agreement between the azimuthal spacing of the peaks of the measured and modelled signals shows that FE is efficient and accurate at predicting the defect signal from current deflection. Uncertainties in the FE model are low and arise from slight differences in current amplitude and the geometry of the real and modelled pipe.

Linearity with Current Amplitude

The integral form of Ampère's law can be derived from equation 2.1 (page 33) using Kelvin-Stokes theorem. It states that the total magnetic field integrated on a closed

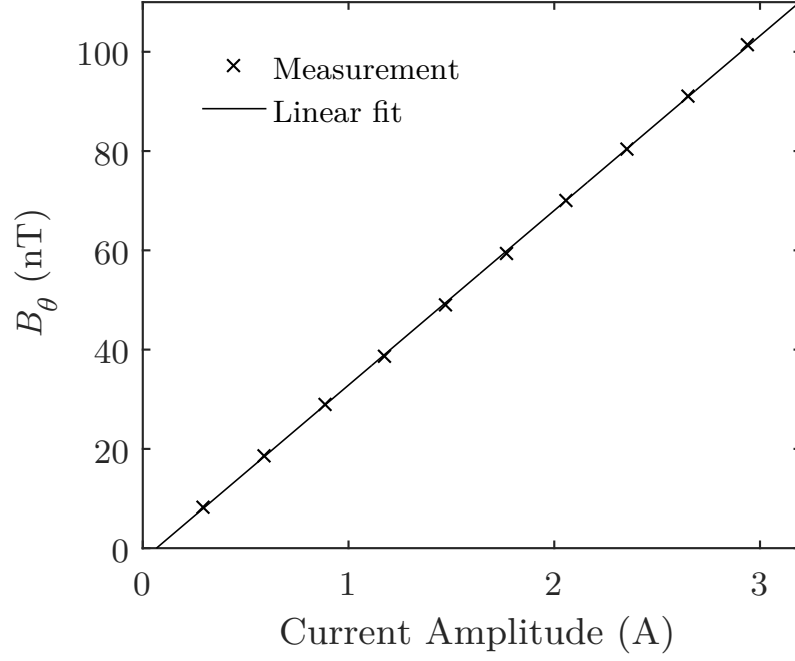


Figure 3.20: Average of B_θ over a 100 mm scan for different values of injected current amplitude.

path C is proportional to the total current passing through the surface S that is bounded by C ,

$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 \iint_S \mathbf{J} \cdot d\mathbf{S} = \mu_0 I_{\text{enc}} \quad (3.3)$$

where all symbols remain as previously defined. The amplitude of the perturbations of the components of $\mathbf{B}$ predicted by the FE model are therefore proportional to the amplitude of the current injected into the pipe. This linear relationship was confirmed experimentally by repeating a scan of B_θ at $\Delta = 10$ mm for a range of current amplitudes between 0 A to 3 A. The scan path was 100 mm long and was centred over a perturbation in B_θ . The average of B_θ over the scan distance is plotted in Fig 3.20. The data fit a linear regression with an R-squared value of 0.9999, confirming both the linearity of $\mathbf{B}$ with current amplitude, and the repeatability of multiple linear scans.

3.4 Conclusions

This chapter has introduced the current deflection NDE technique. The principles of the method were outlined and the effect of the frequency of the injected current on its distribution within the pipe was demonstrated. To be able to investigate the technique under various configurations, an FE model was created. The effect of defect geometry and standoff on the perturbation in $\mathbf{B}$ due to current deflection was investigated, revealing that the peak-to-peak amplitude of the signal decreases rapidly with standoff while the spatial extent of the signal increases. Different defect geometries were modelled which revealed that flaws on the inner-wall produce similar but slightly lower amplitude signals than on the outer-wall. Defects with their principal axis aligned with the pipe axis would be the most difficult to detect as they cause the least amount of current deflection. Experimental measurements of the induced magnetic field surrounding a current-carrying pipe allowed the technique to be demonstrated, and the FE model to be validated. Measurements over slots in an austenitic pipe provided excellent agreement with the model prediction. Validation scans using a $3T \times 3T \times \frac{T}{2}$ defect in a carbon-steel pipe also matched modelled data well, although contributions to the measured signal that did not originate from current deflection around the defect needed to be suppressed. Carbon steel pipes are very commonly used in industry, so the causes of these contributions to the signal will be investigated in more detail in the following chapter.

4 | Practical Challenges for Current Deflection NDE

The validation scans in the previous chapter revealed that there were contributions to the measured signal that did not originate from current deflection around the defect. These were suppressed by synthetically forming a 1D gradiometer comprised of sensors separated by a small axial distance. It is important to understand the origin of these contributions to the signal, so that they can be effectively suppressed, and will not significantly lessen the sensitivity of the technique. This chapter investigates potential contributions to the measured signal and explores the practical challenges faced by the current deflection technique and discusses possible solutions to mitigate them. This chapter partly comprises work that has been published in the journal *NDT & E International* and permission has been obtained by *Elsevier* to reuse text and figures where appropriate (Jarvis et al. 2016).

4.1 Wall Thickness Variations on Defect-Free Pipe

4.1.1 Tolerance Standards for Petrochemical Pipe

There are a number of regional standards outlining the required chemical composition, dimensions and tolerances for steel pipes. It is important to know the degree to which the wall thickness and diameter can vary on an industrial pipe, as these geometric variations will influence the magnitude and distribution of the current density and the magnetic baseline signal. There are a great variety of pipes available. The different manufacturing methods; hot or cold finishing techniques; chemical composition; pipe diameters; application environments and weld types are just some examples of different pipe properties, all of which must have a specified tolerance.

Due to the extremely large number of standards written in order to cover all of these properties, a general overview is given in table 4.1.

Table 4.1 shows that stainless steel pipe is generally manufactured with more strict tolerances on the outer diameter and wall thickness than carbon steel pipe. The most relevant standard from an oil and gas perspective is API 5L which describes line pipes (pipes used to transport product between refineries, facilities etc.). The wall thickness of a line pipe can vary by up to 15 %. The tolerance on the diameter of the pipe is generally given as a specific value for a range of diameters, which usually equals $\pm 1\%$ to $\pm 1.5\%$ of the nominal outer diameter.

4.1.2 Wall Thickness Measurements on Different Pipe Samples

Seamless Austenitic Stainless Steel Pipe to ASTM A312

To investigate the characteristics of the thickness variation on real pipes, digital vernier callipers were used to measure the thickness of a 150 mm nominal bore (6") schedule-40 304 seamless austenitic steel pipe (the first pipe acquired) at 25° intervals around the outer circumference at one of the pipe ends. As the measurement could only be carried out at the pipe end, no information about the axial variation of thickness was revealed. Figure 4.1 shows the average of three measurement repetitions.

The results show that the average wall thickness around the pipe was 7.1 mm, with a standard deviation of 0.12 mm and a maximum variation of 0.45 mm which meets the specified tolerance limits.

Seamless Carbon Steel Pipe to API 5L/ASTM A106B.13

An ultrasonic EMAT scanning system (Powerbox H from Innerspec Technologies Inc., Lynchburg, Virginia, USA) was used to obtain a thickness map of a seamless carbon steel pipe manufactured under the ASTM A106B specification which permits variation of 12.5% from the nominal wall thickness of 7.1 mm and an outer diameter variation of $+1.6/-0.8$ mm (*ASTM A106 / A106M - 14 Standard Specification for Seamless Carbon Steel Pipe for High-Temperature Service* 2014). The system consisted of a rotary encoded EMAT transducer operating at 3.2 MHz and

Table 4.1: A comparison of tolerance standards for different pipe specifications. Where unmarked, dimensions are in mm. OD = outer diameter, T = wall thickness. (American Petroleum Institute 2007; Brensing et al. 2015; British Stainless Steel Association 2015; British Standard 2014)

Standard	Details	Steel Type	Tolerance on Thickness	Tolerance on Outer Diameter
BS EN 10297-2 and EN ISO 1127	Cold finished	Stainless	$\pm 7.5\%$ -10% or ± 0.15 -0.2 (whichever greatest)**	$\pm 0.5\%$ -0.75% or ± 0.1 -0.3 (whichever greatest)**
BS EN 10217-1	OD<219.1	Non-alloy Steel	$T < 5$: $\pm 10\%$ or ± 0.3 $T > 5$: $\pm 8\%$ or ± 0.2	$\pm 1\%$ or ± 0.5
BS EN 10217-1	OD>219.1	Stainless	$T < 5$: $\pm 10\%$ or ± 0.3 $T > 5$: $\pm 8\%$ or ± 0.2	$\pm 0.75\%$ or ± 6
ASTM A999	10.3< OD <457	Stainless	12.5%*	11% at 10.29 OD or 0.65% at 609.60 OD **
ASTM A1016	OD<13	Stainless	$\pm 15\%$	$\pm 1\%$
ASTM A1016	13< OD <203	Stainless	$\pm 10\%$	± 0.5 -0.75%
ANSI B125.1	OD>51	Various	$\pm 12.5\%$	$\pm 1\%$
API 5L	73< OD <508	Carbon	+15%, -12.5%**	$\pm 1\%$ **

*Additional tolerance applies by weight **Diameter dependent

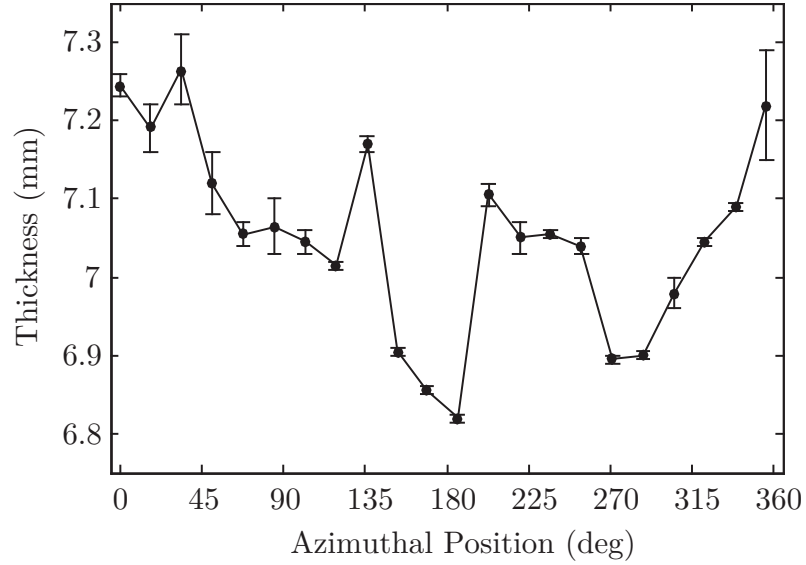


Figure 4.1: Mean of three repetitions of wall thickness measurements taken at the end of the austenitic steel pipe with digital vernier callipers. Error bars are standard deviation on the mean.

driven at 1200 V. The encoder allowed B-scans to be performed along the pipe axis with a spatial resolution of 5 mm. The scans were repeated with 20 mm (13.5°) circumferential intervals and a laser guide was used to ensure parallel scan paths (although slight deviations may have resulted in small changes in the coil orientation which could contribute to the measurement uncertainty due to birefringence of the ultrasonic beam). The thickness was extracted by an algorithm adapted by the author from code available within the research group. Figure 4.2a shows the thickness map which has been linearly interpolated for clarity. Figure 4.2b shows the mean and standard deviation of wall thickness along the axial scan length for each circumferential position.

The mean thickness was 7.14 mm and the maximum and minimum were 7.72 mm and 6.81 mm, respectively. These values fall within the specified tolerances. Similarly to the previous test, a variation in wall thickness was noted around the circumference of the pipe, although this result now reveals that, for this pipe, the variation is much greater in the circumferential direction than in the axial direction. The average standard deviation of the wall thickness around the circumference was 0.20 mm, whereas the average standard deviation of a 1.5 m scan along the axis of the pipe was just 20 μm .

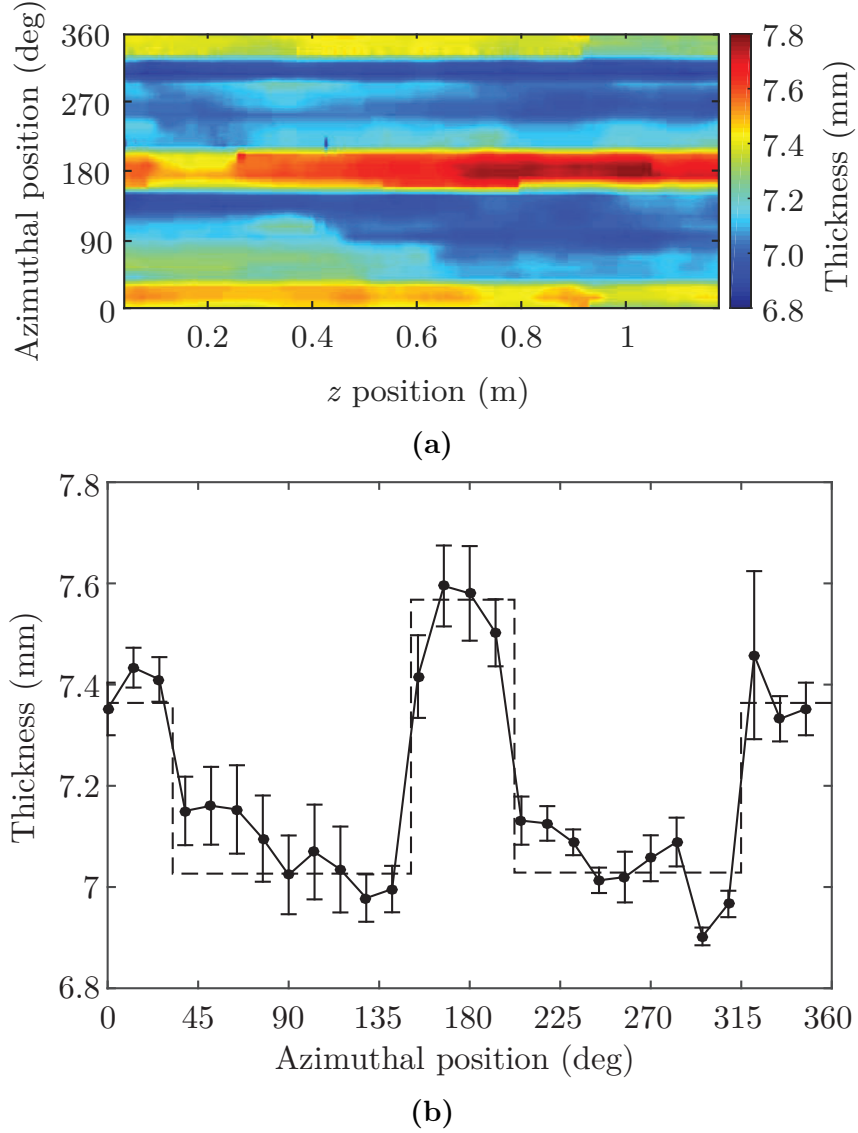


Figure 4.2: (a) Wall thickness map of a seamless 150 mm nominal bore schedule-40 carbon steel pipe linearly interpolated with 1° , 1 mm sampling frequency. (b) Mean wall thickness over the scan length as a function of circumferential position. Error bars show the standard deviation on the mean and dashed line shows approximation used for the FE model in section 4.5.

Longitudinally Seam-Welded Carbon Steel Pipe to API 5L-B

Figure 4.3 shows the thickness profiles of two longitudinally seam-welded carbon steel pipes. One with 200 mm (8") nominal bore (Fig. 4.3a and 4.3b), and another with 150 mm (6") nominal bore (Fig. 4.3c). The thickness profiles were measured with the same EMAT scanning system used previously and the mean thickness was within the specified tolerance. The thickness variation in these seam-welded pipes is smaller than for the previously tested seamless pipes and, as with the seamless pipes, the standard-deviation in the thickness along the ~ 1 m axial scan length is low (typically $< 20 \mu\text{m}$). The seam weld in Fig. 4.3b was at 0° and in Fig. 4.3c it was at 330° which accounts for the erroneous data between 325° to 335° where scattering of the back-wall echo prevented the thickness-extraction algorithm from functioning correctly.

4.1.3 FE Study of the Influence of Thickness Variation on Magnetic Baseline

Although the wall thickness of a small sample of real pipes has been measured, the general effect that nominal wall thickness variation has on the induced magnetic flux density surrounding a pipe should be studied. Assuming that the current density is uniform throughout the cross-section of the pipe (valid in a section of defect-free pipe away from the injection points), this means that the amount of current that flows through a section of the pipe subtending an angle $\delta\theta$ where the wall is thickest will be greater than the amount of current that flows through a region subtending the same angle where the wall is thinnest. Considering the integral form of Ampère's law (equation. 2.1), it is now no longer possible to draw a circular closed path C in which $\mathbf{B}$ is always parallel to $d\mathbf{l}$, so this integral cannot readily be simplified and solved directly with an analytical model.

For this reason, a 2D FE model of a pipe carrying 2 A quasi-DC current was created to study the effect of wall thickness variation on $\mathbf{B}$, in which the wall thickness was defined to have a sinusoidal periodic variation based on the measured wall thickness profile from Fig 4.1. A 2D model is justified as a first order approximation because the axial variation in wall thickness was low in comparison to the circumferential variation for all the pipes measured. Figure 4.1 appears to show a first

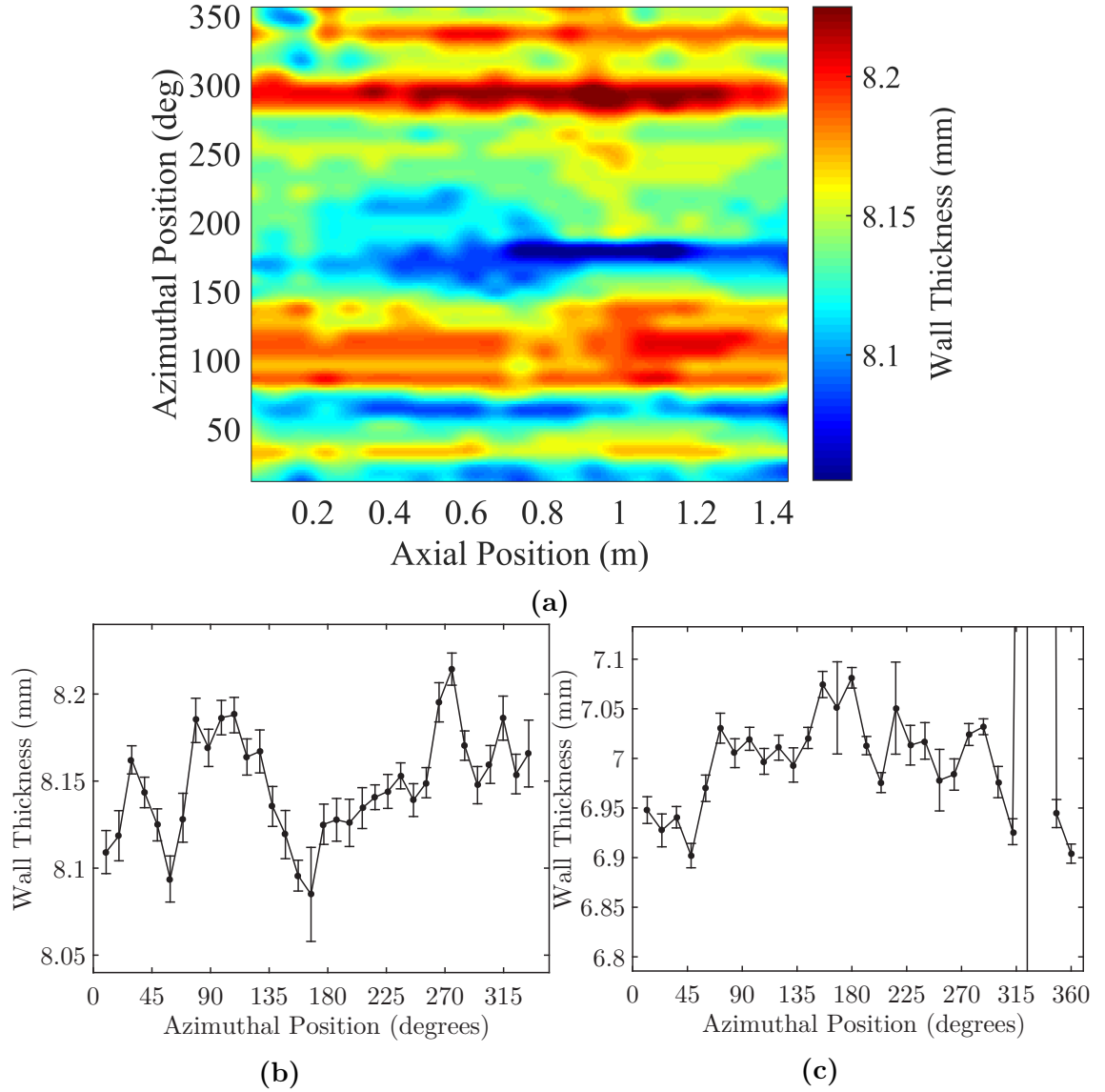


Figure 4.3: (a) Thickness map and (b) circumferential thickness profile of a section of 200 mm nominal bore (8'') schedule-40 longitudinally seam-welded carbon steel pipe manufactured to API 5L-B. (c) Circumferential profile of 150 mm nominal bore (6'') schedule-40 longitudinally seam-welded carbon steel pipe manufactured to API 5L-B

order sinusoidal variation in thickness (maximum at 0° , minimum at 180°), with some smaller higher-order components. Different orders of periodicity were therefore defined with up to six periods of the thickness change around the circumference. The profiles of the modelled pipe cross sections for the order 1, 2 and 4 cases are shown in Fig. 4.4, where the wall thickness changes have been greatly exaggerated for illustrative purposes. The order 1 case is representative of the axis of the central bore being slightly offset with the axis of the pipe, order 2 represents ovality of the pipe, and higher orders represent periodic variations in thickness.

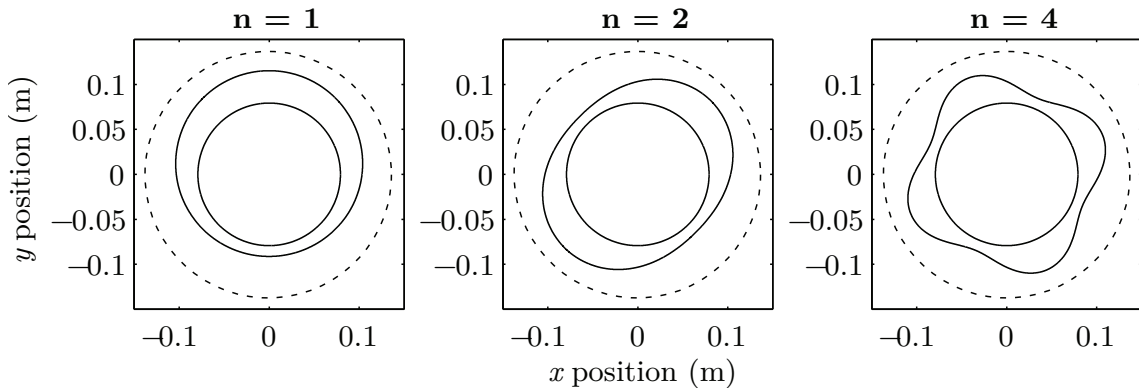


Figure 4.4: Exaggerated shape profiles indicating the different periodic orders of wall thickness variation modelled in a 2D FE study. Dashed lines show example simulated scan path concentric with pipe inner bore. This figure is for illustrative purpose only and the 12 o'clock position does not correspond to the datum in later figures.

Figures 4.5a and 4.5b shows the predicted variations in B_r and B_θ on a circular scan path coaxial with the pipe at a fixed standoff of 50 mm plus the inner pipe radius and the average wall thickness. Due to the wall thickness being constant in the direction of the pipe axis there is no perturbation in B_z , so it has not been plotted.

This result indicates that higher periodic orders of wall thickness change affect the absolute value of the magnetic flux density less than lower orders, although they have a more rapid spatial variation which could be more difficult to correct for from a scanning perspective. The measured wall thickness variation could cause a peak-to-peak magnetic flux density variation of up to 26 nT in B_r and 61 nT in B_θ for the order 1 case, which is of the same order of magnitude as the perturbation due to a defect (table 3.1 on page 58). At a standoff of $\Delta = 10$ mm (not plotted), the peak-to-peak variation due to the modelled periodic wall thickness variation was of the order 100 nT, which is similar to the baseline variation observed during the

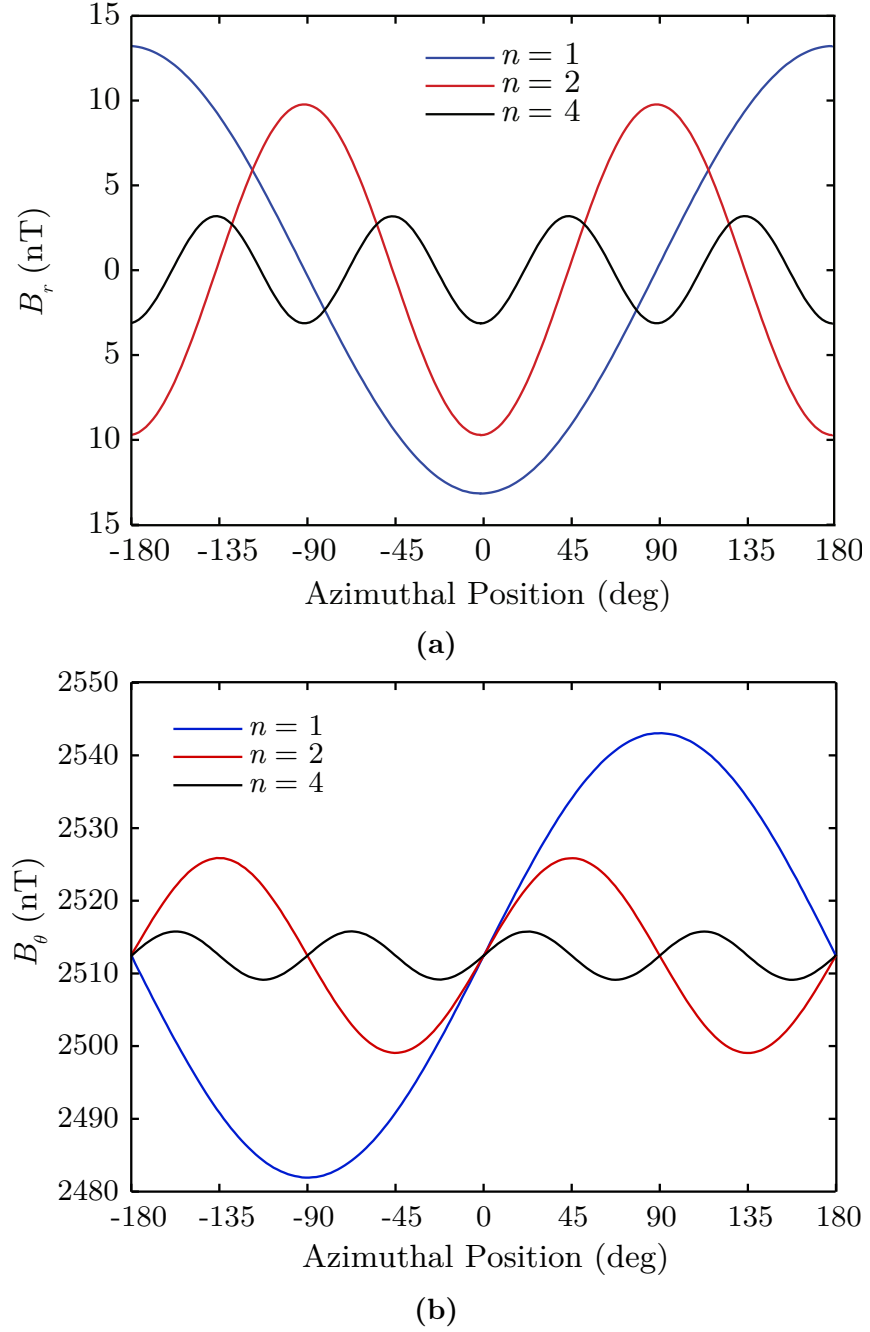


Figure 4.5: Variations in the (a) radial and (b) azimuthal components of $\mathbf{B}$ as a result of a first, second and fourth order wall thickness variation of 0.45 mm at a distance of the mean wall thickness plus 50 mm from the pipe inner radius (c.f. dashed lines in Fig. 4.4).

validation scans in the previous chapter (Fig. 3.18 on page 76 for $s = 75$ mm). In reality, the wall thickness variation on a pipe will be the superposition of a very high number of orders of periodicity of which the intensity of each could be evaluated by Fourier analysis. This explains why the magnetic baseline signal due to tolerances on the thickness can appear more complicated on real pipe than the output of these simple models.

The slow axial variation of the wall thickness (denoted by the small error bars in Figs. 4.2b, 4.3c and 4.3b) implies that a differential sensor configuration could be used to suppress the contribution to the magnetic baseline from wall thickness variations due to manufacturing tolerances. This concept will be explored in more detail towards the end of this chapter. It also implies that the axial component of $\mathbf{B}$ will be least affected by the wall thickness variations from manufacturing tolerances.

4.2 Effect of Defect Roughness

Until this point, corrosion defects have been approximated by a smooth semi-ellipsoid. The depth profile of a real corrosion defect is unlikely to vary smoothly like this, but will have some degree of roughness. The effect of defect roughness was therefore investigated using an FE model in which the current-carrying pipe of wall thickness 7.1 mm was approximated as a plate to allow for simpler digitization for FE. A surface $h(x, y)$ was generated with a Gaussian distribution of depths, which was then multiplied by a flat-topped tapered cosine profile with unity maximum value and diameter of 100 mm. The tail of the distribution of depths was clipped to limit the maximum depth to twice the standard deviation of the RMS depth, and any heights above the surface of the plate were removed to avoid any addition of material. Figure 4.6a shows the resulting surface profile of a defect with a correlation length (length scale of the roughness) of 10 mm and RMS depth 1 mm. These values were based upon the parameters used to describe typical rough corrosion from (Dobson 2015). It is worth noting that the morphology of real corrosion is varied, and the geometry modelled here was chosen simply as a starting point to understand how roughness may influence the current deflection signal. For comparison, the depth profile of a defect with the same total volume but no roughness is also presented.

Figures 4.6b and 4.6c show the induced axial magnetic flux density at distances of 1 mm and 25 mm above the plate, respectively. The greatest disturbances in B_z occur outside the dotted line that outlines the defect extent, demonstrating that the most significant contribution to the signal comes from the overall footprint of the defect and not the roughness. At a standoff of $\Delta = 1$ mm, some roughness induced distortion of the field is visible within the perimeter of the defect; however, the diffusion of the field with standoff means that the current deflection signal from a rough defect is generally indistinguishable from that of a smooth defect of equal size when the standoff is greater than the length scale of the defect roughness. Although not plotted for brevity, B_r and B_θ behaved the same way. This result indicates that realistic defect morphologies can be well approximated by smooth, simple-to-model geometries; therefore, semi-ellipsoidal defects will be used to approximate corrosion defects for the remainder of the thesis.

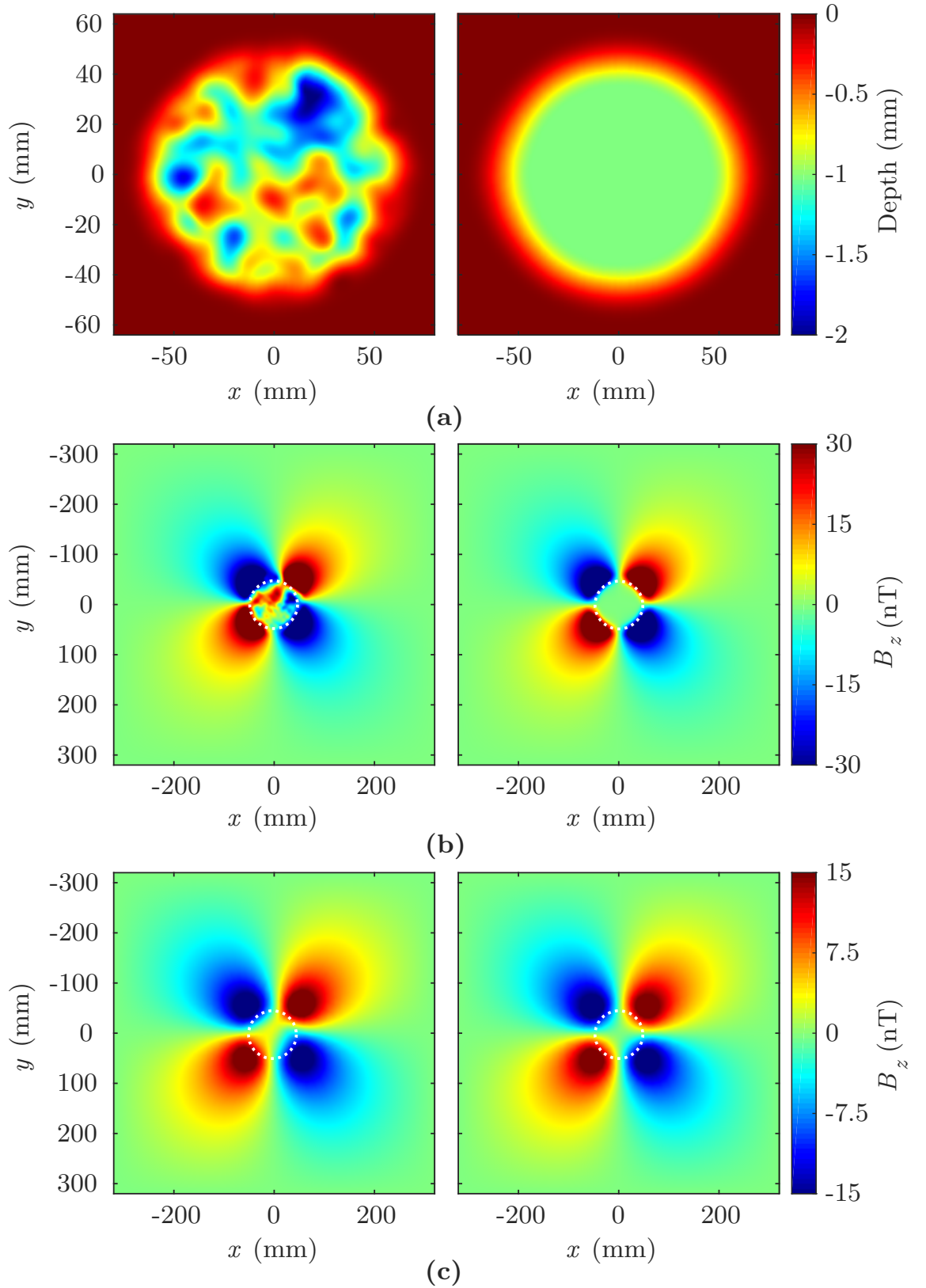


Figure 4.6: (a) Depth profile of a 100 mm diameter, 1 mm RMS depth defect. Left: 10 mm correlation length. Right: no roughness. The resulting B_z profiles from current deflection at standoff of (b) $\Delta = 1$ mm and (c) $\Delta = 25$ mm.

4.3 Effect of Nearby Ferromagnetic Objects

Phase sensitive detection is effective at suppressing spurious magnetic noise from external sources (such as electromagnetic interference at the mains frequency) yet local variations in the spatial distribution of the magnetic flux density can be caused by factors other than current deflection from defects. Ferromagnetic objects concentrate magnetic flux so, if located close to the scanning path of a magnetic sensor array, a local variation in the magnetic flux density would be observed as the sensors move past the object. There is a possibility that this local variation in the magnetic flux density could be misinterpreted as a current deflection signal caused by a defect, leading to an increased false call rate of the technique. This has prompted an FE study to investigate how the presence of a ferromagnetic object external to the pipe affects the sensitivity of the technique.

Two cube-shaped blocks of side length 10 mm and 25 mm were modelled. The relative permeability of the block was set to $\mu_r=100$ (approximately representing a carbon steel), and its centre was positioned at a varying distance between 22 mm to 150 mm from the pipe surface. The magnetic flux density was visualised on a surface at 10 mm or 25 mm standoff. Figure 4.7 shows the perturbation in B_r due to the block. The sensor at location 1 on Fig. 4.7 represents the worst-case-scenario when the block perturbation causes maximum interference with the sensor.

The maxima of the radial and axial components of the magnetic flux density were found for each combination of size of the block and distance from the pipe. The resulting curves are shown in Fig. 4.8a for sensors at a standoff distance of 10 mm, and in Fig. 4.8b for a standoff of 25 mm. On these curves, there is an overlay of the peak-to-peak values resulting from deflection of a 2 A current around a $3T \times 3T \times \frac{T}{3}$ defect positioned in the pipe outer surface, as calculated in the FE study presented in section 3.2.1 of the previous chapter.

Table 4.2 shows the minimum distance between the block and the solution surface for the signal caused by flux concentration from the ferromagnetic block to be equal in amplitude or smaller than the concave defect, i.e. the distance that ferromagnetic objects should be spaced from the sensor in order to minimise false-call risk. When the standoff is 25 mm and if the ferromagnetic block is located closer than 71 mm radially (in the case of a 25 mm side length cube), this could result in an

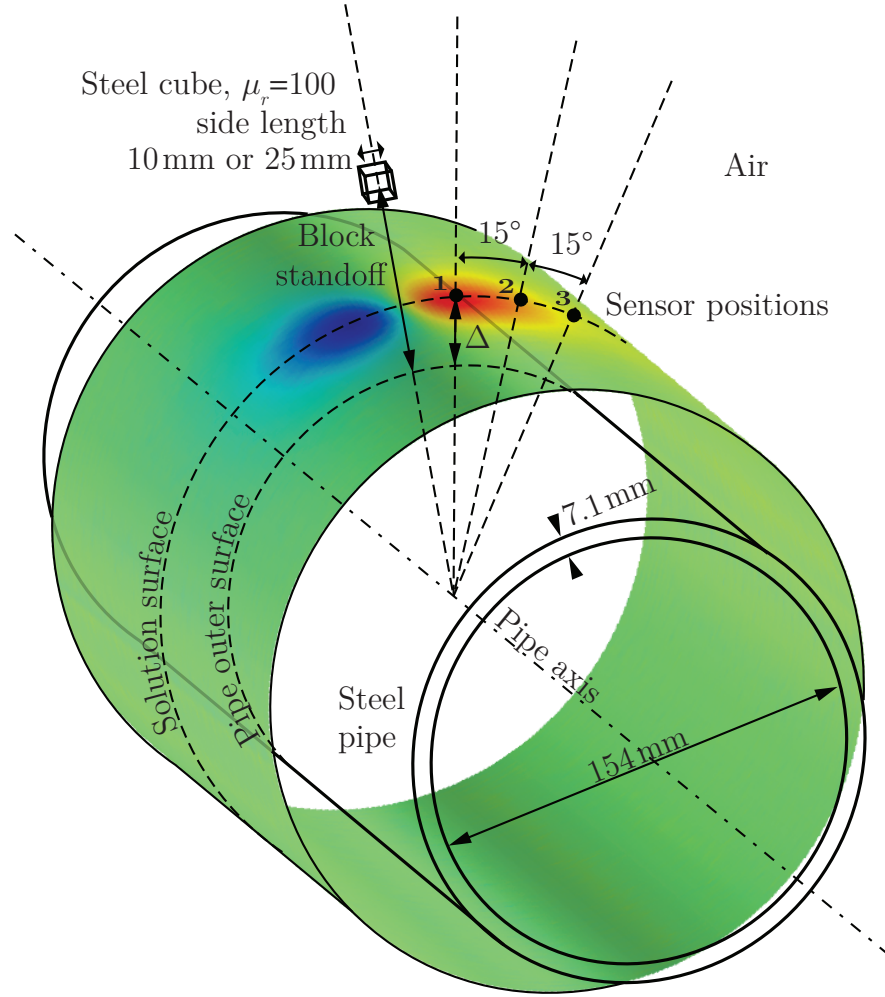


Figure 4.7: Schematic of model geometry. Perturbation in B_r caused by the block plotted at standoff Δ to aid visualisation. The solid marker labelled 1 represents a sensor positioned at the maximum of the block perturbation, and 2 and 3 are offset azimuthally by 15° and 30° respectively.

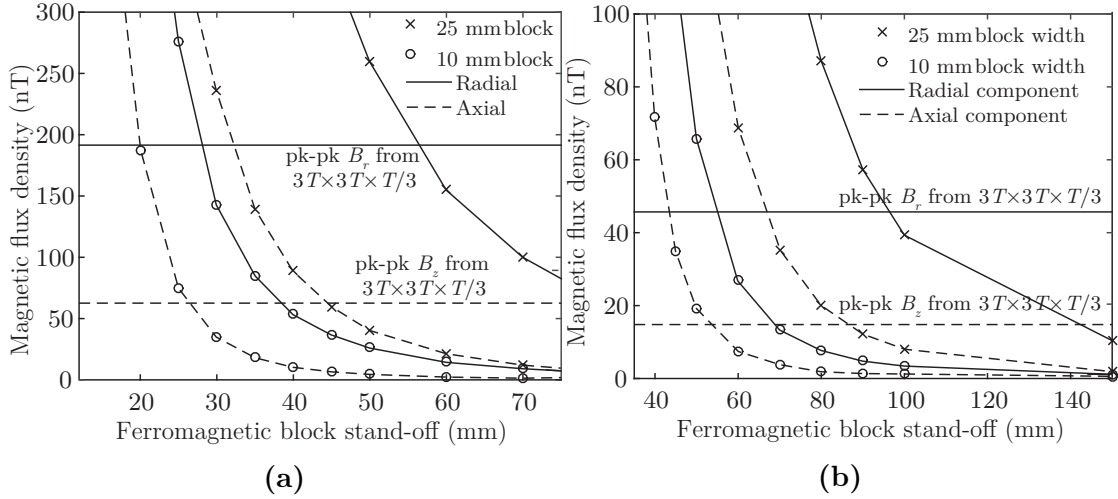


Figure 4.8: Worst-case-scenario magnetic perturbations at (a) 10 mm and (b) 25 mm standoff from a 6" pipe carrying 2 A current when a ferromagnetic ($\mu_r = 100$) block of 10 mm or 25 mm side length is located at a varying radial distance from the pipe. The peak-to-peak values of B_r and B_z from a $3T \times 3T \times \frac{T}{3}$ outer wall defect at the same standoff plotted for comparison. Points joined with straight lines to ease visualisation.

equal amplitude perturbation as a $3T \times 3T \times \frac{T}{3}$ defect when considering the radial component of $\mathbf{B}$. The perturbation of the magnetic flux density by the block affects the axial component less strongly, and it only exceeds the defect signal magnitude when the block is positioned less than 48 mm radially from the pipe surface.

When the sensor is positioned at 25 mm standoff, the measured perturbation from current deflection in the pipe due to the presence of defects will be smaller than when the measurement is taken at 10 mm standoff. This means that the higher standoff measurements are more susceptible to false calls from the presence of an external ferromagnetic object, as it will match the defect signal amplitude at a greater radial separation than if the sensor were closer to the pipe. For example in this case of the 25 mm block, the minimum separation distance between the block and sensor for the block perturbation to match the defect signal amplitude in B_r is 22 mm at 10 mm standoff in comparison to 49 mm at 25 mm standoff.

The data in Fig. 4.8 and Table 4.2 represent the worst-case-scenario where the location of the peaks in the spatial distribution of the magnetic flux density caused by the steel block fall on the same radial line as the sensor. Figures 4.9 and 4.10 show the same relationships as Fig. 4.8, but now with the block circumferentially misaligned with the sensor by 15° (sensor position 2 in Fig. 4.7) and 30° (position 3 in Fig. 4.7) respectively. In these figures, it is shown that the perturbation from

Table 4.2: Comparison of the radial separation between a $\mu_r = 100$ block and a sensor aligned axially and circumferentially with the block for which the resulting perturbation in magnetic flux density profile is of equal magnitude as a $3T \times 3T \times \frac{T}{3}$ concave defect located in the outer surface of the pipe.

Block side-length (mm)	Standoff (mm)	Radial separation at which block signal amplitude matches $3T \times 3T \times \frac{T}{3}$ pk-pk signal (mm)	
		for B_r	for B_z
10	10	18	13
25	10	32	27
10	25	67	29
25	25	71	48

the ferromagnetic block is much less severe than in the case when it is aligned with the sensor.

The angular extent over which the block perturbation is greater than the defect signal amplitude was computed. The results are shown in Fig. 4.11a for $\Delta = 10$ mm and Fig. 4.11b for $\Delta = 25$ mm. To calculate these curves, the block was positioned axially in line with the sensor, and the angular extent over which the absolute values of B_r and B_z exceeded those of the concave defect were calculated as the distance between the block and pipe was increased.

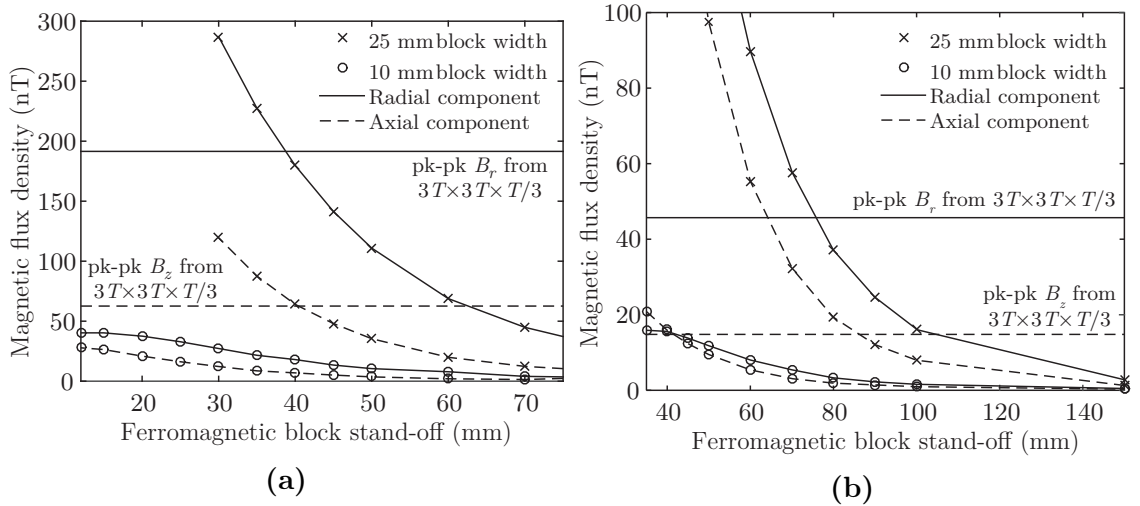


Figure 4.9: Magnetic perturbations at (a) 10 mm and (b) 25 mm standoff from the pipe, sensor is circumferentially offset by 15° from the peak signal due to the block.

The curves in Fig. 4.11 show that when the sensor is positioned at a higher standoff, the perturbation from the steel cube is greater than the defect signal over

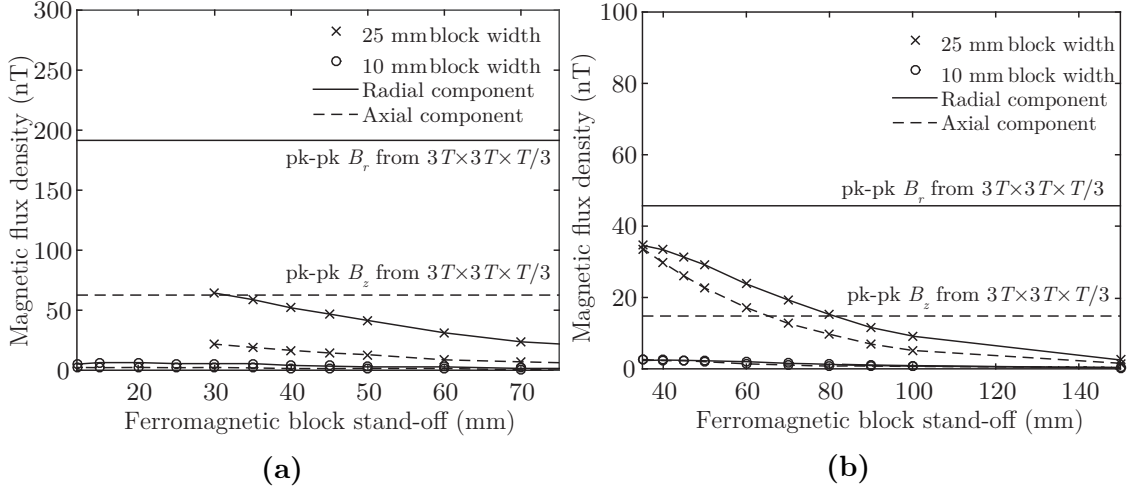


Figure 4.10: Magnetic perturbations at (a) 10 mm and (b) 25 mm standoff from the pipe, sensor is circumferentially offset by 30° from the peak signal due to the block.

a larger angular range than when the sensor is positioned closer to the pipe. Clearly, the larger cube is more detrimental to the signal than the smaller cube. In the worst case scenario modelled, the sensor is at 25 mm standoff and the block is positioned 5 mm further from the pipe than the sensor. Here, there is an angular range of 58° over the circumference where the block perturbation is greater than the defect signal in B_r . For the 10 mm side length block at the same distance, the angular range that exceeds the defect signal falls to 36° in the radial component and 24° in the axial component.

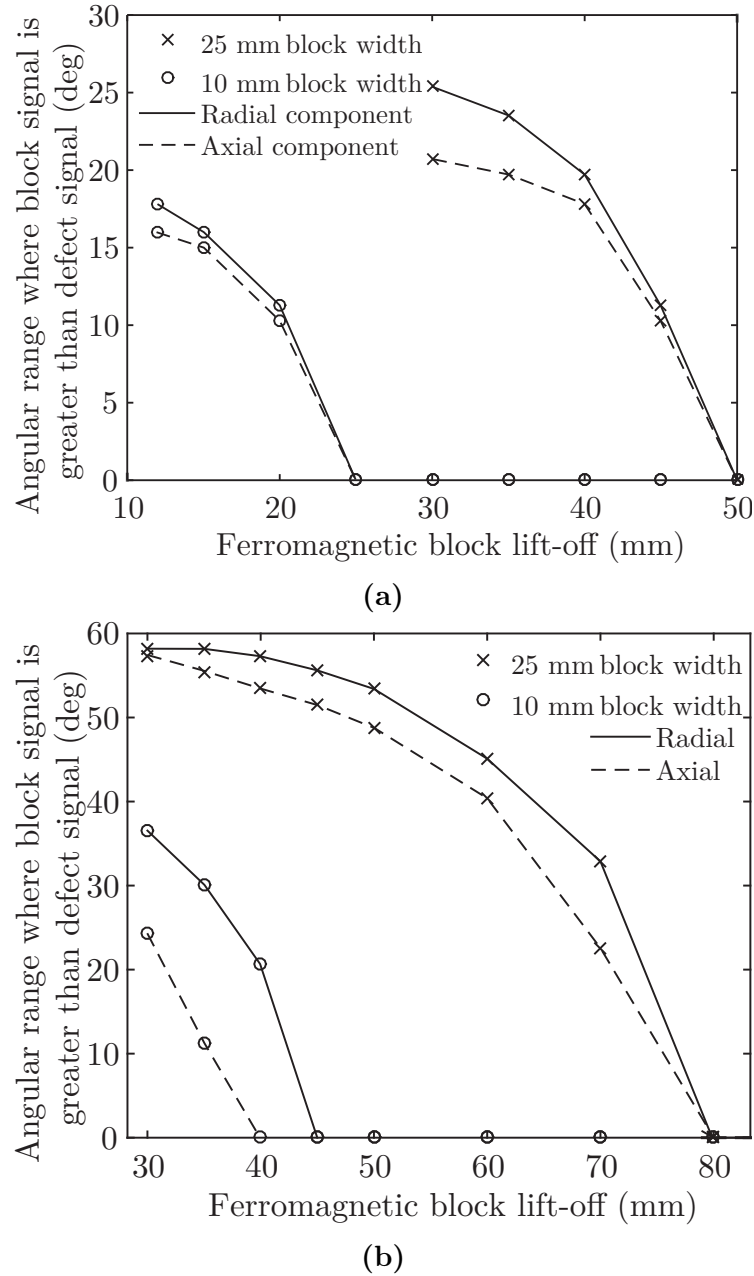


Figure 4.11: The angular range over which the amplitude of the current deflection signal from an outer wall $3T \times 3T \times \frac{T}{3}$ defect is exceeded by the perturbation caused by a 10 mm or 25 mm side length steel cube at various radial distances from a sensor positioned at (a) 10 mm and (b) 25 mm standoff.

Simple Pipe Support or Nearby Pipes

As an extension to the study of magnetic flux density perturbations caused by external ferromagnetic objects, a model was created with two carbon steel ($\mu_r = 100$) 6" schedule-40 pipes crossing perpendicular to one another, where the upper pipe carries 2 A current. The pipes are separated by 50 mm. The geometry was

specified to study the effects of large ferromagnetic objects near the pipe under test. Symmetry was employed to eliminate the need to model where $x < 0$ to reduce the solution time. As the pipes were not in electrical contact, the resulting magnetic perturbation is caused only by flux concentration of the induced field by the lower pipe. Figure 4.12 shows the radial (Fig. 4.12a), axial (Fig. 4.12b) and azimuthal (Fig. 4.12c) components of $\mathbf{B}$ outside the insulation/coating of the top pipe at 25 mm standoff.

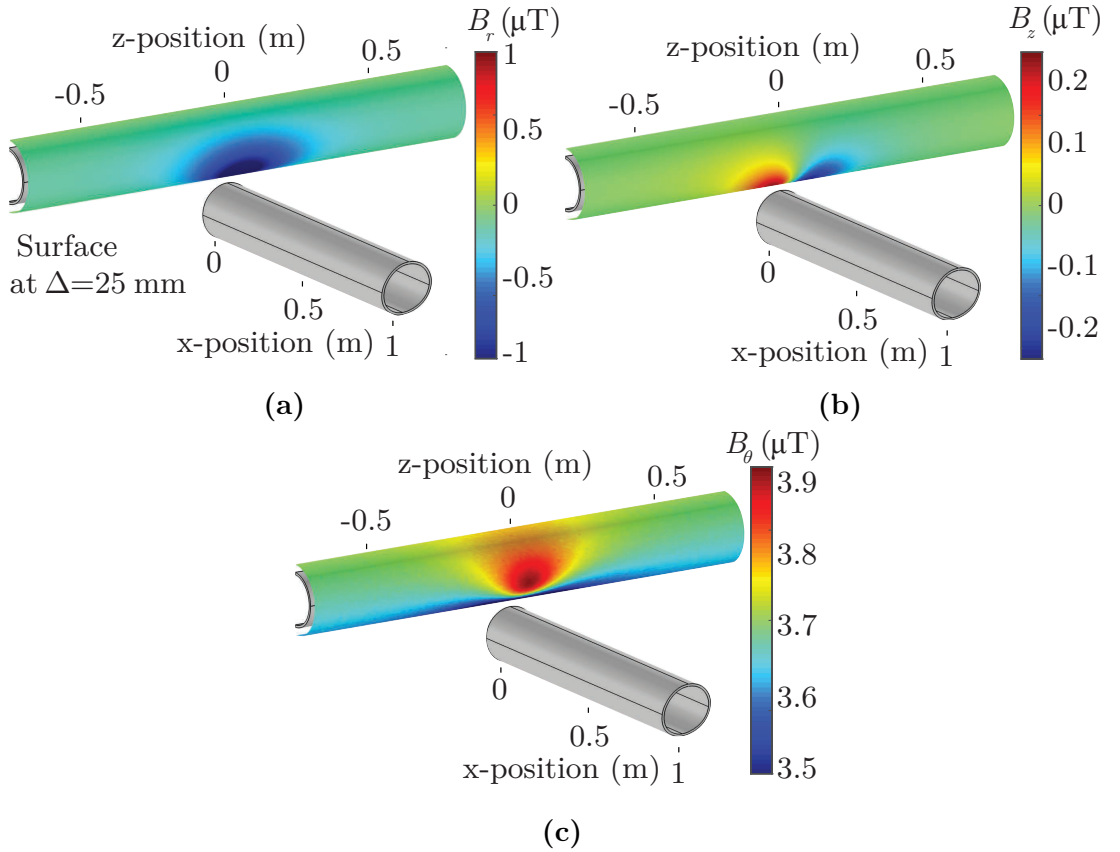


Figure 4.12: Perturbations of (a) B_r (b) B_z and (c) B_θ at 25 mm standoff from a 6" schedule-40 pipe carrying 2 A crossing above a pipe or support of the same dimensions. Minimum pipe separation is 50 mm.

Near to the crossing point, the induced magnetic field becomes greatly distorted (order of μT) by the bottom pipe. The magnitude of the perturbation exceeds that of a $3T \times 3T \times \frac{T}{3}$ outer wall defect for sensors that are axially located more than 1 m from the pipe crossing ($|z| < 1$ m). The magnetic field perturbation spreads out as the distance from its source increases and when $|z| > 0.5$ m, the spatial gradient of the components of $\mathbf{B}$ is low (< 10 nT variation over 50 mm). This suggests that a gradiometer formed by multiple sensors separated by less than 50 mm may be able

to suppress the perturbation due to the pipe crossing while preserving the defect signals local to the gradiometer that vary over a length scale comparable to the sensor separation (c.f. Fig. 3.6, page 59).

The model result suggests that external scanning will be very difficult within around 1 m of where a pipe crosses near to another pipe, or rests on a large ferromagnetic support. If the pipe is in electrical contact with the support (not considered in this model) the current distribution would also be disturbed, which would result in a further perturbation of $\mathbf{B}$. The current density in the remainder of the pipe would reduce after points in which current could escape, which would limit the test range by lowering the sensitivity to defects. This simple model has qualitatively highlighted potential limitations of the technique when scanning near pipe crossings or supports.

4.4 Pipe Bends

At a pipe bend the current will preferentially flow on the inner side of the bend as it offers the shortest path. Consider a coordinate system where $\hat{e}_z$ is defined as parallel to the pipe axis throughout the bend. The axial component of the current density J_z is much higher at the internal radius of the bend than at the external radius so the induced B_θ is also much greater on the inner side of the bend. B_θ is shown in Fig. 4.13c at 25 mm standoff from a 6" pipe with 2 A quasi-DC current, with a bend of 60° and bend radius of $1.5 \times$ the pipe outer diameter, OD. As the signal from current deflection is proportional to the current amplitude, the sensitivity is effectively increased by a factor of 2 at the inner radius while the sensitivity at the outer radius is decreased.

The axial and radial components of $\mathbf{B}$ which are identically zero on a uniform, defect-free section of straight pipe exhibit perturbations due to the bend. Figure 4.13b shows the quadripolar variation in B_z which is induced from the non-zero J_r caused by the current flowing towards the inner radius during the approach to the bend, and to the outer radius at the bend exit. A perturbation in B_r also results from the azimuthal current flow near the bend. For this bend geometry, the peak-to-peak variation in B_r and B_z and B_θ are 300 nT, 280 nT and 2380 nT respectively - orders of magnitude larger than the amplitude of the defects modelled in

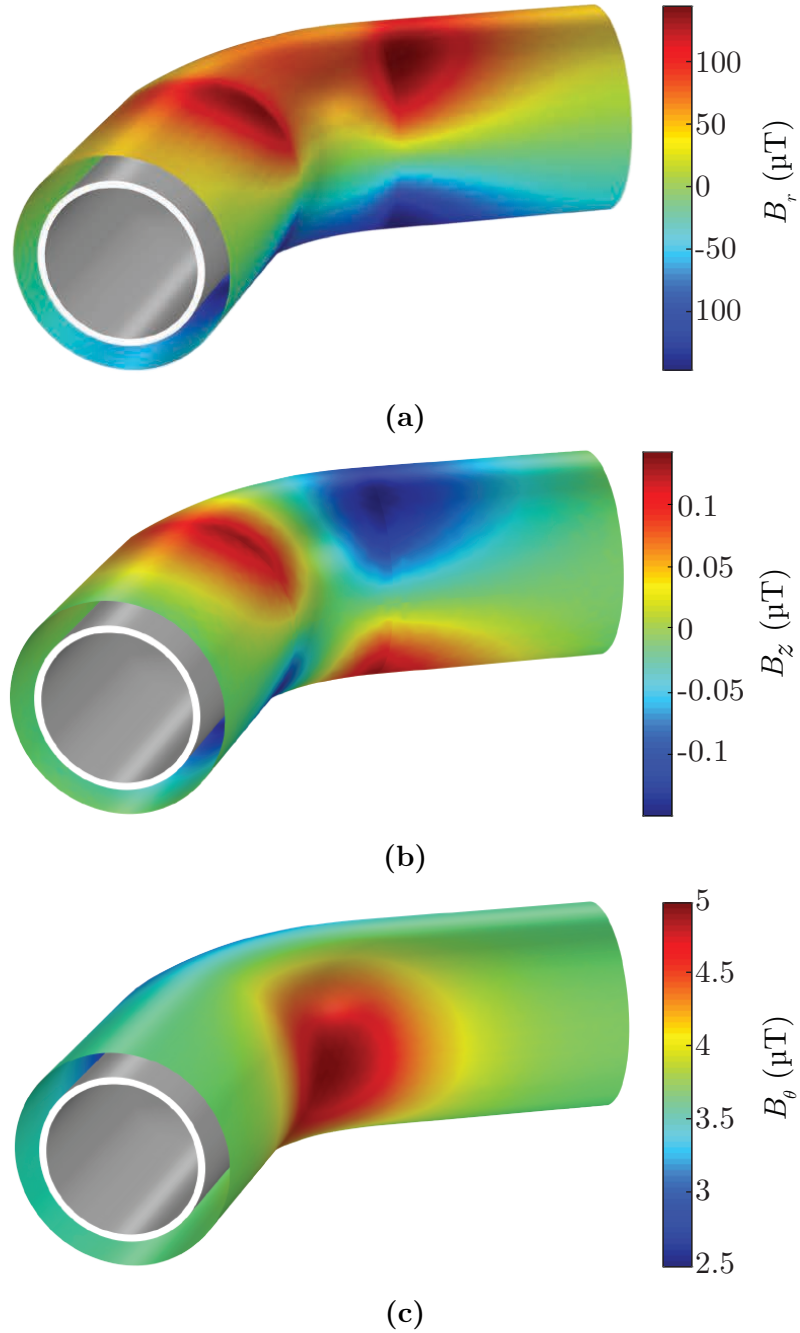


Figure 4.13: (a) Radial, (b) axial and (c) azimuthal components of $\mathbf{B}$ plotted on a surface at 25 mm standoff from a bended section of a 6" schedule-40 pipe carrying 2 A quasi-DC current (bend angle: 60° , radius: $1.5 \times \text{OD}$). The unit vector $\hat{e}_z$ points along the pipe axis.

the previous chapter. Various bend geometries were modelled with angles ranging from 5° to 90° and with radii of $3\text{--}6 \times \text{OD}$. The peak-to-peak variation in B_r , B_z and B_θ increased for bends of smaller radius and greater angles. For the shallowest bend of 5° with a bend radius of $3 \times \text{OD}$, the perturbations in B_r , B_z and B_θ were 50 nT,

44 nT and 311 nT respectively, rising to 330 nT, 300 nT and 2600 nT for a 90° bend with a bend radius of $1.5 \times \text{OD}$. To improve current deflection measurements taken near bends, it may be possible to suppress the perturbations in $\mathbf{B}$ caused by the bend by subtracting the results of an FE model for the same geometry so that only the response from defects remain; however, in practice this may be complex and time consuming to implement.

Maintaining sensor alignment on a sharp bend would also be challenging. The sensors must stay concentric with the intended measurement orientation of $\mathbf{B}$ because, if this were not achieved, the large B_θ may swamp defect signals in B_z or B_r . The issues discussed in this section must be considered when assessing the feasibility of scanning at a bend.

4.5 Seamless Pipe Noise

Two types of pipe are prominent in the petrochemical industry: seamless pipes that are extruded from a solid cylindrical steel “billet”, and seamed pipes that are manufactured by rolling a metal sheet into a tube and joining the seam with a weld. Seamless pipes can be manufactured by piercing the hot billet with a mandrel. Two offset tapered piercing rolls are positioned either side of the billet (Fig. 4.14). The rolls have the effect of drawing the billet forwards whilst deforming it into a rotating ellipse. The shearing force from the ellipse causes a crack to form in the centre of the billet which is forced over the pointed mandrel that sets the inner diameter of the tube. The outer diameter can then be reduced with further shaping rolls, or the inner diameter could be increased by passing the hot tube over an enlarged mandrel. This process is known as the Mannesmann process, and is able to produce tubes up to around 300 mm in diameter. For larger diameter pipes the similar “Stiefel process” is used which replaces the tapered rollers with large conical discs (Brensing et al. 2015; DeGarmo et al. 2003).

When analysing Magnetic Flux Leakage (MFL) data from seamless pipes a helical perturbation in the magnetic signal can often be observed. This has been referred to in the literature as “seamless pipe noise” (SPN), which is problematic as flux leakage from defects can easily be hidden, leading to an increased number of missed defects when pigging (Han 2008). The pipe wall thickness, magnetic property and

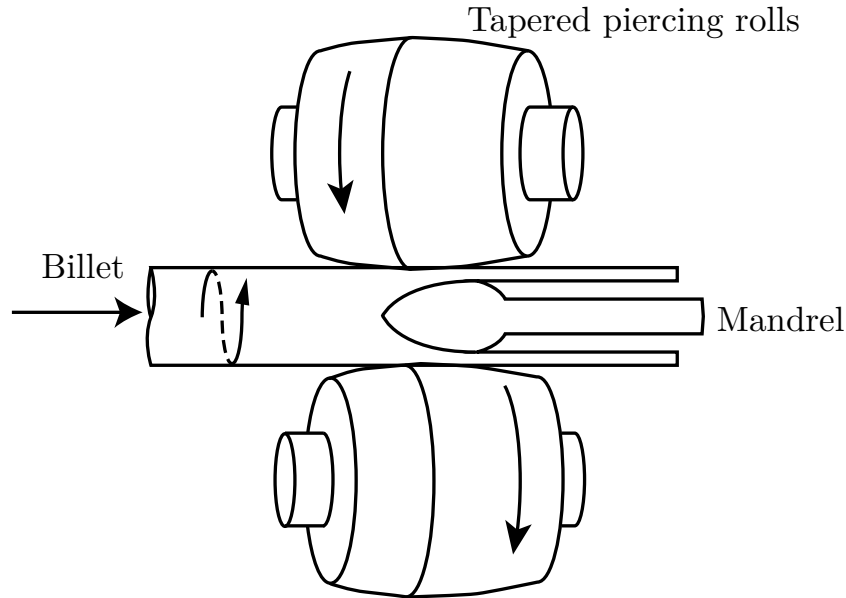


Figure 4.14: The Mannesmann process of manufacturing seamless steel tubes. (Adapted from DeGarmo et al. 2003).

micro-structure variations can all alter the path of magnetic flux, thus contributing to this SPN. Willcock et al. measured the magnetic and metallurgic properties as a function of position around the pipe circumference and found there to be no changes in magnetic properties associated with a four-cycle spiral variation in wall thickness that was associated with the tapered pipe rollers (Willcock et al. 1987). A weaker, single-cycle spiral variation in thickness (likely due to mandrel misalignment) was noted along with an associated change in both magnetic properties and pearlite fraction. Certain phases in steel are ferromagnetic, therefore a change in the relative composition of steel from the different ferromagnetic phases results in changes in magnetic properties (Willcock 1985). The mechanism of how the phase changes occurred during the manufacturing process still remains unclear.

Despite the lack of literature concerning the origins of SPN, a number of different algorithms have been proposed in order to correct for the periodic noise and considerably improve the detectability of defect signals (Afzal, Polikar, et al. 2001; Afzal and Udpa 2002; Han 2008); however, it was not clear how this noise would affect the current deflection technique which has comparatively higher standoff and lower magnetic field levels to MFL. The magnetic flux density surrounding a seamless carbon steel pipe was therefore mapped at standoff distances of 10 mm and 50 mm with a current frequency of 5 Hz and 25 Hz. The axial scanning interval was 5 mm

and the circumferential interval was 20° . The scan was later repeated at the same standoff, but with a much smaller sampling interval of 5° and 10 mm. The results from the scans at $\Delta = 50$ mm with 2 A, 5 Hz current are shown in Fig. 4.15, where the first scan (labelled “measurement A”) has been linearly interpolated to 5 times the scanning resolution to ease visualisation, and the second scan (“measurement B”) has not been interpolated. The figures clearly exhibit the periodic helical variation in **B** associated with SPN, most clearly seen in the axial component (Fig. 4.15b).

In addition to the SPN, there are also regions of increased intensity along the pipe axis centred around 0° and 180° in the radial and azimuthal components of **B** in Fig. 4.15 that can be attributed to the regions of increased wall thickness (shown previously in Fig. 4.2b, page 84). The low standard deviation in thickness along the pipe axis corroborates the fact that the high intensity region is not present in Fig. 4.15b as the current cannot be perturbed much in the azimuthal direction because the wall thickness exhibits very little variation along the pipe axis. Furthermore, the perturbations at the leftmost edge of Fig. 4.15b and Fig. 4.15c can be attributed to the spreading out of current from the injection points. The peak-to-peak amplitudes between measurements A and B are similar, showing good scan repeatability despite having modified the scanning system, and having moved to a new laboratory environment in the 15 months between the measurements. The discrepancies are likely due to slight alignment and standoff variations. A region of increased random noise is present in measurement B around 280° ; this signal is believed to be a measurement artefact.

An FE model was developed to further study the potential causes for the measured profiles of **B**. A pipe carrying 2 A was modelled, and an approximation of the measured thickness profile was incorporated into the model by applying the profile shown by the dotted line in Fig. 4.2b (page 84). A helix with its major axis lying along the pipe centreline and with a pitch of 350 mm was used to define a volume at the pipe outer wall that extended to a maximum depth of a third of the wall thickness, as shown in Fig. 4.16.

This volume was defined to have increased magnetic permeability to the surrounding metal, which had the effect of distorting the induced magnetic field by concentrating the magnetic flux. The values used for the relative magnetic permeability were based on measurements conducted on the pipe. A Fischer FMP30

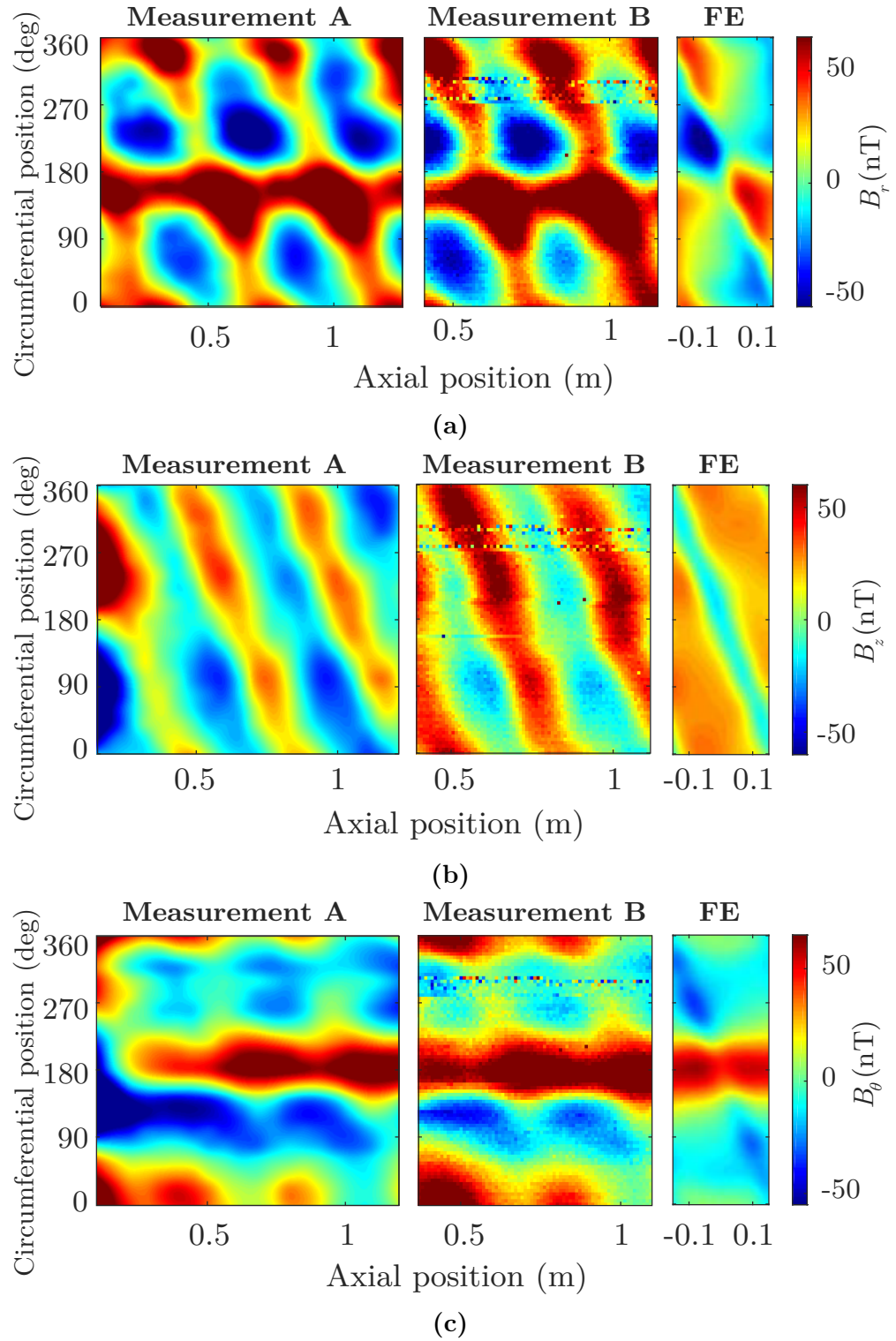


Figure 4.15: Spatial distributions of the (a) radial; (b) axial and (c) azimuthal components of the magnetic flux density measured at 50 mm standoff from a defect free seamless carbon steel pipe carrying 2 A, 5 Hz current. A: March 2015 scan (interpolated). B: June 2016 scan (not interpolated). FE: flux density prediction surrounding a pipe with helical inclusion of increased relative permeability (details in text).

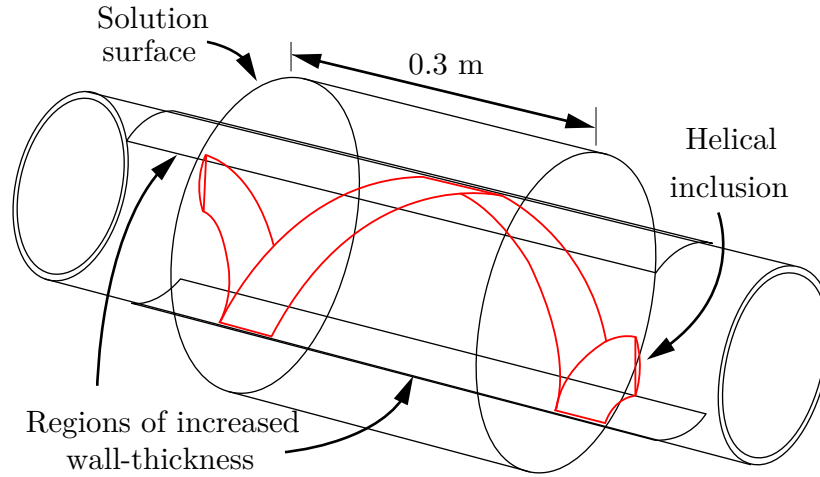


Figure 4.16: Schematic of FE model used to investigate seamless pipe noise. Solution surface at $\Delta = 50$ mm.

feritscope was used to measure the ferrite percentage (Fe%) over at least one period of the helical pattern in Fig. 4.15 (9 axial positions along a 400 mm section in the centre of the pipe at 72° azimuthal increments) and three repetitions were averaged. The measurement frequency of the instrument is 160 Hz, at which the skin depth is approximately 1.6 mm, so the permeability of just the upper layer of the material can be estimated. An empirical relationship from (Yin et al. 2009) was used to convert the measured ferrite percentages to relative permeabilities that could be applied to the FE model of the helical inclusion. The maximum and minimum values are summarised in Table 4.3, where the uncertainty on Fe% is the standard deviation and the uncertainty on μ_r was calculated using standard error propagation formulae.

Table 4.3: Maximum and minimum ferrite percentages of a seamless carbon steel pipe with relative permeability calculated following (Yin et al. 2009).

	Along Axis	Around Circumference
Max Fe%	78 ± 2	78 ± 3
Min Fe%	66 ± 2	65 ± 2
Max μ_r	125 ± 4	125 ± 5
Min μ_r	93 ± 3	91 ± 3

The measured Fe% varied between 65 and 78, which is similar to the range of 72.9 to 85.4 reported by (Willcock 1985) for a similar pipe material. Based upon the measured values, the relative magnetic permeability of the helical volume was set to

a value of $\mu_r = 125$ and the rest of the pipe to $\mu_r = 90$. The FE model was solved and the resulting perturbations in the components of $\mathbf{B}$ are shown in Fig. 4.15 where the spatial and colour scales used are the same as for the plots of the measured data. The features present in the FE results match those present in the measured data, particularly the diagonal striping and the high intensity regions in B_r and B_θ due to the wall thickness profile. The absolute amplitude changes appear smaller in the FE result, which is likely due to uncertainty in the feritscope measurement or the shape of the helical inclusion used in the model. The contact feritscope probe records at a single point on the pipe surface where μ_r may be locally inhomogeneous; however, $\mathbf{B}$ is shown here at $\Delta = 50$ mm where local variations in μ_r will have become smeared. This FE model suggests that local variations in the magnetic permeability are the probable cause of the features noted in current deflection scans of seamless pipe. It is also possible that an electrical conductivity variation in the helical region could also result in a similar magnetic profile, as it would perturb the current in the pipe that induces the magnetic flux density being measured; however, the variation in conductivity within a single steel sample is typically low in comparison to magnetic permeability.

4.5.1 Relative Permeability Measurements Using Eddy Current Techniques

Eddy current testing is capable of distinguishing whether the magnetic response of a material is predominantly due to electrical conductivity or magnetic permeability variations, as these are the two most important physical parameters of conducting materials that directly affect the eddy current response. Eddy current probes are highly sensitive to conductivity variations at high frequencies, whereas the effect of permeability on the impedance of the probe coil is less strongly dependent on frequency and dominates at low frequencies. Faraday's law also states that the induced eddy current amplitude is greater for a faster rate of change of flux. These factors mean that the amount that the magnetic permeability affects the apparent eddy conductivity decreases approximately proportionally to the square root of frequency (Nagy 2011). These effects are illustrated in Fig. 4.17 which shows the complex impedance plane on which the response of the eddy current probe is visualised during testing.

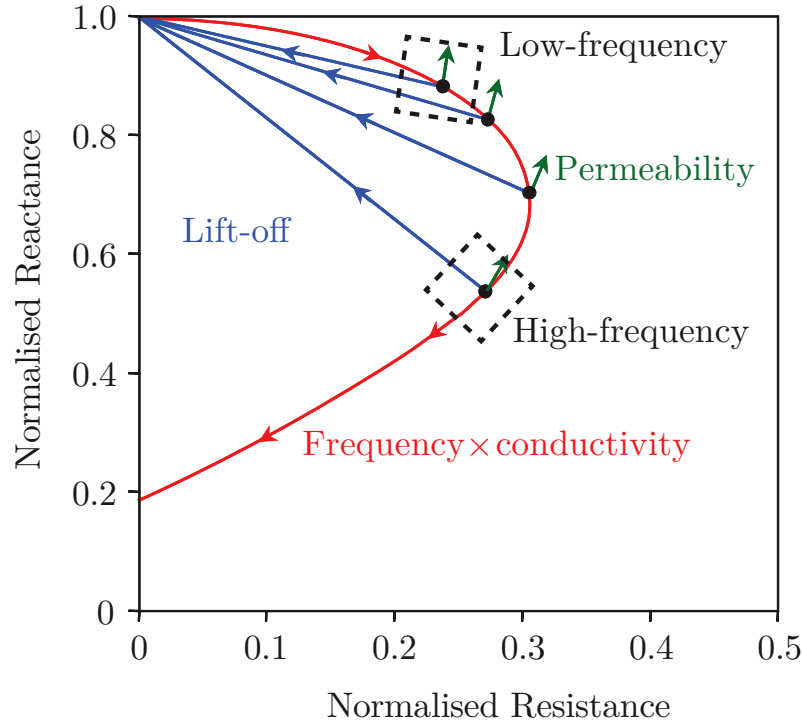


Figure 4.17: A schematic diagram of the complex impedance response of an eddy current probe coil. The coloured arrows show the trajectory of the probe response to a change in conductivity, frequency, probe lift-off or magnetic permeability. Four example cases have been plotted at different frequencies (or conductivities). (Reproduced from Nagy 2011).

On Fig. 4.17, the dotted boxes represent the section of the impedance plane visualised during testing. The box orientations differ because the phase angle is often altered in order to separate the effects of lift-off (standoff in “eddy current terminology”) from the apparent conductivity. In eddy current equations, the electrical conductivity is always multiplied by a coefficient of frequency, so frequency and conductivity variations result in the complex impedance response of the probe following the same trajectory indicated by the red arrows. At high frequencies, the impedance response of the coil is dominated by conductivity variations, and an increase in the magnetic permeability will appear as a small decrease in the apparent conductivity. The probe lift-off trajectory (blue arrows) is out of phase with these two effects, so it can easily be suppressed.

An increased magnetic permeability affects the complex impedance in two ways. Primarily, it increases the magnetic flux density in the coil itself which results in an increase in the reactance of the probe coil. Secondly, it reduces the penetration depth of the secondary eddy current in the material which changes the total flux

crossing the probe coil and results in an increase in resistance. The primary effect is independent of frequency but the secondary effect is proportional to frequency which explains why the green arrows in Fig. 4.17 rotate clockwise with increasing frequency. At low frequencies (typically less than a few hundred Hz), the primary effect dominates and the permeability variation has a relatively large influence on the coil impedance compared to the conductivity. The permeability trajectory is now out of phase with those due to lift-off and conductivity variations; however, this higher selectivity to permeability comes at the cost of lower absolute sensitivity and an inability to separate the effects of lift-off and apparent conductivity.

With respect to the study of SPN, this means that an eddy current test conducted at a low frequency, where the instrument is insensitive to conductivity variations, could determine whether the source of the helical pattern in the magnetic field is due to local variations in the magnetic permeability. A manual scan path of 700 mm along the pipe axis was performed using a Nortec 2000S system, which covered two periods of the helical variation. The probe with the largest coil available was used (15 mm diameter pancake coil) as lift-off effects are difficult to control in smaller probes. In the manual test, the curvature of the pipe meant that lift-off effects were difficult to suppress so the scanning frame was modified to hold the eddy current probe so the lift-off could be well controlled. This is shown in Fig. 4.18 where the probe was spring-loaded against the pipe surface, and a 1 mm protective cap was placed over the probe to ensure the coil was not damaged. The coil voltage data was stored automatically via a LABVIEW interface.

A scan of the pipe surface with an axial resolution of 5 mm and circumferential resolution of 5° was completed at frequencies of 220 Hz, 10 kHz and 30 kHz. The phase angle was adjusted such that the horizontal voltage corresponded to the trajectory of the lift-off. The results can be seen in Fig. 4.19 where the two higher frequency scans have been averaged to reduce noise. The gain was adjusted so that the full voltage range was used, although unintentionally the positive voltage saturated at a number of points in Fig 4.19b. The colour scale has been omitted as the voltage was not calibrated to give absolute values of μ_r ; however, the colour scales of the figures have been approximately matched based upon the maximum and minimum recorded signals, to aid comparison.

The electrical conductivity variation in a steel pipe is expected to be low, so it

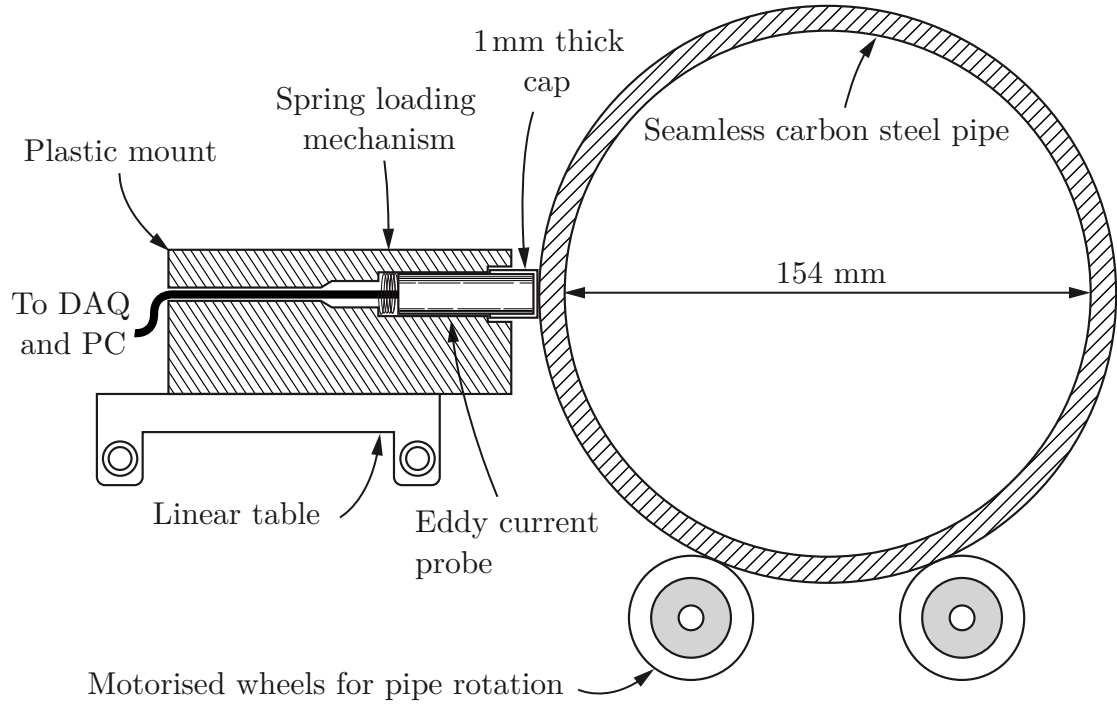


Figure 4.18: Schematic of scanning frame used for mapping permeability and conductivity in a seamless carbon steel pipe.

can be concluded that the pattern in Fig. 4.19 is due to variations in the magnetic permeability. This is further justified by the fact that a similar distribution in the eddy current voltage can be seen in the scans completed at both high and low frequencies, which appear distributed as a helix with the same ~ 350 mm pitch as seen in the **B** scans of Fig. 4.15. There is a feature present between 90° to 135° in 4.19a that is not in 4.19b which corresponded to a strip of oxidised steel on the pipe outer surface. This likely resulted in a lift-off variability that registered a vertical voltage signal in the low-frequency measurement where lift-off and apparent conductivity effects can not be fully separated.

This study has investigated the influence of SPN on current deflection measurements. The peak-to-peak of the variations in **B** from the SPN are of the same order of magnitude as the current deflection signals resulting from a $3T \times 3T \times \frac{T}{3}$ outer wall defect; therefore, it is important that the noise can be suppressed if current deflection NDE is to be applied successfully to flaw detection on seamless pipes by scanning. A literature review and subsequent finite element modelling suggested that the noise was due to variations in the relative permeability caused by the pipe manufacture process. This was subsequently confirmed with eddy current testing.

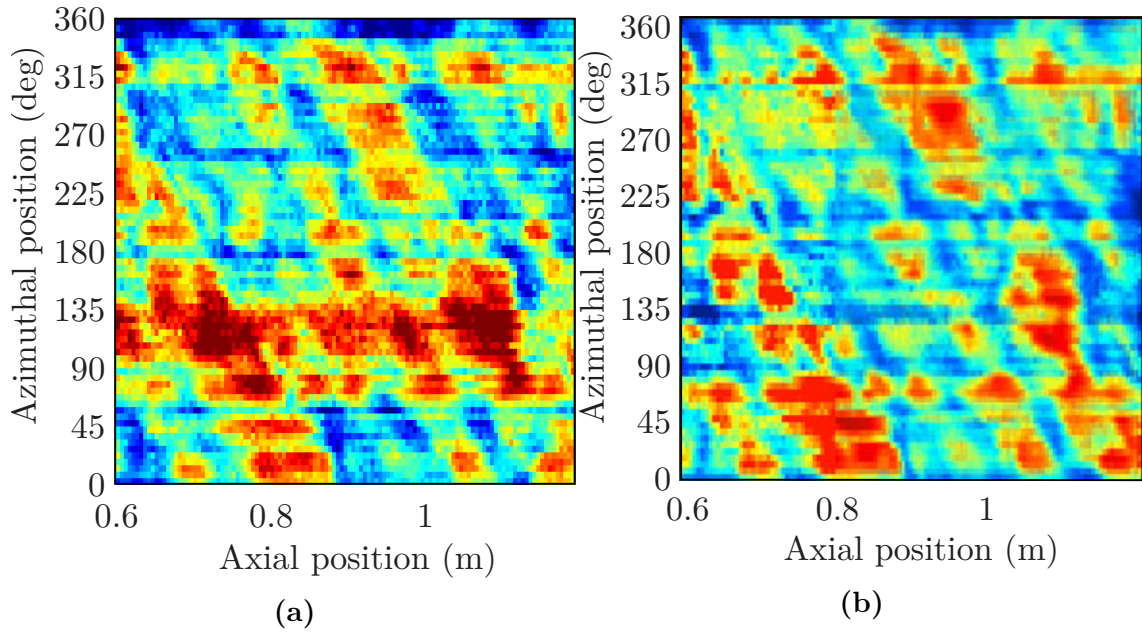


Figure 4.19: Eddy current scans of seamless carbon steel pipe taken at (a) 220 Hz and (b) average of the scans at 10 kHz and 30 kHz. The amplitude scale is arbitrary, although the colour scale of the figures has been approximately matched to ease comparison. (Figure may be clearer if viewed on screen).

As the noise originates during pipe manufacture, the spatial distribution of SPN should not change over time so it should have little effect on the sensitivity of a current deflection SHM solution using permanently installed sensors.

4.6 Effect of Movement during Acquisition

As explained in the previous chapter, phase-sensitive detection is a requirement in order to attain sufficient sensitivity to the weak magnetic signals from current deflection. This involves interrogating the sensor for a number of measurement cycles to attain a satisfactory signal-to-noise ratio. This averaging time is dependent on the frequency of inspection and the noise density of the sensor. For carbon steel pipes with a wall thickness around 10 mm, 1 Hz current is often required for quasi-DC behaviour, which demands an averaging time of 1 s to 10 s (for the selected AMR sensors, Fig. 3.9, page 3.9).

In the laboratory tests, the sensor remains stationary during acquisition which enables a high-resolution map of the magnetic flux to be obtained, but this is only feasible due to the lack of time constraints on the measurement. In the field, the

sensor could be moved between stationary measurements, but a simpler scanner would instead be moved at a constant speed along the pipe which would cause the received magnetic signal to be averaged over the distance in which the sensor moved during acquisition. Two extreme cases were considered, one in which the averaging begins when the sensor is directly over the defect, and the other in which the sensor passes over the defect during the scan which has a total length a , as shown in Fig. 4.20a. The maximum scanning speed v will be restricted by the required averaging time (dictated by the noise level), and the reduction in the axial resolution of the signal that can be tolerated while still being able to detect the defect.

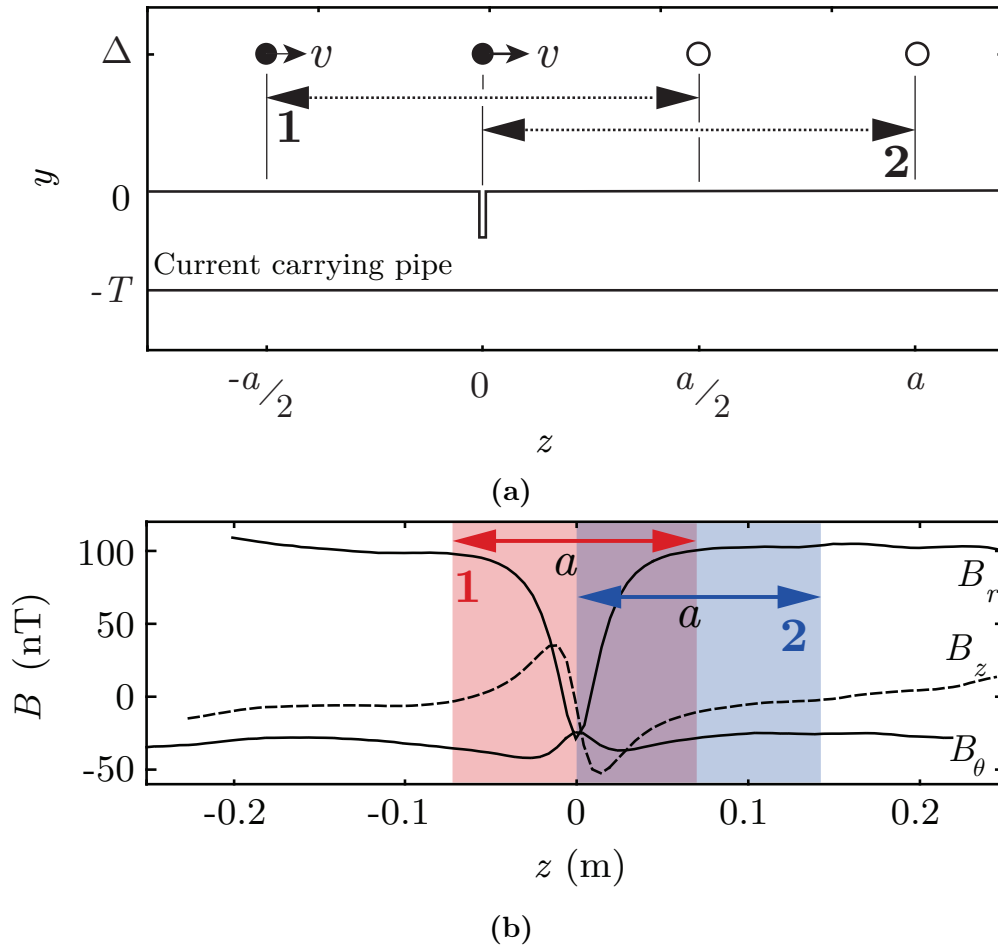


Figure 4.20: The sensor moves from the start position (closed circle) to the finish position (open circle) at a constant speed v . Two measurements are illustrated in (a), **1** where the defect is in the middle of the scan path or **2** for when a scan path of length a begins at the defect centre ($z = 0$). In case **1**, the magnetic flux density profile (measured at $\Delta = 10$ mm above a 2 mm wide $\frac{T}{2}$ flat-bottomed slot) shown in (b) would be averaged over the width of the red area, a . In **2** it would be averaged over width of the blue area.

As the sensor moves at a constant speed, the smearing effect can be studied by averaging the defect profile (measured using finely sampled stationary measurements) over the scan length. This is practically simpler than taking multiple measurements for different scan lengths as the spatial distribution of the defect can be obtained in a single measurement (as shown in Fig. 4.20b) or FE model. In order to prove that these two scenarios are equivalent, a sensor was interrogated during axial paths of various lengths that passed over the edge of a defect, as shown in Fig. 4.21. A scan path passing over the azimuthal centre over the defect was not chosen, as B_z and B_r are identically zero here (for clarity on this statement, see Figs. 3.6a and 3.6b, page 59). The result was compared to the average of the magnetic flux density profile over a distance a , as illustrated in Fig. 4.20b.

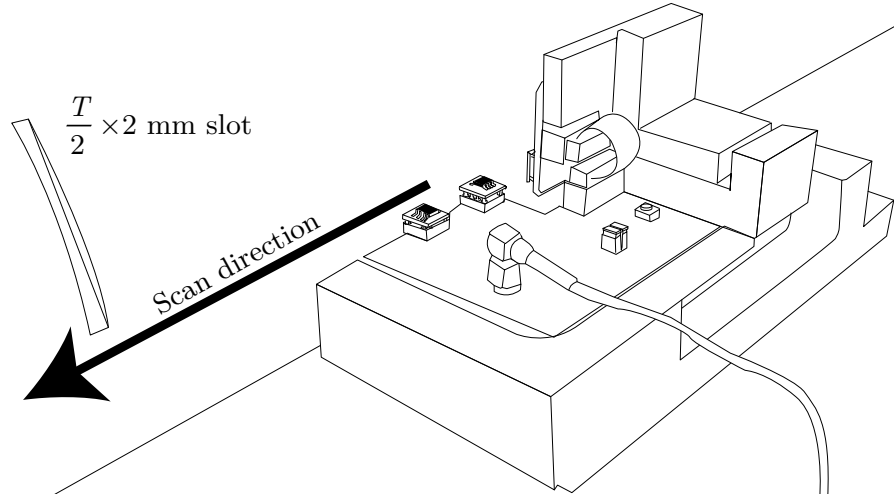


Figure 4.21: Scan path of sensor array relative to $\frac{T}{2}$ flat-bottomed slot.

The perturbations in Fig. 4.20b centred at $z = 0$ mm are due to current deflection from the 2 mm wide $\frac{T}{2}$ flat-bottomed slot. Figure 4.22 shows the comparison of the measurements acquired with a sensor moving a distance a in 20 s to those generated by averaging the $\mathbf{B}$ profile over the same distance a . There is good agreement between the dashed and solid curves, demonstrating their equivalence.

The curves in Fig. 4.22 tend to the baseline values of each component of B shown in Fig. 4.20b, so the maximum deviation from the baseline (i.e. the signal) is recorded with a point measurement or an averaging distance of $a = 0$ mm. B_z shows very little deviation from the baseline value because, unlike B_r and B_θ , the perturbation is almost entirely antisymmetric about the defect centre, so the positive and negative excitation from either side of the defect will cancel one another. In

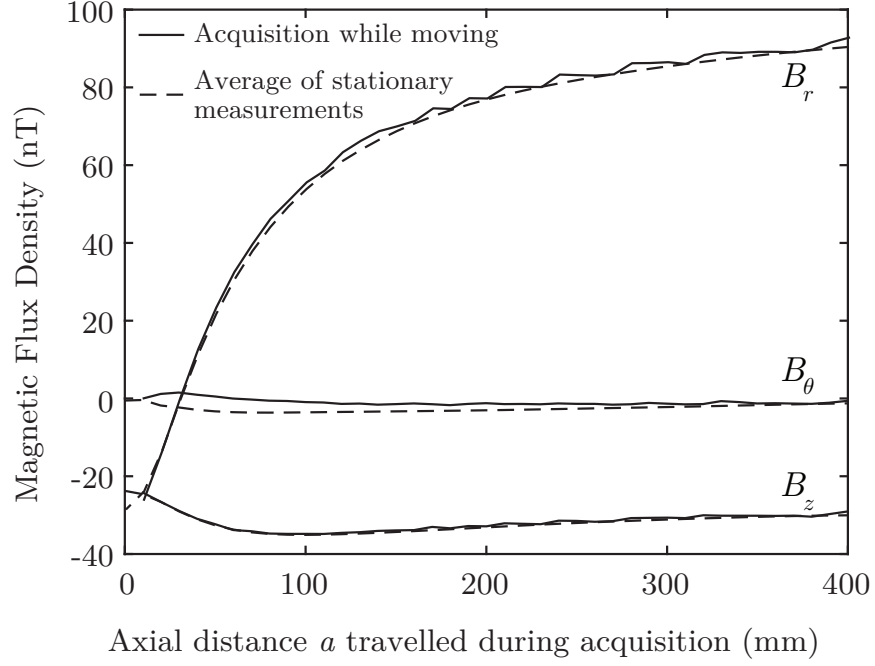


Figure 4.22: Taking multiple scans of different lengths at $\Delta=10$ mm above a 2 mm wide $\frac{T}{2}$ flat-bottomed slot is equivalent to averaging many stationary measurements over a distance a .

this case, where $\Delta = 10$ mm, the perturbation in B_r when $a = 65$ mm is half of the amplitude from the baseline compared to when $a = 0$ mm. Assuming an averaging time of 1 s, this corresponds to a measurement speed of 65 mm s^{-1} .

A validated FE model of the scenario shown in Fig. 4.20a was used to study the effect of other parameters such as the standoff on the measurement speed. The trajectory of the scan was in the axial direction and over the edge of $3T \times 3T \times \frac{T}{3}$ defect for the radial and axial components of $\mathbf{B}$ and directly over the defect for B_θ . To analyse how much the movement of the sensor could reduce the sensitivity, the average of the magnetic flux density components over a were then normalised to their maximum amplitude, which is equivalent to a stationary sensor positioned in line with the defect for B_r and B_θ ($a = 0$). For B_z , the signal is antisymmetric about the defect centre, so the maximum value occurs in the region $0 < a < 0.1$ m. In figures 4.23a-4.23c, the perturbation is more diffuse at higher standoff, causing the signal amplitude to reduce more slowly with increasing a . This result seems to indicate that faster movement would be permitted at higher standoff; however, the signal is also a lower amplitude here, so a longer averaging time may be required to achieve a satisfactory signal to noise ratio for the weaker signal which may negate

the apparent increase in speed.

The dashed and solid lines in Fig. 4.23 show the two extreme cases of when the sensor interrogation begins directly above the defect (solid lines), or when the defect is directly at the centre of the distance travelled during acquisition (dashed lines). Figure 4.23a and 4.23c show that the signal amplitude drops almost twice as quickly with a for scenario 1 because the average distance from the sensor to the defect over the scan is twice as large as for the scenario 2. Averaging while moving will have the effect of reducing the axial scan resolution so features with axial antisymmetry such as B_z signal will often be completely suppressed if the averaging distance a is much larger than the axial extent of the signal. This is the reason why the amplitude of scan 1 is zero in Fig. 4.23b.

This study has illustrated the factors that should be considered when determining the maximum scanning speed. As is common in NDE, there is a compromise between sensitivity or resolution and scanning speed. It is not possible to determine the exact speed limits of a scanning system as it will be dependent on the standoff, current amplitude, defect geometry, ambient noise level etc.; however, some assumptions can be made for a typical scenario to give an order of magnitude estimate. Assume that the signal from a $3T \times 3T \times \frac{T}{3}$ defect could be detected with a 1 s averaging time at $\Delta = 25$ mm, and the current amplitude meant the defect signal strength were high enough that a 50 % reduction in amplitude due the sensor movement could be tolerated. The maximum scanning speed in this case would be around 100 mm per second.

4.7 Sensor Alignment

The previous sections in this chapter have demonstrated that the signal measured outside the pipe consists of not only contributions from current deflection from defects, but also from spurious signals that arise from changes in the current distribution due to slight wall thickness changes, pipe features, external ferromagnetic objects etc. As these effects often vary over a much longer wavelength than the defect, they can be effectively suppressed by combining the measurements from multiple sensors to form a gradiometer. This principle has successfully been applied to detect magnetic anomalies in geophysics (Beiki et al. 2012; Z. Li, Dixon, Cawley,

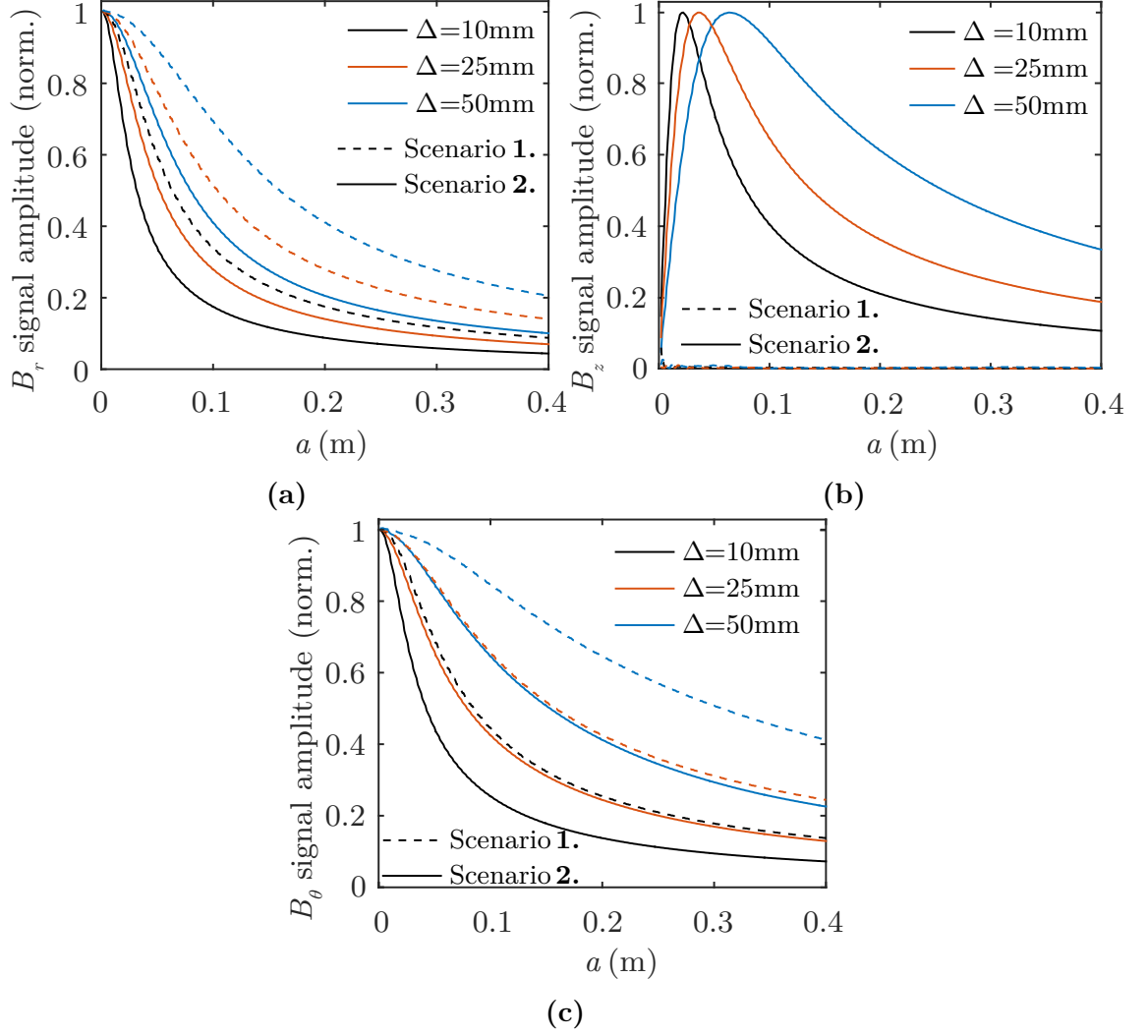


Figure 4.23: Predicted amplitude of a signal received by a (a) radially, (b) axially (where scenario 1 is at zero amplitude.) or (c) azimuthally oriented sensor moving at a constant speed in an axial scanning path of length a above the edge of a $3T \times 3T \times \frac{T}{3}$ outer wall defect. Signal has been normalised to the maximum amplitude. The scenario numbers correspond to those shown in Fig. 4.20a.

Jarvis, and Nagy 2017), and to locate ferromagnetic targets in the presence of the geomagnetic field (Gang et al. 2016; Janošek et al. 2016). Recently, the concept has been adapted for magnetic NDE of pipelines (Song et al. 2017). In the current deflection method, the static geomagnetic field is suppressed by using alternating current injection and sensing; however, the injected current in the pipe induces a large azimuthal component which could saturate the sensors and mask the defect signal if any misalignment were to occur during the scan. A second-order gradiometer is proposed to suppress the slowly varying magnetic signals, and to reduce the severity of errors due to sensor misalignment.

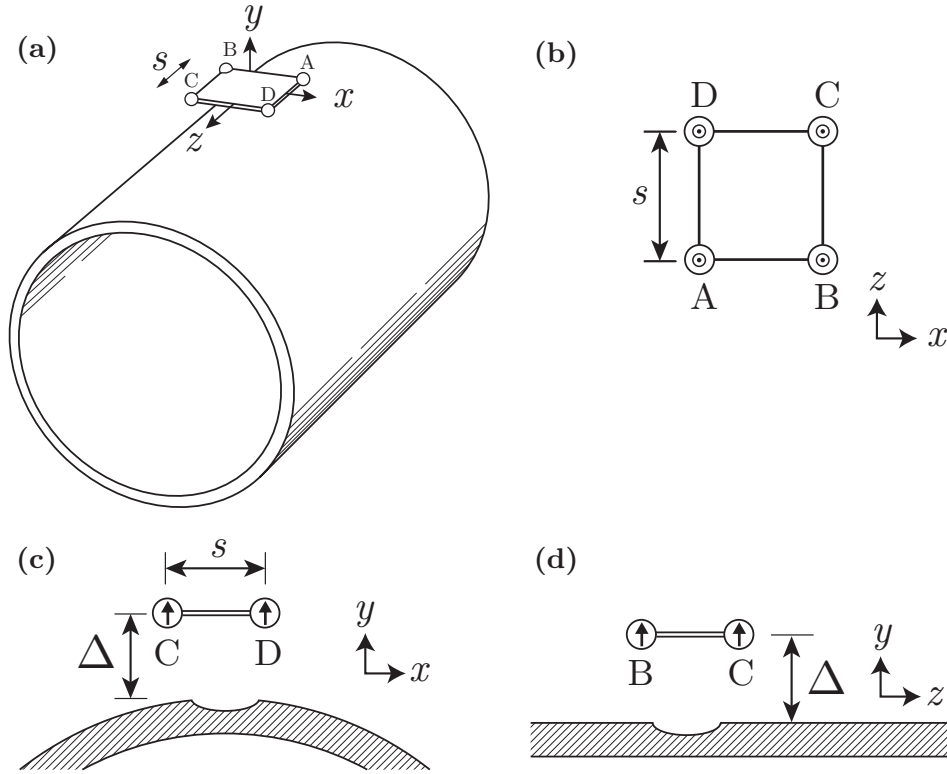


Figure 4.24: Schematic of 2nd order gradiometer sensor configuration. Sensors shown are radially oriented. (a) 3D view (b) top-down (c) slice through axis, (d) slice along axis.

Magnetic vector sensors are positioned at each corner of a square as shown in Fig. 4.24 where the constituent sensors are oriented to detect the radial field. Note that a local co-ordinate system (x, y, z) with origin in the centre of the gradiometer is used in addition to the global co-ordinate system of the pipe (r, θ, z) where y is approximately aligned with r and x with θ . The measured quantity is the second-order gradient of the field with respect to x and z . Using a finite difference approximation,

the gradient at the centre of the gradiometer is given by

$$\frac{\partial^2 B_\alpha}{\partial x \partial z} s^2 \approx B_{\alpha,A} + B_{\alpha,C} - B_{\alpha,B} - B_{\alpha,D} \quad (4.1)$$

where $\alpha = x, y$ or z , s is the sensor separation and the subscripts A-D refer to the different sensors shown in Fig. 4.24. The gradiometer is more effective at suppressing misalignment errors at higher standoff as the azimuthal field drops with $\frac{1}{r}$. In all of the results presented in this thesis, the scans were completed with single sensors and the gradiometer was formed synthetically which allowed the parameter s to be investigated without needing to manufacture multiple sensor arrays. In the field, however, a scanning system offering precise sensor positioning would likely not be possible, so the gradiometer must be formed with hardware. Hardware subtraction is only effective if the sensitivity of each constituent sensor is matched. Sensitivity variation can be caused by thermal gradients, sensor ageing, nonlinearity etc.; for the chosen sensors, this can usually be confined to less than 1% (Sensitec MagnetoResistive Sensors 2011). The gradiometer will enhance signals whose peak locations are separated in either x or θ by the the sensor separation, s , while simultaneously suppressing signals whose amplitude varies on a length scale much greater than s . This will be investigated in more detail in a later section.

4.8 Conclusions

This chapter has explored a variety of factors that have potential to contribute to the signal measured using current deflection NDE. Firstly, the magnetic signal due to slight wall thickness variations within the manufacturing tolerances of a number of pipes was investigated. Mapping the wall thickness of sections of steel pipe revealed a thickness variation that was stronger in the circumferential direction than in the axial direction. This conclusion, which was true for both seamless and longitudinally seam-welded pipes, prompted the development of a 2D FE model which revealed that the distribution of current in a pipe of non-uniform thickness could cause variations in the magnetic flux density that are similar in magnitude to the current deflection signals from defects. A study into the roughness of a semi-ellipsoidal defect revealed that the roughness perturbation is only significant at a low standoff. The perturbations in $\mathbf{B}$ due to roughness diffuse with standoff and the

signal from a rough defect resembles that of a smooth one of equal volume.

Ferromagnetic objects concentrate magnetic flux and, if located near the sensors, could cause field perturbations that may be misinterpreted as defects. An FE study showed how this effect could potentially result in false positives if an object such as a steel nail were located near (tens of mm) to the sensor. The influence of a much larger ferromagnetic object such as a pipe was modelled which revealed that the distortion caused by flux concentration is likely to significantly impair the sensitivity when the sensors are around 1 m from the interfering object. An additional numerical model implied that scanning would be difficult near a bend in the pipe due to perturbations in $\mathbf{B}$ because of the redistribution of the current caused by the bend. Grounded pipe supports or earth connections would limit the distance between current injection points.

Measurements of the induced $\mathbf{B}$ surrounding a current-carrying seamless pipe revealed a signal that was distributed in a helix. It was discovered through a literature review that this signal is known as “seamless pipe noise” and subsequent testing revealed that it is due to variations in the magnetic permeability that likely occur during the pipe manufacture process. The amplitude of this signal is similar to that expected from current deflection around defects, which implies that the scanning of seamless pipes will be difficult. A number of algorithms for the suppression of similar signals exist, and future investigation into their performance with respect to current deflection signals would be beneficial, however this was out of the scope of the current work.

The use of phase-sensitive detection at low frequencies (0.1 Hz to 10 Hz) demands a relatively long (order of seconds) acquisition time. Movement of the magnetic sensors during this time will reduce the measurement resolution in the direction of movement. This effect places a speed limit on the scan whose amplitude will be determined by how much of a reduction in resolution can be tolerated in order to sustain an acceptable performance. The instability of the sensor orientation throughout the scan has potential to limit sensitivity due to the large azimuthal field polluting the other components of $\mathbf{B}$ where small changes due to defects are expected.

The effects discussed so far are all detrimental to the technique performance and should be suppressed. In certain cases this can be achieved by combining multiple

sensors to form a gradiometer. For example, the interference in $\mathbf{B}$ that results from deviations in wall thickness within manufacturing tolerances varies more slowly with axial position than the expected perturbation from a $3T \times 3T \times \frac{T}{3}$ defect; therefore, it can be suppressed with a gradiometer. The gradiometer also removes the large azimuthal signal and enables suppression of the noise due to misalignment of the sensor throughout the scan.

Many of the practical challenges explored in this chapter are problematic because they produce a signal that varies as the sensor is moved. Provided they are stable, permanently installed sensors are not affected by spatial variations in $\mathbf{B}$, so techniques such as baseline subtraction would leave an SHM method unaffected by each of the discussed effects that are not expected to change over time (e.g. bends, SPN, thickness variation at pipe manufacture). The suitability of current deflection as an SHM solution will be explored in a later chapter, while the following chapter analyses the performance of the technique in scanning mode by considering how the concepts introduced here might contribute to a practical test.

5 | Performance Evaluation of Current Deflection Scanning using a Model Assisted Probability of Detection Framework

5.1 Introduction

The results presented in chapter 3 suggested that current deflection from defects in a pipe could be detectable using AMR sensors at around 50 mm standoff using a few amps of injected current. However, before any NDE technique can reliably be implemented for general use in an industrial setting, its performance must first be rigorously studied.

The most common metrics of performance for NDE techniques are the expressions of the Probability of Detection (POD), which describes the likelihood of correctly identifying a defect, and the Probability of False Alarm (PFA), which describes the probability of labelling an undamaged area as defective. The Receiver Operating Characteristics (ROC) method expresses both the POD and PFA as orthogonal axes of the same graph and is a convenient way of illustrating the performance of an NDE technique (Swets 1983).

Traditionally, ROCs have been determined entirely empirically by manufacturing test pieces containing artificially produced defects of interest that increase in size or depth (Knopp et al. 2007). The number of test pieces must be large enough to account for statistical variability and the scatter in measurements that may be expected in a practical setting, e.g. due to changing Environmental Operating Condi-

tions (EOC), must be accounted for. Blind tests are then performed which determine the POD and PFA accordingly. The manufacture and subsequent examination of a large number of test pieces with different defect morphologies over different EOC is expensive and time consuming. Due to the rapid advancement of computing power in the last decade, Finite Element (FE) modelling now permits a very accurate and rapid prediction of the signal from a large number of defect geometries; therefore, there have been efforts to use Model-Assisted Probability of Detection (MAPOD) to generate POD and ROC curves more quickly and efficiently. Multi-parameter POD studies can be completed, and even a “volume POD” can be created that encompasses all possible test parameters (Carboni et al. 2012; Knopp et al. 2007; C. Liu et al. 2017; Müller et al. 2009).

A framework for efficiently generating the ROCs of practical Structural Health Monitoring (SHM) applications has been presented by Liu et al. (C. Liu et al. 2017). In their proposed methodology, experimental data is collected for an undamaged structure over multiple EOC onto which synthetic damage signals are added by superposition. Decoupling the effects of environmental variations and damage growth on the received signal allows the performance of a permanently installed SHM system to be evaluated in a practical setting. Although this framework was designed for the evaluation of SHM techniques, a similar principle can be applied to predict the performance of one-off inspections. In this chapter, the performance of current deflection NDE for defect detection by scanning will be evaluated with this method.

As the signal from current deflection can easily be predicted using numerical modelling techniques, the key challenge is to establish a realistic estimate of the magnetic signal due to *everything but* the defect to capture the variation in the signal that may be expected in a practical scan. In Liu’s framework, different EOC were the key drivers for signal variation so measurements of an undamaged structure were taken at a range of temperatures; however, for the current deflection technique, the following effects (most of which have been individually discussed in the previous two chapters) contribute to the measured signal:

1. sensor and electronics noise;
2. temperature effects;

3. variations in magnetic permeability (μ) within the pipe, or nearby ferromagnetic objects causing distortion of the induced field from the injected current;
4. electromagnetic interference e.g. mains/line frequency at 50/60Hz;
5. variations in current distribution due to slight geometry changes in the pipe from the wall thickness varying within manufacturing tolerances,
6. current distortion from non-critical general pipe corrosion.
7. misalignment of magnetic vector sensors during a scan

The amount by which each of these factors contributes to the total scan signal can be determined from a mixture of experimental and FE analysis. FE can be used where there is confidence that it is representative of a true practical scenario, and for all other cases, experimental measurements of an undamaged structure must be taken. A variety of defect signals can then be superposed onto the undamaged structure signals (a combination of measurement and FE) to give different defect scenarios with varying severity, position etc. which include the measurement variations seen on an undamaged structure. The undamaged structures for these scans should be similar in condition, material and geometry to the structure on which the desired NDE technique is to be used. The flowchart in Fig. 5.1a represents the initial data collection of the undamaged structure signals, FE contributions to the undamaged structure signal, and the synthetic defect signals. Figure 5.1b outlines how each of these data are used to generate an estimate of the ROC.

The chapter is structured as follows. The synthetic scan is first introduced in section 5.2.1, with subsections outlining how each of the contributions to the scan are obtained. Section 5.3 then outlines how a detection algorithm is applied to the generated scan to obtain ROC curves, which are then presented in section 5.4 for a number of potential scan configurations. The discussion and conclusions then follows in section 5.5. This chapter mostly comprises work that has been published in *NDT & E International* (Jarvis et al. 2017a) (open access and licensed under CC BY).

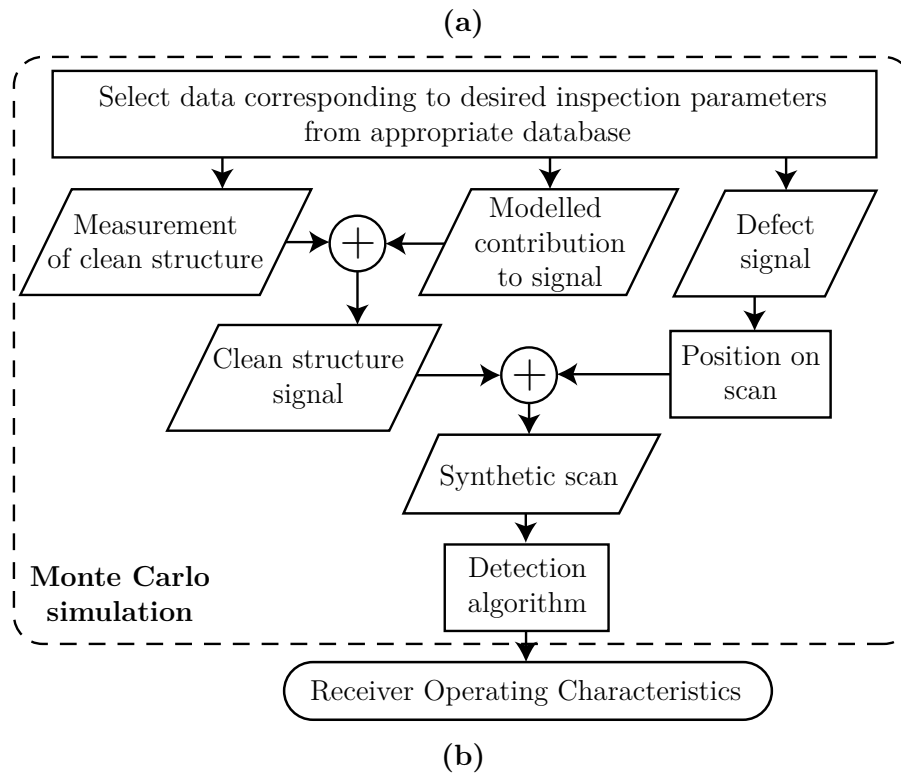
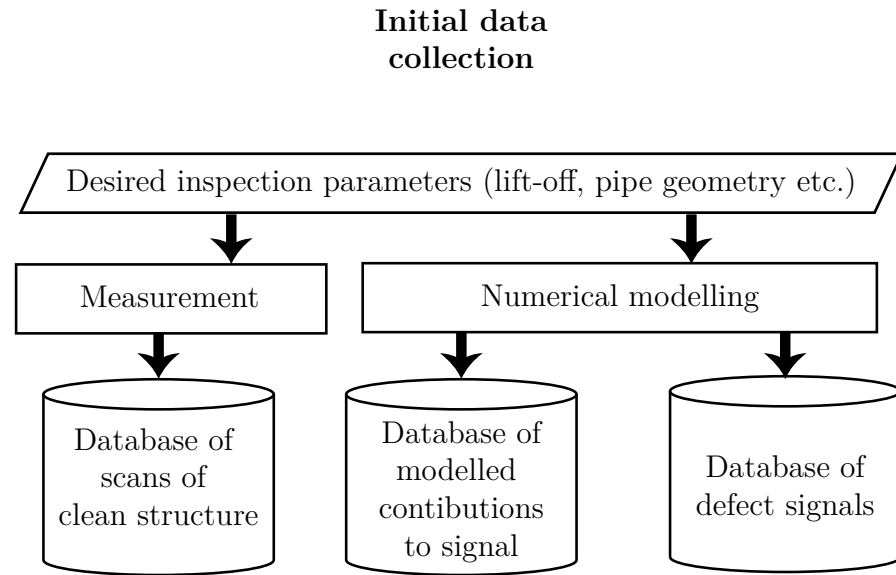


Figure 5.1: Flowcharts for (a) data collection and (b) the model-assisted ROC prediction for low frequency current deflection.

5.2 Constructing the Synthetic Scan

5.2.1 Contribution from Scan of Undamaged Structure

Longitudinally seam-welded carbon steel pipe

Scans of the magnetic flux density surrounding a longitudinally-seam welded 6" schedule-40 carbon steel pipe carrying 2 A current at 5 Hz were completed at stand-off distances of $\Delta = 25$ mm and 50 mm to represent typical pipe insulation/coating thickness. Figure 5.2 shows the induced magnetic flux density from a scan at $\Delta = 25$ mm with 2 A of current at 5 Hz. The axial pipe weld is located at 90° . In the radial and azimuthal components of $\mathbf{B}$, a perturbation can be noticed at this azimuthal location, likely due to the weld material having different magnetic properties from the surrounding metal. In the radial component this is shown by a positive region between 0° to 90° and a negative region between 90° to 175° where the magnetic field is being drawn in over the weld. This also causes the region of high intensity in the azimuthal scan centred over the weld. Each of the scans exhibit a magnetic flux density that varies slowly in the axial direction. The peak-to-peak variation in the field is on the order of tens of nT for the scans of B_r and B_z and hundreds of nT for B_θ implying it would be preferable to use the radial and axial components of $\mathbf{B}$ for defect detection. In practice, the azimuthal component of $\mathbf{B}$ would vary from a value of around 1 μ T to 2 μ T at these standoffs; however, it has been suppressed by the rod used for the return current path in these experiments.

The measurements presented here represent a much more realistic signal set for the scan of a similar structure than could be predicted using FE alone as the noise from a real transducer and instrumentation and the variability across a real pipe are included. Time variation of the signal was determined to be minimal in this study as the residual between repeated measurements on 4 consecutive days was less than 1 nT in the B_r and B_z and 2.5 nT in B_θ , which are orders of magnitude smaller than the signal expected from defects of interest. At each sensor location, 35 averages were taken to ensure that random noise was effectively suppressed. At low-frequencies (<5 Hz) each measurement should last several seconds to achieve a good Signal-to-Noise Ratio (SNR); however, for practical tests where inspection time must be minimised, an array of sensors could be manufactured to record data at multiple

locations simultaneously. The passive environmental magnetic field of the laboratory was measured over 0.1 Hz to 100 Hz prior to the test to ensure an operating frequency free from electromagnetic interference that could reduce the SNR was chosen. The result did not influence the choice of operating frequency as there was no significant electromagnetic interference over this range; however, it would be important to repeat this step for practical tests in an industrial environment. The bandwidth of the lock-in amplifier should also be set to achieve a satisfactory SNR with maximum measurement speed.

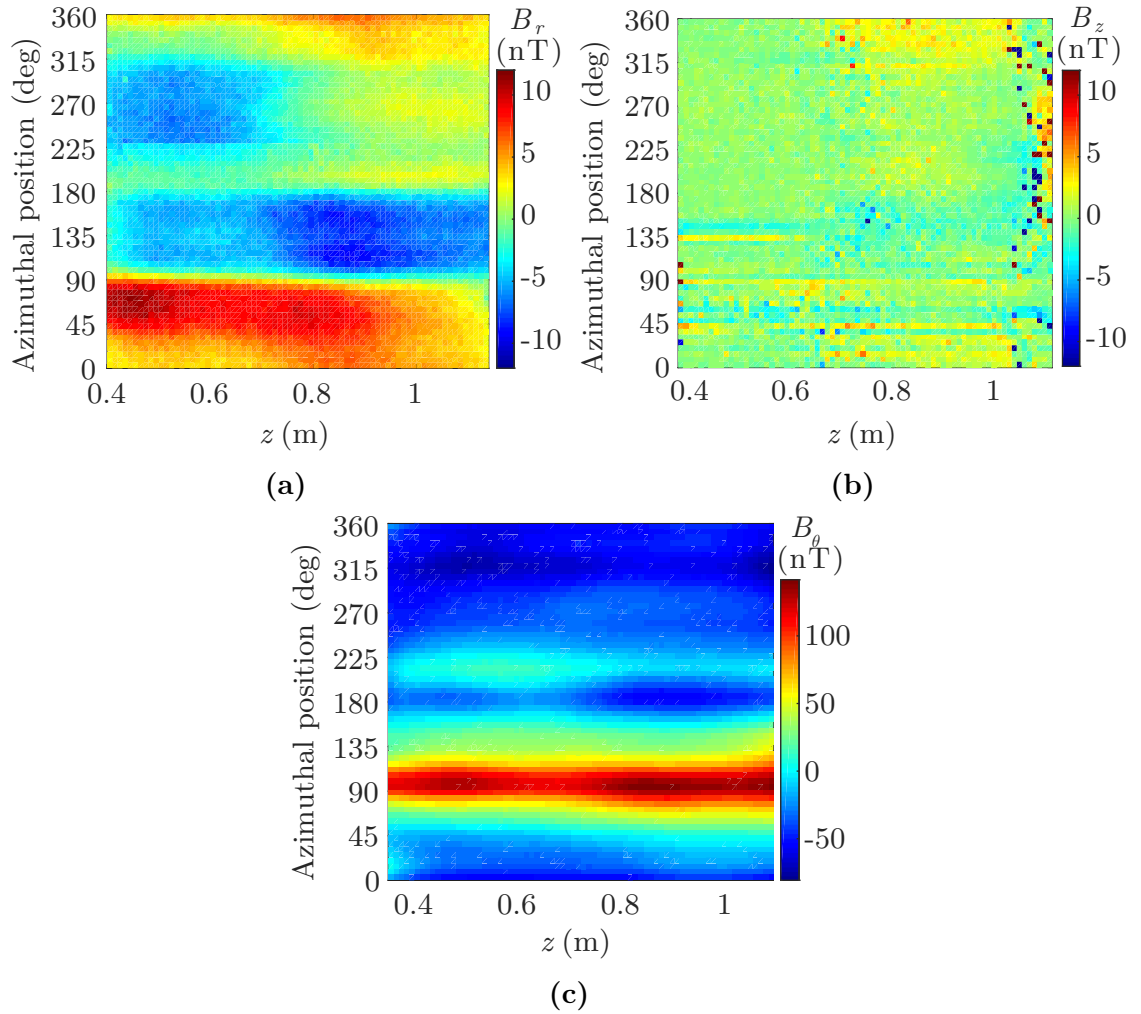


Figure 5.2: (a) Radial, (b) axial and (c) azimuthal components of the magnetic flux density at 25 mm standoff from a longitudinally seamed-welded carbon steel pipe carrying 2 A current at 1 Hz.

Coated ex-service riser pipe

The results shown in the preceding section in Fig. 5.2 are from a pipe purchased directly from the manufacturer so, to see how the signal would change on an more realistic pipe, a scan of the magnetic flux density was also completed on an ex-service riser pipe provided by Oceaneering International (Oceaneering International 2017). Prior to the measurement, the pipe specifications were unknown, other than its dimensions of 150 mm nominal bore (6") schedule 80 (wall thickness, $T = 11$ mm), and 15 mm polyethylene coating thickness. As the wall thickness is more than 3 mm greater than previously tested pipes, a lower frequency current to ensure quasi-DC operation was necessary. Assuming $\mu_r = 100$, the skin-depth, δ , is approximately 17.7 mm so a lower frequency 2 A current at 1 Hz was used to account for inhomogeneities in the material properties that have potential to reduce δ . The sensor standoff, Δ , was 25 mm from the pipe outer surface (10 mm above the coating).

There are a number of distinctive features in the scans. The azimuthal flux density in Fig. 5.3c exhibits a stronger variation in the circumferential direction than the axial direction which is likely due to wall-thickness variations that would not change significantly along the pipe axis. This could not be confirmed because it was not possible to map the wall thickness without stripping the insulation coating; however, it is consistent with the behaviour of $\mathbf{B}$ on the scans of seamless carbon steel pipe presented in the previous chapter (Fig. 4.15, page 104). The axial component of $\mathbf{B}$ is not strongly affected by thickness changes, so B_z shows the distinctive helical pattern associated with seamless pipe noise (SPN). The peak-to-peak amplitude variation in B_z is approximately half of the other two components. The radial component of $\mathbf{B}$ is affected by both SPN and the variations in thickness where the latter effect dominates.

Only the undamaged structure scans of the longitudinally seam-welded pipe will be considered in this chapter because a simple example is best suited to the demonstration of the performance evaluation framework. The ex-service pipe will be considered in the performance evaluation of current deflection SHM in the following chapter, where spatial variations in $\mathbf{B}$ should not degrade the sensitivity.

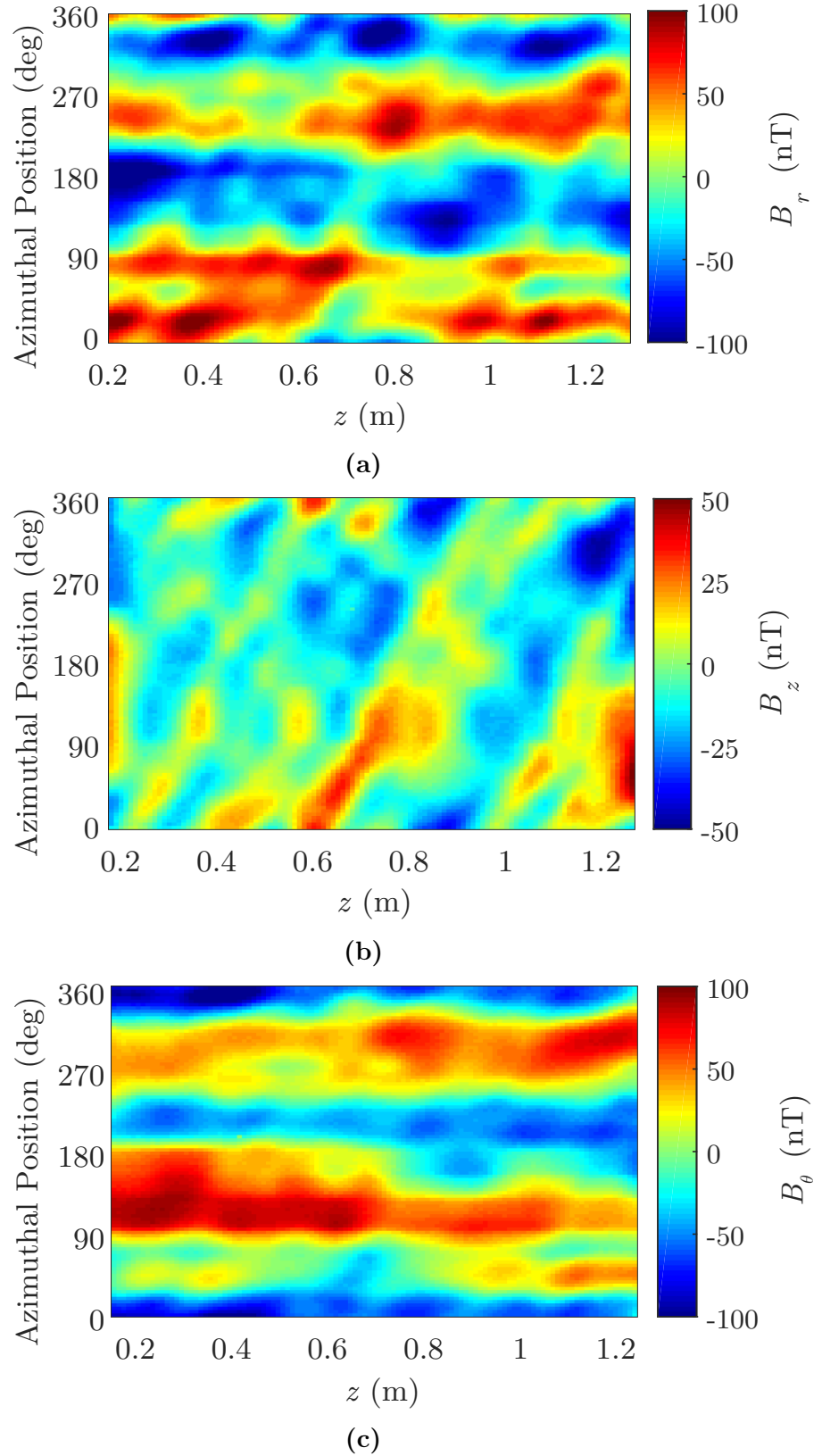


Figure 5.3: (a) Radial, (b) axial and (c) azimuthal components of the magnetic flux density surrounding a seamless carbon steel ex-service riser pipe at 25 mm standoff with 2 A current at 1 Hz.

5.2.2 Contribution from Shallow General Corrosion

In many cases, there may be some additional contributions to the signal that cannot easily be captured with the scan of an undamaged structure. The undamaged pipe scanned in Fig. 5.2 was procured in a “new” state; however, shallow general corrosion will cause some perturbation in the current distribution in the test piece, and therefore in the induced magnetic field. In order not overestimate the performance of the technique, this should be accounted for.

It has been shown in the literature that general uniform corrosion (i.e. not including pitting) can be described statistically (Stone 2009), and several experimentally measured surfaces have followed a Gaussian distribution of depths (Stone 2009; TWI ltd. 2002). A surface profile was therefore generated using a Gaussian distribution of depths with root mean square depth of 0.1 mm and correlation length of 5 mm, based upon the levels used to model the general shallow corrosion from an undamaged section of pipe from (Dobson 2015), although ideally these would be matched to the roughness characteristics of the target test structure. In a way similar to the method described in section 4.2, the pipe was approximated as a 1 m², 7.1 mm thick plate to allow for simpler digitisation for FE and the generated roughness profile was applied to the plate top surface. This methodology was used to generate 25 different profiles with the same roughness characteristics.

The FE simulation could not be readily solved at this point due to the computational burden of the requirement of having an element size small enough to resolve the roughness. However, the roughness-induced disturbance to the field is not of interest at the surface of the conductor but at some standoff distance Δ so a spatial-frequency Low-Pass Filter (LPF) may be used to approximate the representative roughness profile for different standoff distances and so to simplify the FE mesh. Assuming a linear filter, a magnetic dipole oriented parallel to the current direction was used as the impulse function to approximate the LPF transfer function. This approach assumes that the roughness can be represented by many magnetic dipoles, which is a valid approximation for when the standoff is greater than the correlation length. The magnetic field from a dipole is

$$\mathbf{B}(\mathbf{r}) = -\nabla\psi = \frac{\mu_0}{4\pi} \left(\frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3} \right) \quad (5.1)$$

where $\mathbf{r}$ is the distance vector from the dipole to the sensor plane, ψ is the scalar potential and $\mathbf{m}$ is the magnetic dipole moment defined in this case to be $\mathbf{m} = m_z$. In order to obtain the second-order LPF, a 2D Fourier transform was conducted in the plane of observation at standoff $\Delta = 25$ mm or 50 mm, and also at a low standoff of 1 mm. The filter transfer function was then the ratio of the output spectrum (spatial frequency of the dipole field at Δ) and the input spectrum (spatial frequency at 1 mm standoff). The lack of periodicity at the edges of the representative roughness bring in high-frequency components that do not satisfy the Nyquist criterion (Rice 1951). For this reason, the filtering approach breaks down at low standoff values comparable to the roughness correlation length; however, due to the size of the representative rough surface and the fact that Δ is larger than the correlation length, this was not an issue.

The diffusion filter was applied to the 25 original representative rough surfaces to smooth them to effective rough surfaces that could digitised for FE and solved readily. For example, the representative rough surface shown in Fig. 5.4a was filtered to effective surfaces at 25 mm and 50 mm shown in Figs. 5.4b and 5.4c respectively. Note the effect of the LPF on the spatial frequency and amplitude of the surface profiles. The effective rough surfaces were imported into the FE model and used to define the thickness profile of the plate which could readily be digitized for FE, as far fewer elements were required to satisfy the Nyquist criterion for resolving the roughness. The FE model was then solved for B_r , B_θ and B_z at 1 mm above the current carrying plate, which was approximately equivalent to solving the model with the representative rough surface at the higher standoff.

Figure 5.5 shows examples of the perturbation in the components of $\mathbf{B}$ due to the current deflection from the the 10 mm correlation length, 0.1 mm RMS depth rough surface shown in Fig. 5.4a. The current flows in the positive z direction. The perturbation in B_x and B_y corresponding to the azimuthal and radial components on a pipe scan exhibit approximately double the amplitude as in B_z , consistent with the behaviour observed for the scan of the ex-service pipe (Fig. 5.3). To combine this result with the defect-free scan when forming the synthetic scan, the respective components of B for the same-off are summed over the scan area. This is demonstrated visually in section 5.2.5.

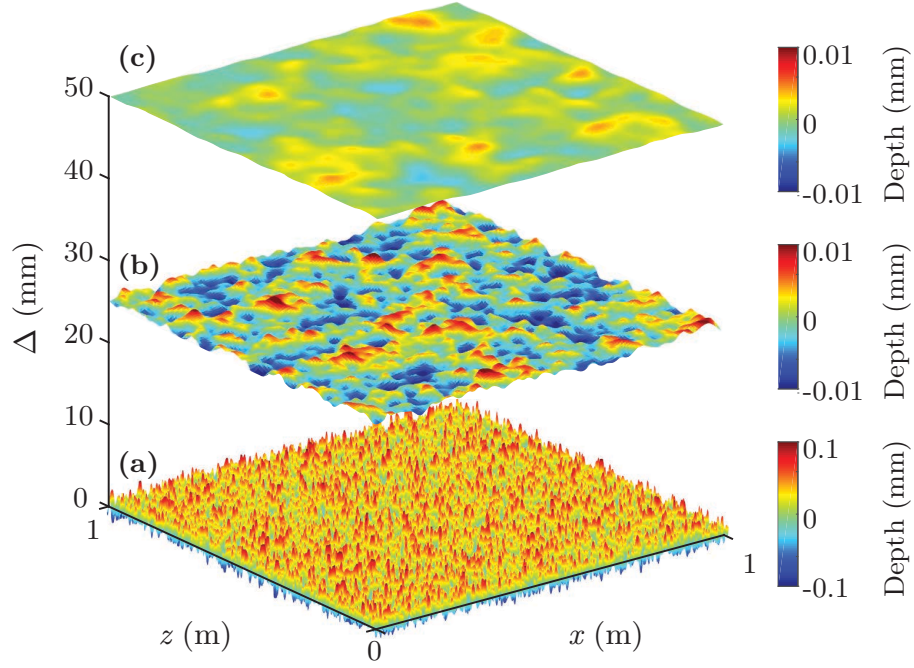


Figure 5.4: (a) Rough surface profiles generated with RMS depth of 0.1 mm, then filtered to find the effective surface for sensors at (b) $\Delta = 25$ mm and (c) $\Delta = 50$ mm.

5.2.3 Contribution from Defects

The validated FE model used for the prediction of current deflection defect signals has been discussed previously in chapter 3. Semi-ellipsoidal defects with $3 \times T$ diameter, and constant-depth longitudinal and transverse slots were considered. The defect geometry is as shown in Fig. 3.5, page 57, although the slots in this study have a narrower opening of 0.5 mm. The amplitude of the predicted defect perturbations were similar to the results summarised in table 3.1, page 58.

5.2.4 Contribution from Gradiometer Misalignment and Sensitivity Mismatch

In most practical applications, it is expected that misalignment will be the greatest contributor to the noise; therefore, only by completing the scans of undamaged pipes with a precise positioning system and applying realistic misalignment noise by post-processing is it possible to separately study each of the contributions to the signal outlined at the beginning of the chapter. The pipe scanning system (shown in Fig. 3.11, page 68) uses a rod at the centre of the pipe for the return current which

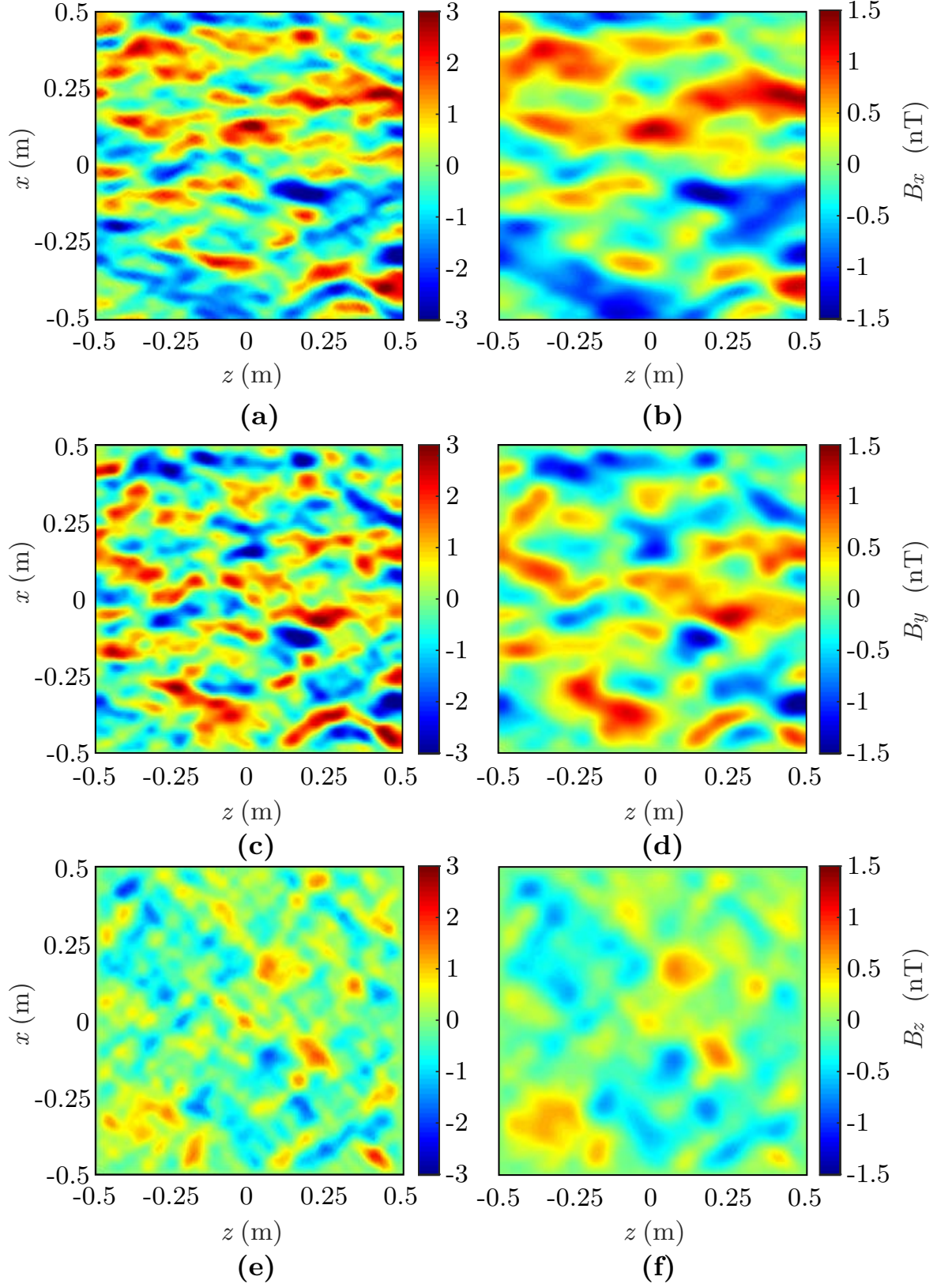


Figure 5.5: Perturbations in (a, b) B_x (c.f. azimuthal), (c, d) B_y (c.f. radial) and (e, f) B_z (c.f. axial) due to a rough surface with 10 mm correlation length, 0.1 mm RMS depth at (a, c, e) 25 mm and (b, d, f) 50 mm standoff. The mean field has been subtracted for the plots of B_x .

suppresses the large B_θ . The sensor and pipe movement is precisely controlled, and constant alignment can be maintained throughout the scan; therefore, the equivalent B_θ that would be measured without the rod could be added to the azimuthal scans by superposition where necessary. A scan performed under realistic conditions is unlikely to be able to maintain such precise sensor orientation throughout the scan. A study was therefore completed to predict the amount by which potential misorientation of the sensors during a practical scan would affect the sensitivity due to pollution of the small B_r and B_z components with the large B_θ . A gradiometer formed of four sensors (Fig. 4.24, page 116) allows the misalignment error to be reduced but not completely eliminated.

As discussed in section 4.7, the separation of sensors within the gradiometer, s , should be chosen so that erroneous signals not associated with the defect are effectively suppressed while not diminishing the defect signal amplitude. To illustrate this, Fig. 5.6 plots the predicted gradiometer output for different sensor separation distances at 25 mm standoff with a 1.5 mm deep $3T$ diameter defect centred at $z = 0.87$ m and $\theta = 270^\circ$. These figures were obtained by post-processing the single-sensor scan with equation 4.1 (page 117).

Without simulating a gradiometer, the defect signal amplitude is similar to the unwanted scan features that do not originate from the defect. The gradiometer effectively suppresses these features, which increases the contrast between the defect signal and the background. At $\Delta = 25$ mm, the sensor separation s was chosen to be 30 mm to maximise the defect signal amplitude while achieving good suppression of extraneous features. For the scans at $\Delta = 50$ mm, s was chosen to be 50 mm. The plots in Fig. 5.6 show the effect of using different sensor separations. If s is too small, the defect signal will also be suppressed, and if it is too large, the background suppression is less effective, and the defect signal becomes disconnected.

The data in Fig. 5.6 assumed constant alignment and standoff throughout the scan, which would likely not be achievable in practice. To account for potential instability during a scan, a random orientation of up to 2° in each of the three degrees of freedom of potential gradiometer rotation, shown by α , β and γ in Fig. 5.7a ¹, was assigned to every location in the scan. The assumption is therefore that there is a random re-orientation of the gradiometer of up to a few degrees between each

¹The definition assigned in the nomenclature for β does not apply here.

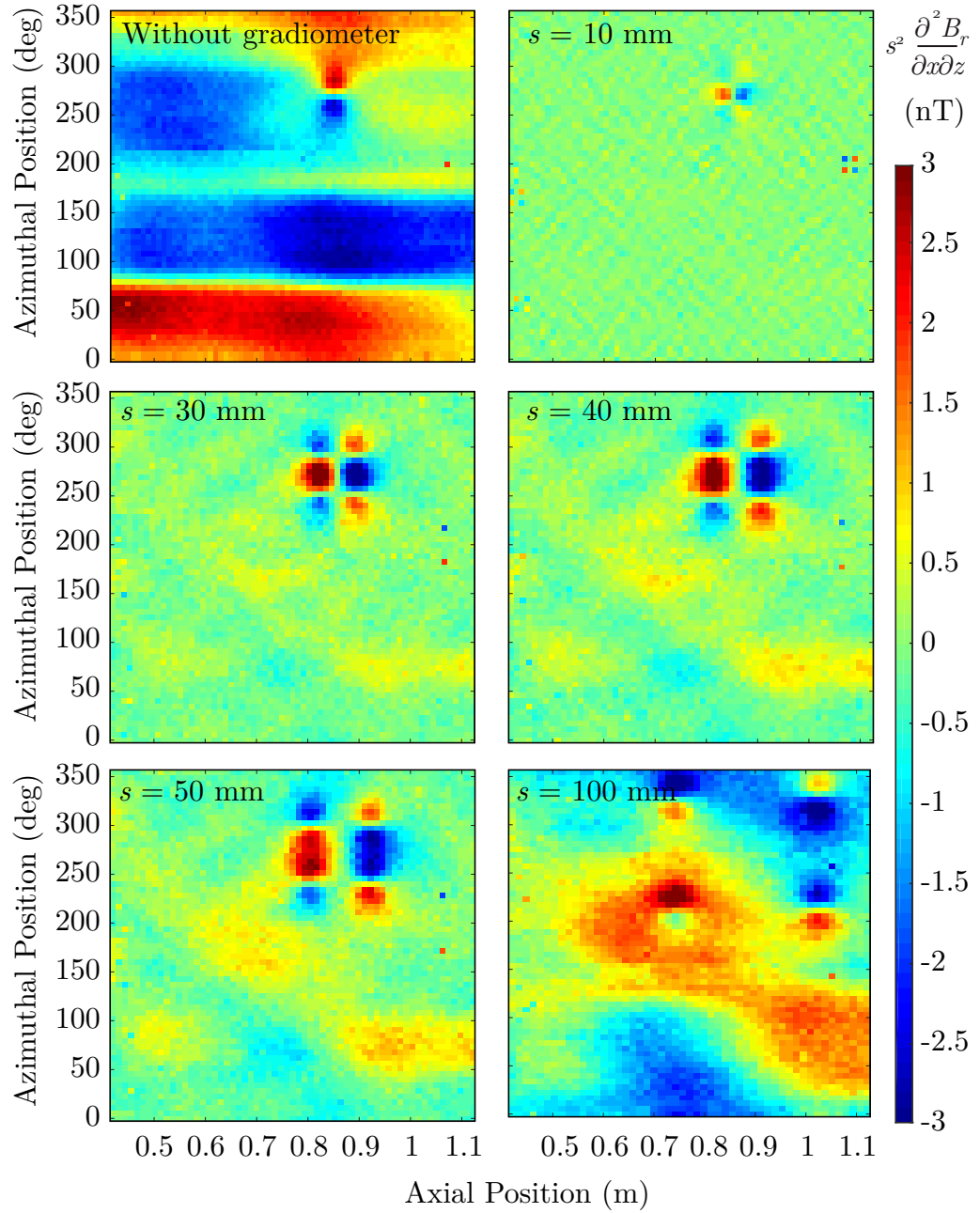


Figure 5.6: Predicted gradiometer output applied to a scan of a defect-free pipe with perturbation from a 1.5 mm deep $3T$ diameter defect added. The data obtained using different sensor separations is compared to a single-sensor scan. The colour scale shown is used for all gradiometer scans. No general roughness or gradiometer misalignment was considered here.

position on the scan. This assumption could be refined following a test under realistic operating conditions.

The gradiometer will only be effective if the sensitivity of each constituent sensor is matched. Thermal gradients, nonlinearity, sensor ageing etc. can cause the absolute sensitivity to vary between sensors, which will cause a variation in the measured gradient. It is usually possible to match the absolute sensitivities of the same sensor type to within 1%, so a random sensitivity variation of 0% to 1% was assigned to each sensor forming the gradiometer. The noise in the gradiometer output due to the misalignment and the sensitivity differential was then calculated for every location on the scan for the given inspection parameters (standoff, sensor separation etc.). This generated a Gaussian noise profile that could be combined with the measured scan of the undamaged structure to account for the fact that a practical scan, unlike the scan completed in the laboratory, would have significant noise due to misalignment. Figure 5.7b shows the predicted noise due to misalignment and sensitivity mismatch of a gradiometer. Only the gradient for the radially oriented sensors is shown for brevity, but the same approach was used for other sensor orientations. It should be noted that it is unlikely that the noise profile due to misalignment of a real scanning system would be Gaussian; however, this serves as an example that could be improved upon when more information is known about the particular scanning system.

The standoff of the centre of rotation of the gradiometer was constant throughout the scan, whereas practically, a variation may occur from the sensor passing over bumps in the insulation/coating etc. At a mean standoff greater than 25° on a 6" pipe, this variation is not likely to cause more than a few nT of noise in the signal measurement so it was not considered in this preliminary study. This effect would become more important when the amplitude of the signals change more rapidly with standoff e.g. pipes with thin coatings or small diameters.

5.2.5 Data Fusion

Figure 5.8 visually illustrates the process of combining the different data sets to form the the synthetic scan. The predicted defect signal from FE, **b**, described in sections 3.2.1 and 5.2.3, is down-sampled to the same spatial sampling frequency as the measurement of the undamaged structure, **a**, from section 5.2.1, and the two are

MODEL INPUTS			
Sensor separation s	Standoff distance Δ	Limits of mis-alignment in each orientation $\alpha \quad \beta \quad \gamma$	Sensitivity variation within gradiometer δS

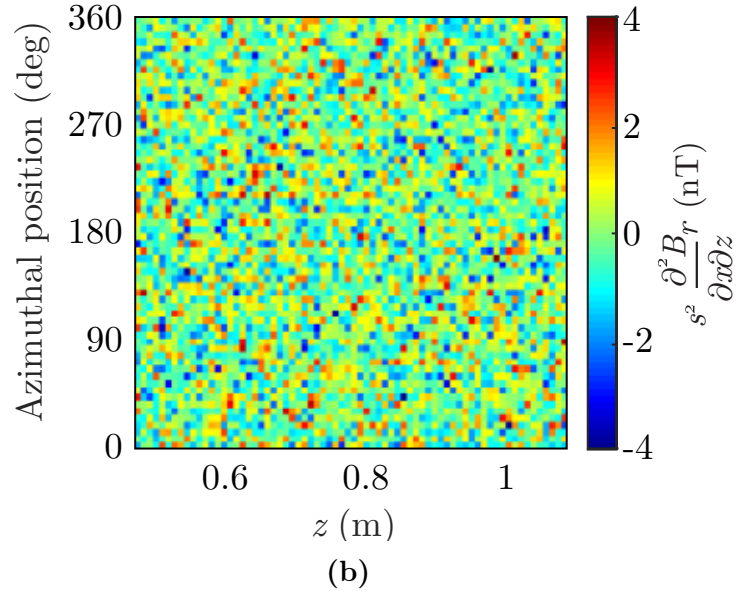
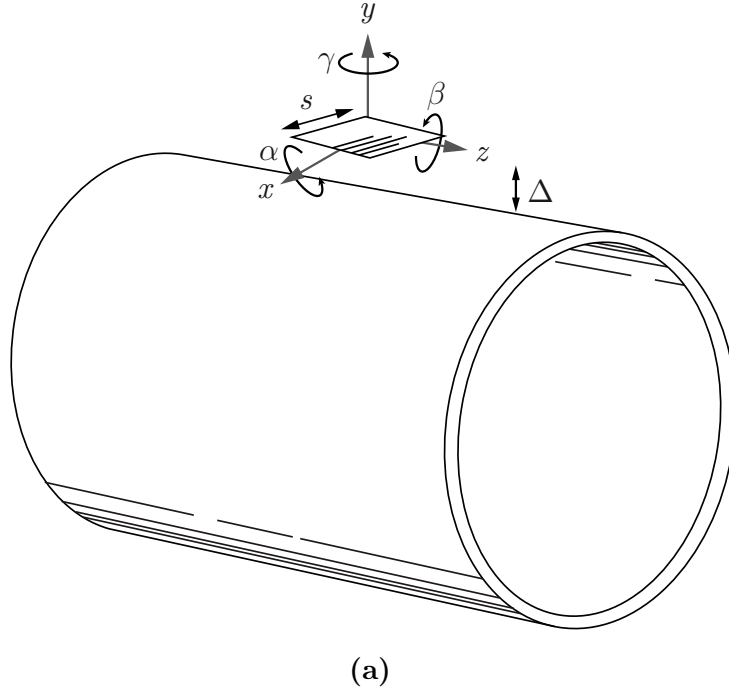


Figure 5.7: (a) The effective field from the misaligned gradiometer is calculated for a random misalignment at every point on the scan for the selected input parameters. (b) Example output of the misalignment model which can then be incorporated to the synthetic scan. Here, $s = 50$ mm, $\alpha = \beta = \gamma = 2^\circ$, $\Delta = 25$ mm, $\delta S = 1\%$.

combined by superposition. The assumption that the defect signal is independent from the baseline is valid based on the results of previous measurements (Fig. 3.18, page 76). The additional contribution to the signal from general roughness, **c**, (section 5.2.2) is also added to the scan. The result, shown in **d**, is a synthetic scan of a pipe with a defect completed by a single sensor with no misalignment errors.

Gradiometric sensing, which would be essential in a practical scan, is then simulated. The sensor separation is chosen as described in section 5.2.4. The noise due to gradiometer misalignment and sensitivity mismatch is calculated as outlined in section 5.2.4. These steps are shown in **e** and **f**.

After summing each component of the synthetic scan, the final result, **g**, is obtained that represents the signal that would be measured from scanning a defective structure under “realistic” test conditions. Decoupling each contribution to the signal in this way allows simulation of the wide variation of scanning conditions that are required to determine ROC for the technique. The ROC are calculated for a particular set of scanning parameters. For example, different ROC would be obtained for different defects, gradiometer, standoff etc.

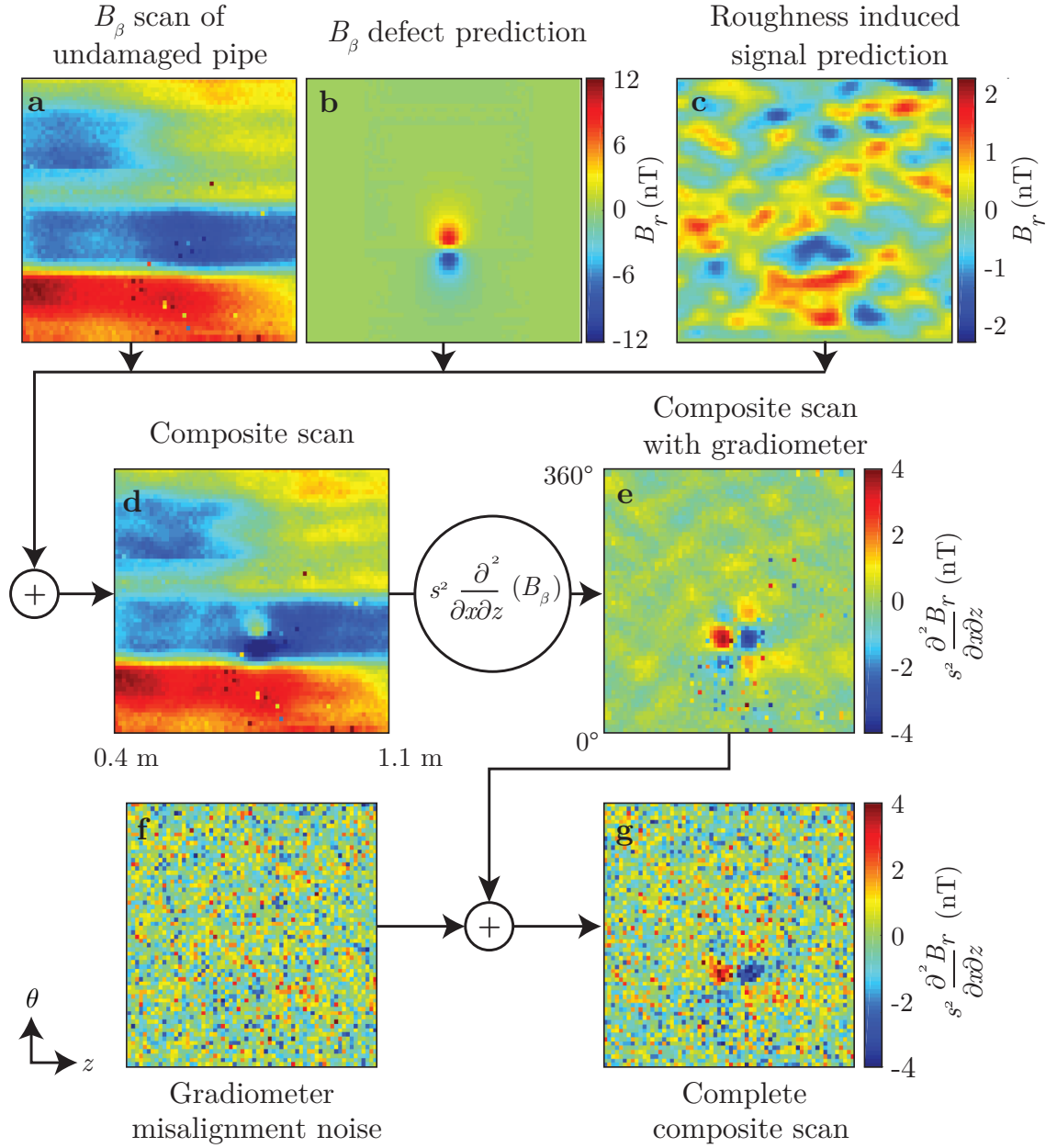


Figure 5.8: Visualisation of data synthesis showing a 21mm $\times$ 21mm $\times$ 1.5 mm semi-ellipsoidal defect at 25 mm standoff. $\beta = r$, θ or z ($\beta = r$ in displayed plots). (a, b, d) plotted using same scale, as are (f, g).

5.3 Defect Detection Methodology

A detection algorithm was chosen that exploits the fact that the defect profiles are always multipolar, with the local minima and maxima occurring near the defect edges. Firstly, the median of the scan is subtracted so that adjacent peaks have opposite polarity. Where a peak exceeds a threshold level, the location of the peak is recorded as well as the area that exceed the threshold; the peaks that have an area less than A are discarded. The optimal value of A will increase with the standoff as the defect signals diffuse. The distances between the remaining peaks and their closest neighbours of opposite polarity are then found, and if this distance is greater than κ , no detection is recorded. κ should be set depending on the standoff and the largest defect signal of interest, where the peaks will be separated by the largest amount. The circumferential continuity of the scan was accounted for when applying this detection algorithm in the cases where the defect signal spanned both the top and bottom of the scan due to the choice of datum in the azimuthal axis. Figure 5.9 shows a decision tree for the detection algorithm.

It is important to note that any arbitrary damage detection methodology could equally be investigated in the presented MAPOD framework and the one outlined here serves purely as an illustration. The algorithm could be improved to further distinguish true and false positives via additional filters. Machine vision or machine learning algorithms have proved very effective in automatically recognising defects in NDT scans (Khodayari-Rostamabad et al. 2009; Mao et al. 2014; Sadr et al. 2016; Slessarev et al. 2006) and could well serve this application, although the optimisation of such solutions is out of the scope of the current study.

The outputs of the detection algorithm are the number of true and false positives and false negatives (i.e. defects missed) at the selected threshold level. The framework allows a practical scan of any defect geometry, under any set of operating conditions to be produced. In this way, a Monte Carlo simulation can be performed to give the POD and PFA required to calculate the ROC.

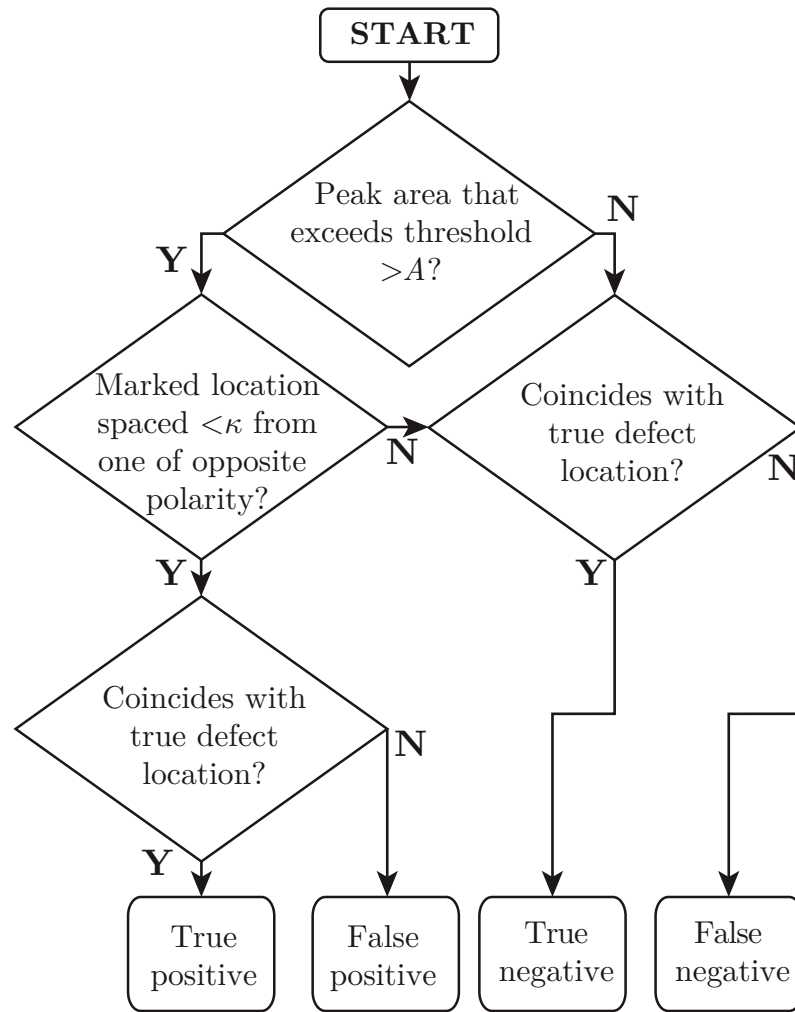


Figure 5.9: Decision tree for defect detection used in MAPOD study. N and κ are parameters that can be optimised depending upon measurement characteristics. $A = 20 \text{ mm}^2$, $\kappa = 50 \text{ mm}$ for $\Delta = 25 \text{ mm}$ scans and $A = 40 \text{ mm}^2$, $\kappa = 75 \text{ mm}$ for $\Delta = 50 \text{ mm}$ scans.

5.4 Receiver Operating Characteristics for a Longitudinally Seam-Welded Pipe

Figure 5.10 shows the ROC curves generated by the framework for increasing depth $3T \times 3T \times d$ bowl defects on the outer surface of a 150 mm nominal bore (6") schedule-40 carbon steel pipe at two standoffs. The ROC curve allows the relative performance of different test conditions to be compared. Perfect detection with no false calls occurs when the Area Under the Curve (AUC) is unity, implying POD unity even at zero PFA. As the performance degrades, the ROC can approach the $\text{POD} = \text{PFA}$ line that corresponds to a random guess (Georgiou 2006); in this case, $\text{AUC} = 0.5$. For the geometry modelled, $\text{AUC} = 1$ for the $d = 1$ mm defect (14% of the 7.1 mm wall thickness) at $\Delta = 25$ mm. For shallower defects, the AUC falls as the defect amplitude becomes less distinguishable from the background signal. With $\Delta = 50$ mm, the corresponding curves on the ROC plot drop away from the ideal and the AUC decreases, indicating poorer detection performance as the defect signals become broader and reduce in amplitude. It is clear that the shallower defects are approaching $\text{AUC}=0.5$, so they could not reliably be detected in practice. The ROC curve for each defect depth is calculated from the mean of a distribution of 1000 synthetic scans with different defect locations and values of all random calculated parameters at each threshold level. The dashed lines below the solid ROC curves show the 95% confidence limits. On this curve we are 95% confident that the ROC curve in a given test will be above this level (Georgiou 2006).

The ROC presented in Fig. 5.10 consider a gradiometer formed of sensors whose sensitivity is perfectly matched, and that maintains perfect alignment throughout the scan. Figure 5.11 shows the equivalent of Fig. 5.10a, but now considers a sensitivity variation of up to 1% between the sensors forming the gradiometer, and misalignment in each degree of freedom shown in Fig. 5.7a of up to 2° throughout the scan. The detection performance for equivalent depth defects is reduced by consideration of the misalignment. For example, the ROC curve for the $d = 0.7$ mm (10% of T) defect in Fig. 5.10a is similar to that of the $d = 0.9$ mm (13% of T) defect in Fig. 5.11. The AUC for each scenario are summarised in Table 5.1.

Figure 5.12 shows the ROC curves for the detection of flat-bottomed slots at $\Delta = 25$ mm when using a second-order gradiometer formed of sensors measuring the

Table 5.1: AUC for $3T \times 3T \times d$ bowl defects. In only the column marked †, a misalignment of up to 2° throughout the scan and a mismatch of the sensitivity between the sensors comprising the gradiometer of 1% were considered.

d (mm)	Area Under ROC Curve (AUC)		
	$\Delta = 25$ mm	$\Delta = 25$ mm†	$\Delta = 50$ mm
0.5	0.65	-	0.50
0.6	0.80	0.55	0.56
0.7	0.92	0.68	0.71
0.8	0.99	0.84	0.82
0.9	1.00	0.93	0.90
1	1.00	0.98	0.93
1.5	1.00	1.00	0.94

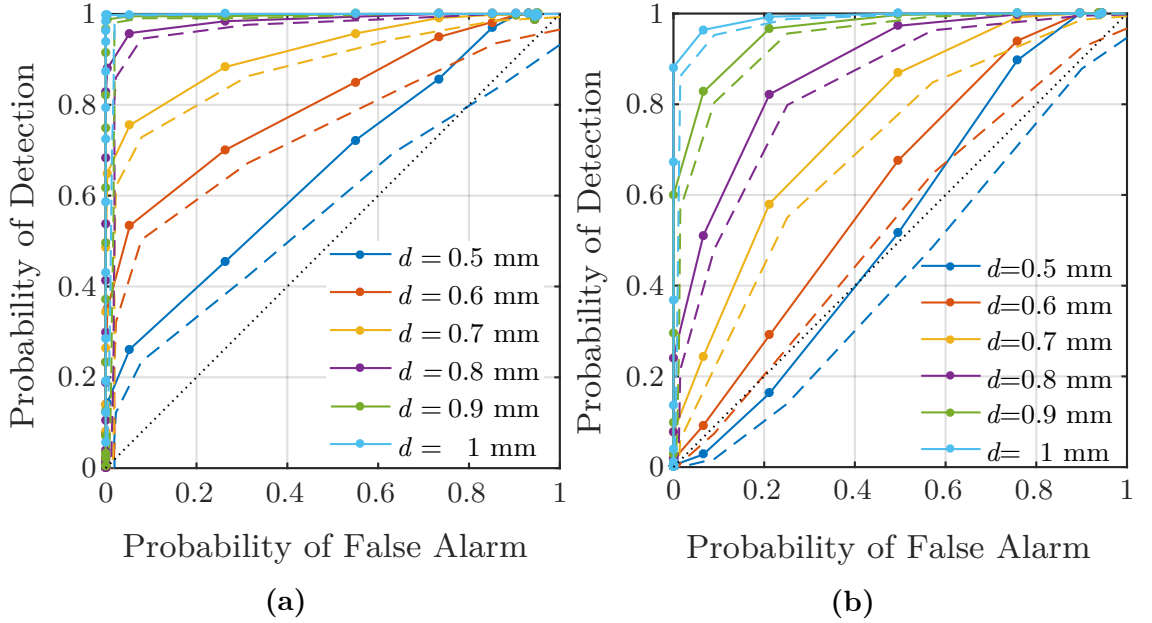


Figure 5.10: ROC prediction for $3T \times 3T \times d$ defects in a seamed carbon steel pipe with 2 A, 5 Hz current and at (a) $\Delta = 25$ mm and (b) $\Delta = 50$ mm. Sensor alignment constant throughout scan. Dashed lines show 95% confidence bounds.

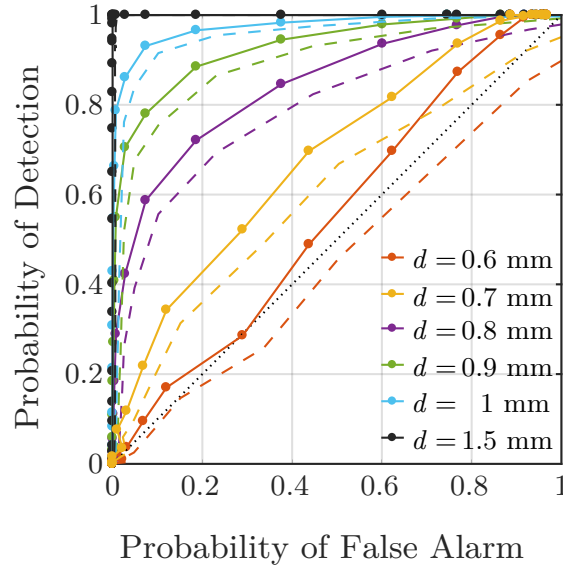


Figure 5.11: Equivalent to Fig. 5.10a but considering misalignment of up to 2° throughout the scan, and a mismatch of the sensitivity between the sensors comprising the gradiometer of 1%.

radial and axial components of $\mathbf{B}$. The gradiometer maintains constant alignment throughout the scan. The detection performance decreases with the slot depth, and measurement of the gradient of B_r results in better performance than using B_z , likely due to the fact that the magnetic signal from current deflection is of a higher amplitude in B_r than B_z .

5.5 Conclusions

This chapter has presented a framework for rapid and efficient ROC prediction for magnetic NDE techniques achieved by the combination of numerical modelling and experimental data. The framework has been applied to the analysis of the low-frequency current deflection technique that has shown promise for the in-situ detection of corrosion-like defects on insulated and coated pipes with remotely injected current.

The methodology allowed each contribution to the signal and noise to be analysed in isolation. This revealed that misalignment of the second-order gradiometer in combination with variations in the sensitivities of its constituent sensors are the limiting factor on the sensitivity of the technique. This is due to the difficulty in detecting small perturbations of the field in the presence of a large azimuthal

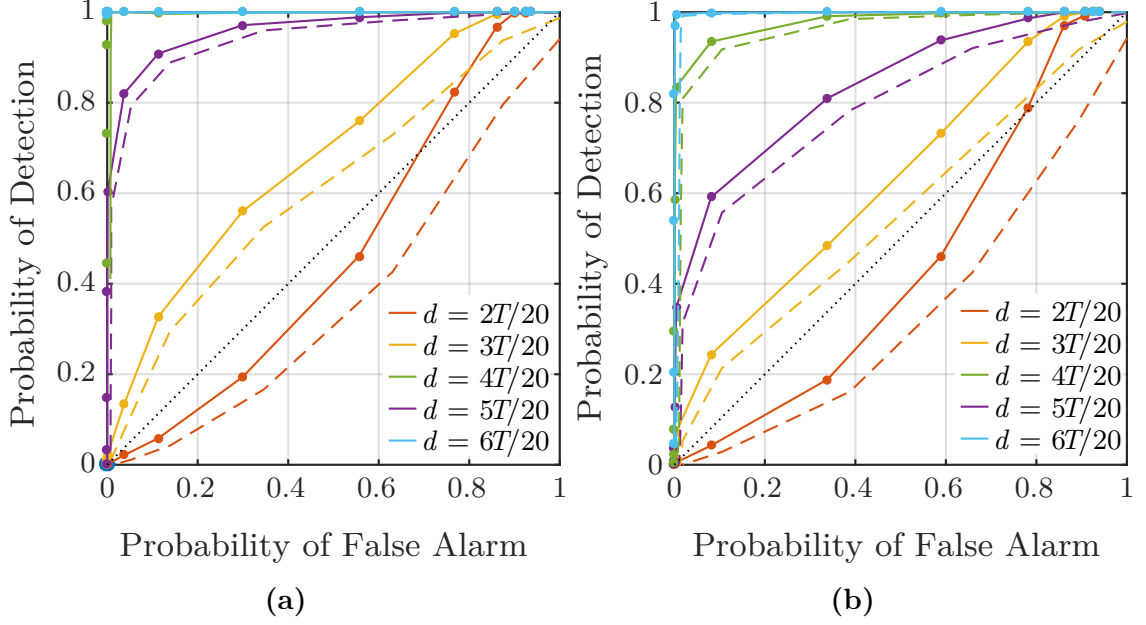


Figure 5.12: ROC for circumferential slots of constant depth d with 1 mm opening, 30° circumferential extent (44 mm absolute length). 2 A, 5 Hz current in 6" pipe using gradiometer measuring (a) B_r and (b) B_z at $\Delta = 25$ mm, no misalignment error considered.

field. The experimental measurements were completed using a scanning frame that ensured constant alignment throughout the scan, and with a return current path via a rod that suppressed the large B_θ . This enabled varying degrees of misalignment to be simulated by adding back B_θ and post processing the scan data. Performing the experiments in a controlled environment like this demonstrates how the modular nature of the framework is powerful, as it allows each contribution to the final signal to be analysed separately, and it supports simple implementation of updates and improvements to the noise model. This method assumed the contributions to the signal were independent and could be combined with superposition. This has been shown to be true for the defect and clean structure signals (section 3.3.4), although future work should verify this assumption for the other contributions to the composite scan.

Other contributions to the noise were identified by measuring the field surrounding an undamaged pipe. Slowly varying background signals due to slight wall thickness variations and magnetic property variations (e.g. in the pipe weld) were effectively suppressed by using the second-order gradiometer. For the most accurate performance evaluation, the undamaged structure should have similar surface characteristics to the structure to be tested. The undamaged pipes scanned in this study

were procured new, so it was demonstrated that a validated FE model could be used to identify the contribution to the scan from the perturbation of current in a generally corroded conductor. At higher standoff, the signal due to roughness diffuses and significantly reduces in amplitude suggesting that the sensitivity is most affected by very rough surfaces when measuring close to the pipe.

Receiver operating characteristics were generated under various scenarios using corrosion and slot-like defects. Without consideration of misalignment and sensor variation, an area under ROC curve (AUC) above 0.91 was predicted for $3T \times 3T \times d$ bowl defects with d greater than 12% of the wall thickness at a standoff of 25 mm, implying that at 92% POD and 95% confidence, the PFA is 0.5%. When considering a misalignment of up to 2° in each degree of freedom of the gradiometer, the AUC was reduced by 15%. In this case, a PFA of $<1\%$ at $>99\%$ POD and 95% confidence was predicted for corrosion defects deeper than 20% of the wall thickness, T . The sensitivity reduced when the standoff was doubled to 50 mm, with the AUC decreasing by 17% on average. These results suggest that the technique is practical for scanning outside of pipe insulation.

Valuable future work to develop the magnetic field measurement technique would be to measure the uncertainty on readings of in-service pipe using a hardware gradiometer in order to characterise the repeatability achievable in practice when scanning.

6 | Performance Evaluation Framework for Current Deflection SHM

6.1 Introduction

The previous chapters have explored the possibility of defect detection by scanning the induced magnetic field surrounding current carrying pipes and measuring perturbations due to the deflection of the current around defects. It was shown in chapter 4 that perturbations in the field can originate not only from defects, but also from material property changes within the pipe (e.g. seamless pipe noise), wall thickness variations within the manufacturing tolerances, sensor instability, or nearby ferromagnetic objects such as pipes. For each of these effects, the signal intensity has a complex spatial dependence which complicates defect detection by scanning. If the sensors are permanently fixed in position, however, spatial variations in the signal would not interfere with the measurement provided they are temporally stable.

The maintenance of critical structures is possible using Structural Health Monitoring (SHM), which describes the permanent installation of sensors to a component and the monitoring of the sensor data over time. The availability of the time-history of the sensor data allows data processing methods not available using scanning methods, such as baseline subtraction or more complex statistical methods (C. Liu et al. 2017), which permit increased defect sensitivity and earlier defect detection (Mittra et al. 2016). SHM can also monitor the growth of sub-critical defects whose premature replacement would incur a significant cost (Z. Liu 2012). As the sensors are installed permanently, the ability to retrieve data without requiring personnel to work under dangerous conditions is also advantageous.

The Anisotropic Magnetoresistive (AMR) sensors selected for experimentation

offer excellent sensitivity to low-amplitude (nanotesla) fields with phase-sensitive detection (Cheng 2012; Díaz-Michelena et al. 2015; Jarvis et al. 2016), and are inexpensive; therefore, there is interest in developing the current deflection NDE method for monitoring of corrosion under insulation using an array of permanently installed sensors. Thermal drifts can affect their sensitivity by $\sim 0.25\% ^\circ\text{C}^{-1}$ to $0.27\% ^\circ\text{C}^{-1}$ due to the variation of resistivity and the magnetoresistive effect with temperature, in addition to a temperature dependent bridge offset (Díaz-Michelena et al. 2015). In previous chapters, these effects were negligible due to the short test time, but they become far more important with the much longer time scales associated with SHM.

To further develop the technique into a deployable SHM solution requires an understanding of the limitations of the sensitivity in practical SHM. Conventionally, this is achieved with many controlled tests of structures containing defects that are physically grown, but this can be time consuming and expensive. Furthermore, the tests should be completed over the range of “Environmental Operating Conditions” (EOC) that may occur in the field in order not to overestimate the sensitivity. The rapid advance in computational efficiency has recently permitted the development of three-dimensional numerical models that can accurately predict the signals that would result from realistic defect scenarios (COMSOL 2017; Jarvis et al. 2016); however, such models often fail to effectively account for the variations in the signal that occur due to the changing EOC, as the interdependence of the effects is frequently complex (Sohn 2007).

The framework first introduced in chapter 5 circumvents this problem by combining the accurate prediction of defect signals from validated FE models with measurements of a real structure over a range of EOC that would be expected to affect the sensitivity of a practical measurement (C. Liu et al. 2017). In doing this, realistic limits of the performance of a technique under realistic operating conditions can be established. The performance of SHM can be illustrated using “Receiver Operating Characteristics” (ROC) - curves that show the probability of detection and expected false-call rate for target defects. ROC were first introduced in chapter 5.1, and in this chapter, a similar framework is used to evaluate the performance of the current deflection technique as an SHM solution applied to pipes in order to screen for corrosion defects present under the insulation or cladding.

An example of a difficult-to-inspect pipe is the riser that connects the petrochemical reservoir wellhead to the drilling platform. 92% of pipe failures by corrosion in the Gulf of Mexico have occurred in the risers (Santos et al. 2013). In-Line Inspection (ILI) is possible on a number of risers; however, the large wall thickness can reduce the effectiveness of such devices. The flow means that the pig speed is also difficult to control, and obstructions can cause it to become stuck (Agthoven et al. 2007). Tethered ILI devices with ultrasonic sensors can also be used for riser inspection, although the requirement for access to the inside of the pipe necessitates complete shut down and decompression of the pipe (Agthoven et al. 2007). Furthermore, the presence of the splash zone (the area surrounding the mean water level on an offshore drilling platform) makes manual inspection dangerous. This area is of particular concern as the water level continuously rises and falls with the tide and with waves, and exposure of metal to salty water and oxygen will lead to corrosion, often at rates as fast as ~ 1 mm per year (Santos et al. 2013). In order to prevent corrosion, cathodic protection is routinely used, however it is a challenge to provide complete protection for the splash zone due to the changing water level. The area is usually insulated with rubber-like materials that possess high electrical, water and impact resistance to prevent corrosion or impact damage, therefore their removal is undesirable. PEC can be applied without removing the coating; however, scans must be completed which warrant either high-risk manual operation of the sensor, or deployment of complex and expensive robotic crawlers. Although the framework described in this chapter is general, it is applied to SHM of CUI on a riser pipe as an example.

The chapter consists of two studies. In the first, the ROC curves for the technique are calculated by performing measurements on a real pipe over multiple temperature cycles and simulating defect growth via a 3D FE model. Possible array configurations for the detection of different sizes of defect are then investigated. The effect of defect size, sensor standoff and sensor orientation on the array configurations are explored. In the second study, current deflection SHM is demonstrated experimentally by electrochemically growing a defect on a steel plate. The experiment also serves to validate the FE model used. The key conclusions are presented in the final section of the chapter. This chapter comprises work that has been accepted for publication in *Structural Health Monitoring* (Jarvis et al. 2017b).

6.2 Performance Evaluation of Current Deflection SHM

For most SHM techniques, the growth of a defect is inferred from the change in signal from a baseline; therefore, any variation in the baseline signal over time, and over the varying EOC that will occur in the testing environment, should be minimised and quantified, as it is this variation that will limit the sensitivity to defect growth.

The signal recorded by the magnetic sensors over time is a function of the defect signal, the electronics noise, and the signal variations from changing EOC. Since the sensitivity of AMR sensors is temperature dependent, it is essential that the contribution to the signal from the time-dependent environmental temperature variation is suppressed so that any change in the baseline signal over time can be attributed only to the contribution from current deflection due to defect growth.

6.2.1 Measurements on Pipe without Defect Growth

The total noise was quantified by simulating an SHM test over multiple temperature cycles for a structure on which no defect growth was expected. A schematic diagram of the experiment is shown in Fig. 6.1a, and a photo in Fig. 6.1b. Three identical magnetic sensor arrays were produced, each with three AFF755B AMR sensors (Sensitec MagnetoResistive Sensors 2011) oriented in the radial, axial and azimuthal directions. The arrays were mounted to 3D-printed holders and were permanently fixed to the outside of a section of ex-service riser pipe provided by (Oceaneering International 2017) who reported the pipe as defect-free. Before each measurement, a pulse was applied to an internal “flip-coil” within the AMR sensors to re-magnetise their ferromagnetic core in order to ensure optimal sensitivity (Fúra et al. 2016). The pipe inner diameter was 147 mm and the wall thickness was 11 mm (6” schedule 80), and the polyethylene coating was 15 mm thick. The pipe was cut to 1.2 m in length to fit in a floorstanding temperature and climatic test chamber (*Temperature & Climatic Test Chambers - Weiss Technik UK* 2017) and a 2 A, 2 Hz current was injected into the pipe via aluminium end-caps connected to the pipe with springs every 20° around the circumference (in a way similar to that described in section 3.3.2, page 66) to minimise the distance from pipe end required for the current to spread out uniformly over the pipe cross-section. Note that the rod at the central

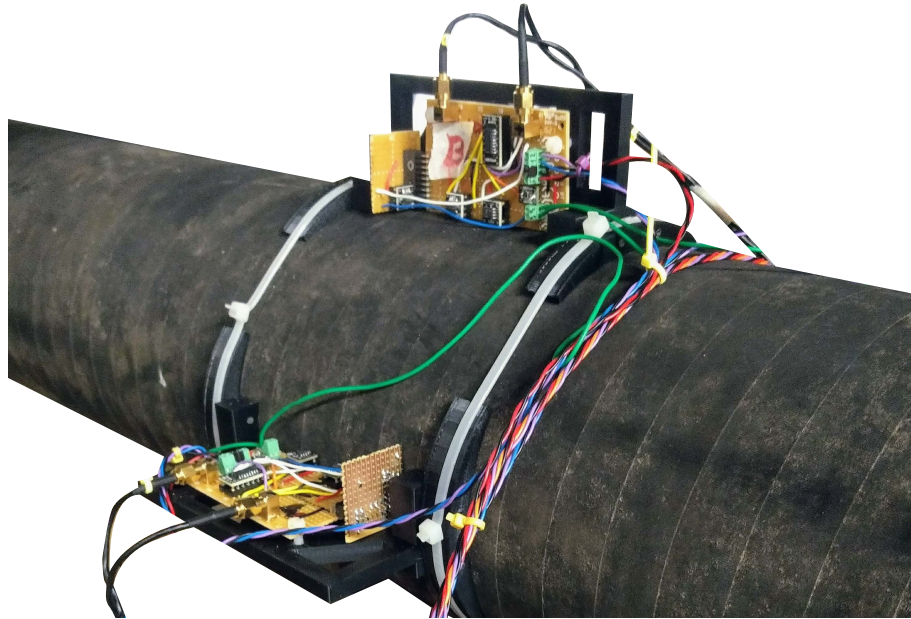
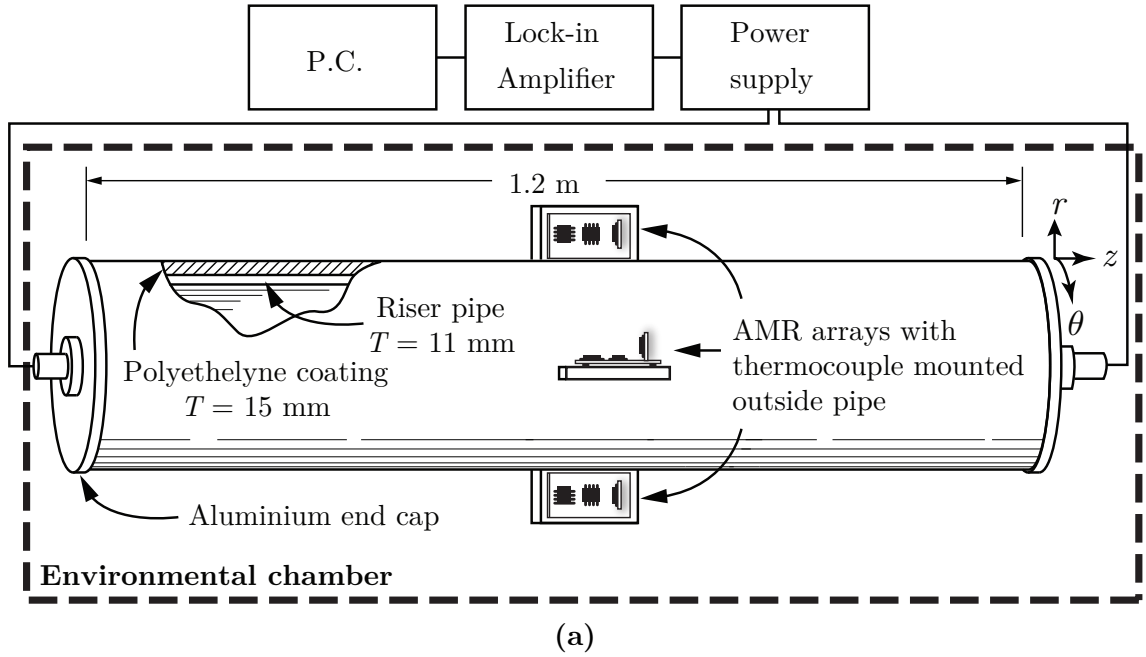


Figure 6.1: (a) Schematic of experiment to determine stability of magnetic measurement of current deflection in a coated riser pipe at varying temperatures. (b) Photograph of sensor boards outside the pipe coating (neither optimised for size nor environmentally protected in this lab based experiment).

axis of the pipe in previous experiments was not used in this study.

The chamber was used to vary the temperature between 0°C to 40°C sinusoidally with a one-day period, representing the daily temperature variation one might expect under unfavourable field conditions. A lock-in amplifier was used to provide the reference 2 Hz signal for the current and to read the sensor output at the same frequency which effectively suppressed the geomagnetic field and the temperature dependent offset of the AMR sensor. The measurement bandwidth can be varied in order to improve suppression of spurious signals close to the reference frequency by changing the time-constant of the lock-in amplifier and/or modifying the low-pass filter slope. In this test, a bandwidth of 0.16 Hz and an averaging time of 22 s were used. Each sensor was interrogated at five minute intervals and the total test time was over 1000 hours. Temperature compensation was achieved using either thermocouples placed on each sensor board or an integrated coil within the sensor chip. With a constant current of 100 mA passed through this coil, a strong biasing field was created which could provide a reference that allowed the temperature coefficient of sensitivity to be determined for each sensor.

6.2.2 Results

Figure 6.2 shows the magnetic field for the azimuthal and axial sensors before and after compensation using the integrated coil. Due to thermal effects, B_θ varies by 400 nT between the maximum and minimum temperature before compensation, while B_z varies by 50 nT over the same period. The break in periodicity at ~550 hours was due to a temporary fault in the environmental chamber. B_θ has a much higher average value than B_z due to the current density in the pipe having purely an axial component. The variation in B_r , which also exhibited the same compensatable temperature effects that affected the other sensors, has not been plotted for brevity. As the real pipe was provided in a defect-free state, no current deflection was expected and B_z and B_r would have zero average and would therefore be largely unaffected by temperature variations if the sensor were perfectly aligned with the pipe axis. The non-zero B_z average illustrates the difficulty in aligning the sensors with their intended orientation.

A moving average filter was applied to the temperature compensated data to simulate a longer averaging time of 3.5 minutes. More than 95% suppression of

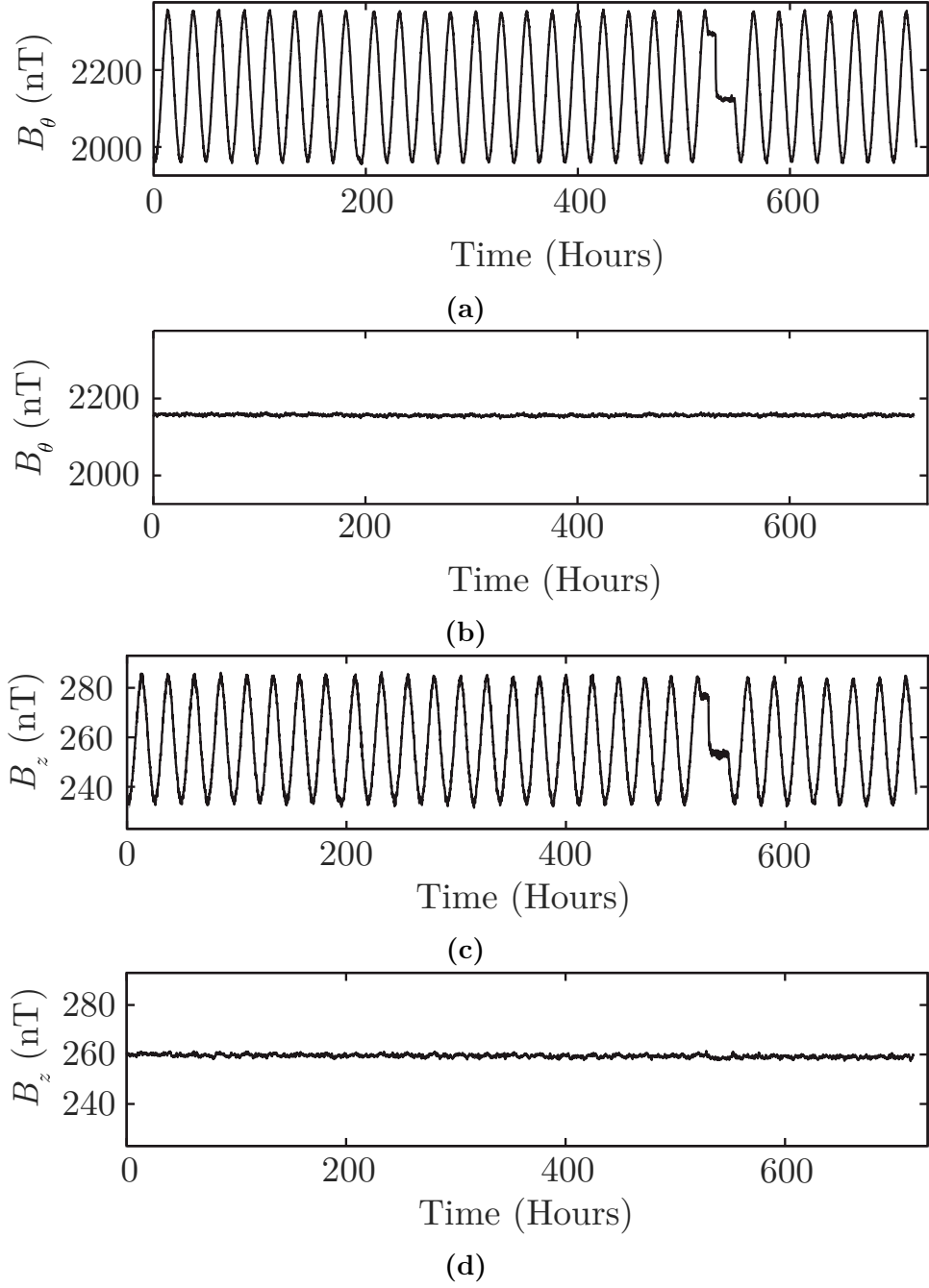


Figure 6.2: B_θ variation measured over 750 hours in environmental chamber before (a) and after (b) temperature compensation and 10 point moving average giving an effective 3.5 min integration time. B_z before (c) and after (d) compensation and averaging, plotted on a different vertical scale for clarity.

temperature effects was possible by using the reference field produced by activating the coil within the sensor. The standard deviation in B_θ and B_z was 2.5 nT and 0.6 nT after compensation. There were no drifts or systematic errors affecting the measurements in the laboratory environment; however, it is imperative that this test be repeated under industrial conditions to determine whether this holds true in the field over much longer time periods. The thermocouples positioned on each sensor board enabled an alternative means of temperature compensation, although the use of the integrated calibration coil is preferable as it requires no additional hardware so only the results using the coil are shown for brevity.

The positions of the sensors and pipe were fixed, and the pipe condition remained constant throughout the test, so the baseline variation of 0.5 nT to 3 nT represents the limit of resolution of the magnetic field that could be attributed to defect growth following baseline suppression. Contextually, this is approximately equivalent to the peak defect signal from a $3T \times 3T \times \frac{T}{10}$ semi-ellipsoidal defect in a pipe carrying 2 A current, at 50 mm standoff (table 3.1, page 58 and (Jarvis et al. 2016)).

6.2.3 Receiver Operating Characteristics

The clean structure measurements revealed the expected variation in the baseline signal and, in each sensor orientation, this noise was normally distributed (verified with linearity of quartile-quartile plot, and analysis of kurtosis and skewness). The defect signal distribution was then obtained by offsetting the baseline distribution by some magnetic field ΔB_β (where $\beta = z, r$ or θ) equivalent to the change in signal expected for a target defect, as shown in Fig. 6.3a. It is assumed that the standard deviation of the baseline and defect signals are identical as the measurement variation is caused by the changing EOC and electronics noise etc., which should equally affect measurements of a clean or a defective structure. The distributions are obtained by randomly selecting 100 samples from the complete data set, which corresponds to a total measurement time of approximately 6 h.

The Probability of Detection (POD) and Probability of False Alarm (PFA) are determined by moving a detection threshold (dashed line in Fig. 6.3a) across the probability distributions and applying the relationships (Fücsök et al. 2005)

$$\text{POD} = \frac{\text{TP}}{\text{TP} + \text{FN}} \quad (6.1)$$

$$\text{PFA} = \frac{\text{FP}}{\text{TN} + \text{FP}} \quad (6.2)$$

where TP (True Positive) and FP (False Positive) are the respective signal and noise above threshold level, and TN (True Negative) and FN (False Negative) are the signal and noise below the threshold level. In this preliminary study, the simplest possible methodology for change detection was used whereby a reading that exceeded the threshold was considered a detection, i.e. a step change in the mean of the distribution is detected. There are many effective methods for detecting changes in normally distributed random variables which, when applied to condition monitoring applications, can significantly improve performance (Basseville et al. 1993; Galvagni et al. 2014; C. Liu et al. 2017). The availability of frequent readings from permanently installed sensors could allow the growth rate of the defect to be monitored, which would improve the sensitivity (C. Liu et al. 2017). These more complex methodologies are out of the scope of this preliminary study.

Figure 6.3b and 6.3c show the ROC for the detection of various defect signal amplitudes with axially and azimuthally oriented sensors. The dotted line labelled “random guess” illustrates an equal probability of correctly or incorrectly calling a defect. Improved detection performance with a low rate of false calls is observed for higher amplitude signals, where the curves are close to the top-left corner in ROC space. When the sensor is oriented in the axial direction, the detection performance is better than when in the azimuthal direction due to the much lower amplitude baseline signal that varied less with temperature (Fig. 6.2) and is therefore less likely to swamp the defect signal. For example, using the axial sensor, a 2 nT perturbation can be measured with 90 % POD and 3 % PFA, whereas for the same perturbation in the azimuthal case, 70 % POD and 35 % PFA is predicted.

The mean curve (solid line) suggests axially oriented sensors can measure a 2.5 nT perturbation with 90 % POD at 0.4 % PFA, and using the lower 95 % confidence bound of the mean (dashed line), 90 % POD at 1 % PFA. The ROC curves for the radially oriented sensors were similar to those for the axially oriented sensors so have not been plotted as the main purpose of the ROCs is to illustrate the framework. For the azimuthal sensors, 90 % POD at 0.2 % PFA is achieved for defects producing

a change in magnetic flux density of 9 nT whereas the lower 95 % confidence gives 90 % POD at 0.8 % PFA. The absolute magnitude of the changes in signal due to defect growth are of a similar magnitude in each orientation of $\mathbf{B}$, suggesting sensors oriented in the radial and axial orientations will be most effective when forming an array (Jarvis et al. 2016).

6.2.4 Predicted Array Configurations for SHM

With knowledge of the expected detection performance of the magnetic sensors, an FE model could be used to determine how many sensors would be required for the detection of target defects, chosen to be semi-ellipsoidal in shape with dimensions of $3T \times 3T \times \frac{T}{3}$, and $3T \times 3T \times \frac{T}{10}$ as a stretch case. The distribution of the magnetic perturbations resulting from current deflection around defects can be analysed using FE which can determine the range of positions in which sensors could be located to detect these defects. The model, shown schematically in Fig. 6.4, contains a current carrying pipe of the same dimensions as in Fig. 6.1a. This model has been previously validated with experimental scans of the magnetic field perturbation due to the target defect geometry (Jarvis et al. 2017a).

The solution to the magnetostatic form of Ampère’s law was found for each finite element using the inbuilt stationary solver in COMSOL. On the external boundaries, a “magnetic insulation” boundary condition was imposed that sets the normal component of $\mathbf{B}$ to zero (COMSOL 2017). The magnetic field in the radial, axial and azimuthal directions was then found at a standoff distance Δ . On this surface, a regular grid of AMR sensors is defined with a pitch, $p_{\alpha,\beta}$, where α is the axial (z), or azimuthal (θ) direction of the pitch and β is the sensor orientation which could be z , r or θ , or a combination of all three (analogous to a tri-axial sensor). The model geometry and the perturbation in B_z due to a defect on the top of the pipe is shown in Fig. 6.4. The model parameters are summarised in Table 6.1.

From the mean ROC curves, the required threshold for 90 % POD at 0.1 % PFA was found to be 2.8 nT using the radial or axial sensors, and 10.0 nT for the azimuthal sensors. These detection thresholds were then applied to the distributions of the magnetic flux density on the surface at standoff Δ calculated using the FE model, to find the areas in which the amplitude of the perturbation exceeded these levels. These areas, labelled A_s and with units of m^2 , are plotted for different sensor

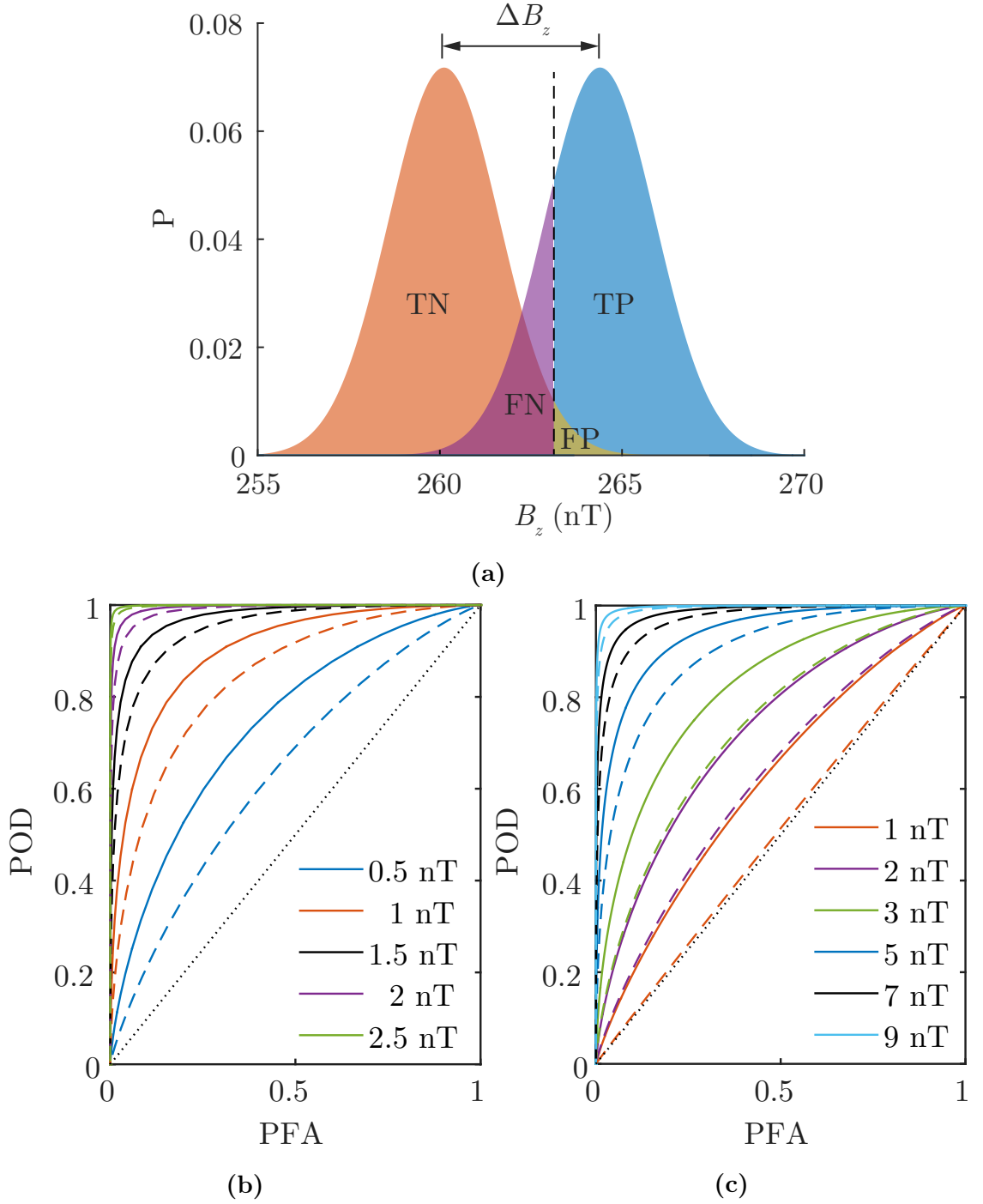


Figure 6.3: (a) Methodology for calculating ROC, and generated curves for (b) axially and (c) azimuthally oriented sensors. Dashed lines show lower 95 % confidence interval of mean and dotted line represents performance for a random guess. The different field amplitudes in (b) and (c) represent the perturbations caused by current deflection around defects.

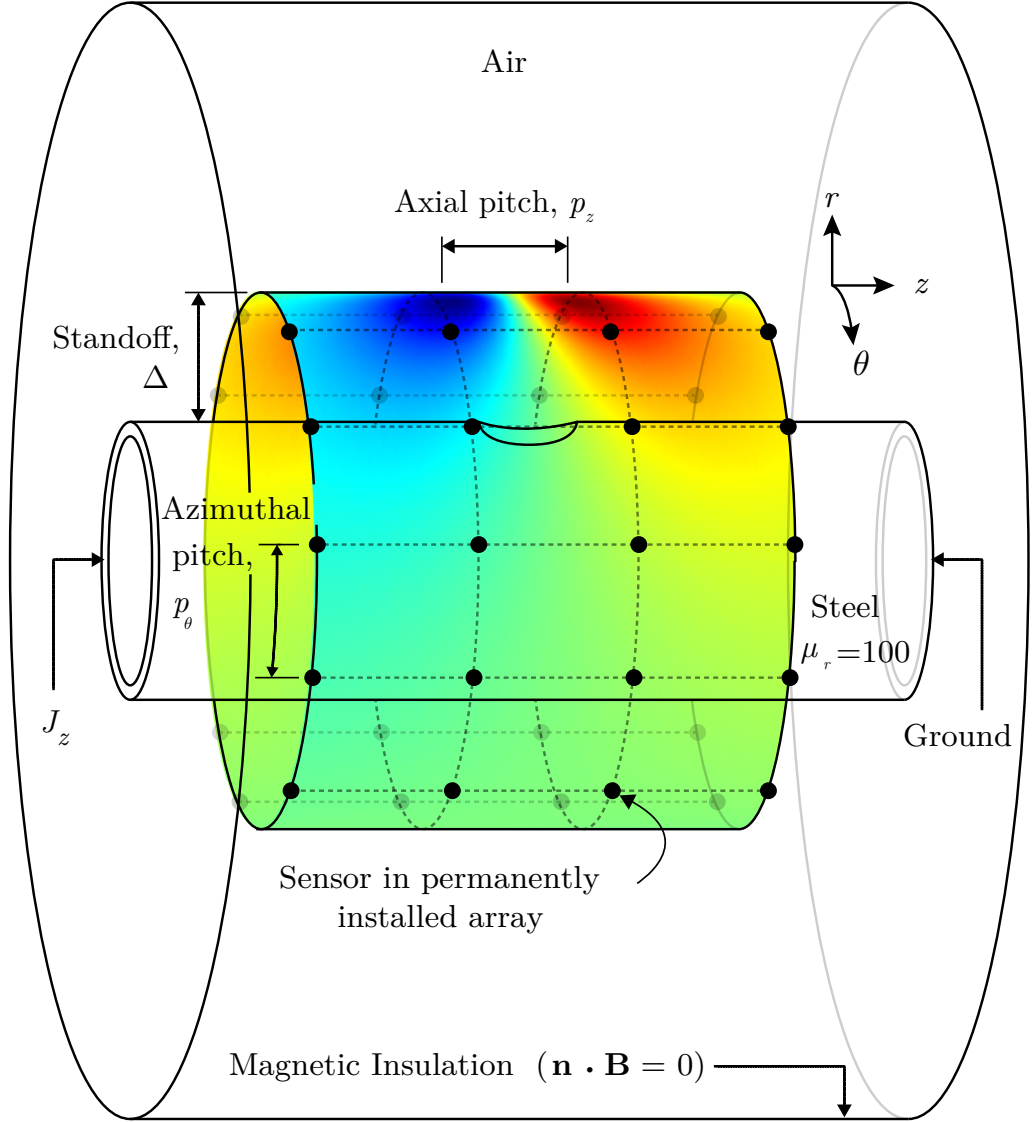


Figure 6.4: Schematic of FE model showing the array of permanently installed sensors (solid circles) surrounding a pipe with coating thickness Δ . The defect shown at the top of the pipe could occur anywhere underneath the array. The predicted perturbation in B_z at the array surface has been shown to help the reader in visualising the physics.

Table 6.1: SHM test parameters used in FE model to determine sensor configuration.

Parameter	Value	Unit
Pipe diameter	147	mm
Wall thickness (T)	11	mm
Quasi-DC current	4	A
Equivalent current density	737	A/m ²
Standoff	10, 25, 50	mm
Defect diameter	25	mm
Target defect depth	10	% of T
Critical defect depth	30	% of T

orientations in Fig. 6.5 and represent the region over which a sensor is able to detect defect growth, or the “zone of sensitivity”.

Determination of the optimal sensor layout is somewhat complicated by the fact that A_s is not rectangular in $\theta - z$ space, so the number of sensors required per meter of pipe cannot be found by simply taking the reciprocal of the area of A_s . Instead, Fig. 6.5 shows the maximum distance that sensors in an array should be spaced to maintain full coverage. The pitch is determined as the maximum distance between adjacent sensors (red dots) in the z direction ($p_{z,\beta}$) or the θ direction ($p_{\theta,\beta}$) in order for the entire surface to be covered by the zone of sensitivity of at least one sensor.

The outline of A_s for an adjacent sensor in the array is shown with a dashed line to visualise the overlap of the zones of sensitivity that is required to maintain full coverage. This may have practical advantages as the amplitude of the defect signal, and therefore also the signal-to-noise ratio (SNR), decrease as the defect is positioned closer to the boundary of A_s , and it is these lower SNR regions that generally overlap. It may therefore be possible to corroborate the detection of defects in low-SNR regions using adjacent sensors. Figure 6.5d demonstrates that a tri-axial sensor with equal sensitivity to three single-axis sensors may provide greater area coverage, and therefore permit an increased pitch.

Figure 6.6 plots the sensor pitch required for 90 % POD at 0.1 % PFA for various defect sizes, sensor orientations and standoff distances. Values close to the top-right of the figure represent a more sparsely populated array, and those to the bottom left represent a denser array. The grey dashed lines are to aid interpretation, e.g. the open red star positioned at 180° and 310 mm implies that triaxial sensors at 25 mm standoff would detect the growth of a $3T \times 3T \times \frac{T}{3}$ defect occurring anywhere on the pipe when 2 sensors are installed around the circumference every 310 mm.

It is immediately apparent that by using tri-axial sensors, it would be possible to have a much more sparsely populated array to achieve the same sensitivity as one containing single-axis sensors. Due to the morphology of the radial defect signal (Fig. 6.5b), a smaller pitch is required along the pipe axis than the around its circumference, and vice versa for the azimuthal signal (Fig. 6.5c). The required pitch decreases with increasing standoff, Δ , as the defect signal reduces in amplitude and becomes more diffuse. The difference in the required pitch for arrays at standoff distances of 10 mm to 50 mm is small because the amplitude and extent of the

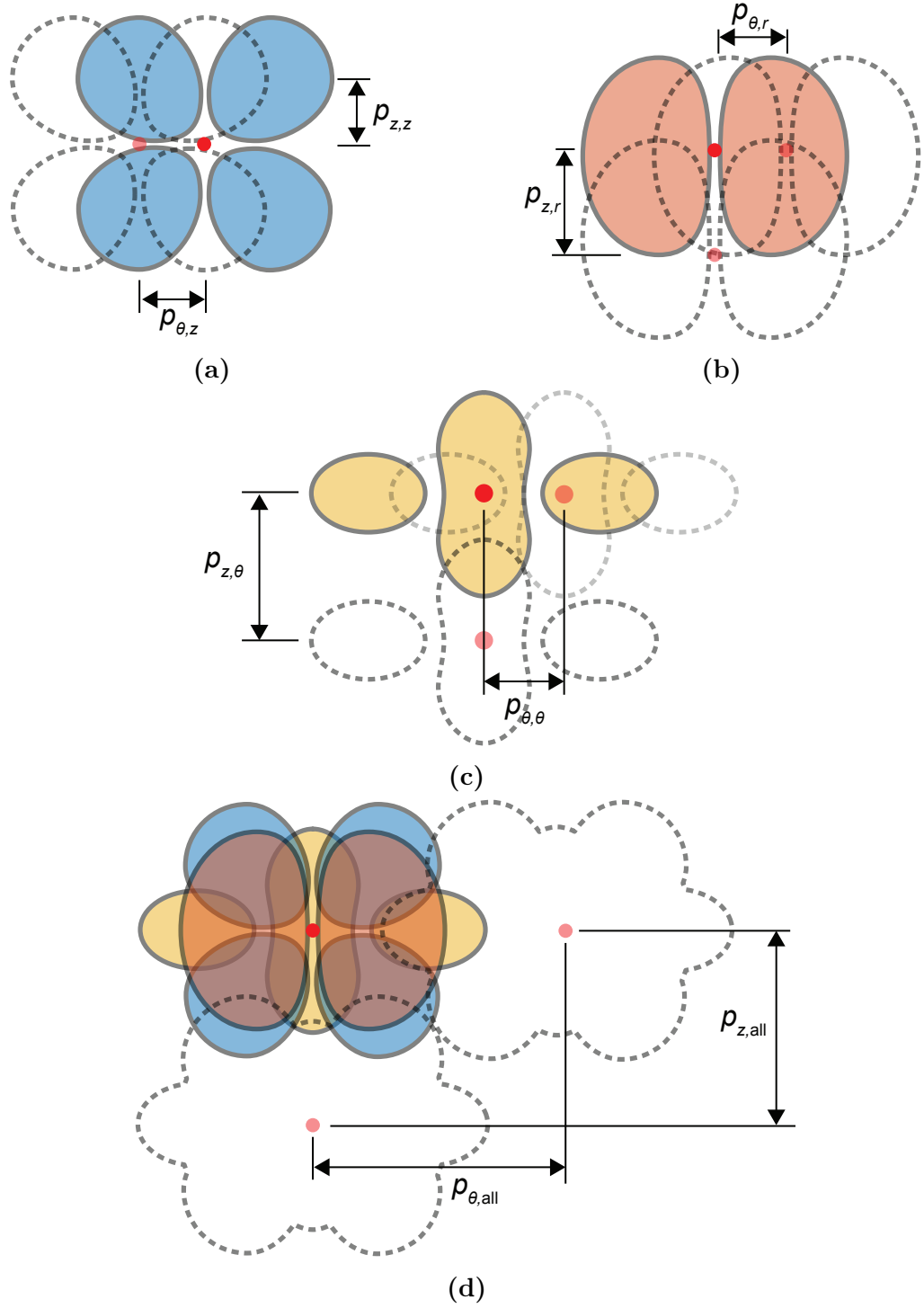


Figure 6.5: Schematic of zone of sensitivity to defects for a (a) axially (z), (b) radially (r), (c) azimuthally (θ) oriented sensor positioned at the red dot. (d) shows coverage for a tri-axial sensor (all). p is the minimum array pitch required for full coverage. The co-ordinates r , z , and θ are defined in Fig. 6.4. Dotted curves show the boundary of the zone of sensitivity for adjacent sensors in the array.

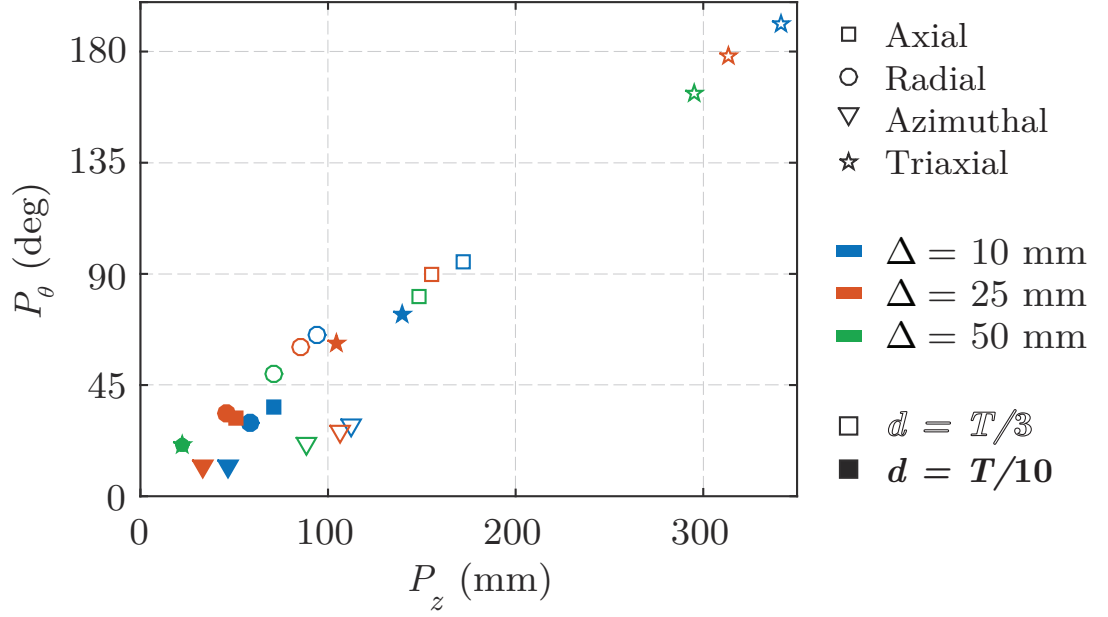


Figure 6.6: Variation in pitch for 2 A quasi-DC current-deflection SHM of a $3T \times 3T$ concave defect of different depth, d , for different values of standoff, Δ and sensor orientation. Markers are distinguished by shapes for sensor orientation, colours for standoff and solid/outline for defect depth.

signal changes much more rapidly at low (e.g. < 10 mm) standoff than when already far from the pipe, implying that SHM will only become marginally more difficult for thick than thin insulation/coating. To compensate for the reduction in signal amplitude at large standoff, it may be possible to increase the current amplitude to improve the SNR.

The results suggest tri-axial sensors with two to three sensors positioned around the circumference of the pipe and with an axial pitch of 100 mm to 300 mm, or approximately 10 to 50 sensors per meter of pipe, would be sufficient for the detection of the growth of a $3T \times 3T \times \frac{T}{3}$ from an initial defect-free state. For the detection of a $\frac{T}{10}$ defect from an initially defect-free state using the same current amplitude, a denser array would be required, as indicated by the solid markers in the bottom-left of Fig. 6.6. It should be emphasised that these results used the simplest possible detection methodology based on a step change in readings. Future development of the current deflection technique would benefit from investigating how the required number of sensors would change when using more complex change detection methodologies such as the statistical methods presented in (Basseville et al. 1993; Galvagni et al. 2014; C. Liu et al. 2017) which exploit the availability of the time-history of the defect response in order to greatly improve detection performance.

6.3 Experimental Demonstration and FE Validation

To demonstrate the SHM technique, AMR sensors were used to measure the current deflection signal from an electrochemically grown corrosion defect. Although the technique is being investigated for SHM of pipes, it is a challenge to create a corrosion cell on the curved surface of a pipe with the ultrasonic transducer required for tracking wall loss mounted on the opposing wall. The current injection end caps enclosing the pipe would also cause access issues. For this reason, a plate was used in place of a pipe which also gave the advantage of facilitating the placing of sensor arrays on the near and far side of the defect and allowed a simpler method of current injection. The current deflection principle is the same for both plate and pipe geometries, so the experiment could also be used to validate a flexible FE model which could simulate the signal from any conductor and defect geometry, such as that in Fig. 6.4.

6.3.1 Methodology

Figure 6.7 schematically shows the experiment and an equivalent photo is presented in Fig. 6.8a. The plate used was 78 mm wide, 15 mm thick and 847 mm long, and carried a 3 A current at 1 Hz injected by wires clipped to the ends of the plate. Due to the smaller cross-sectional area of the plate, the current density was 2 to 3 times higher than in the pipe used previously.

Sensors 1 to 4 and 9 to 12 were oriented in the axial direction, z . Along the central axis of the plate, sensors 5 to 8 and 13 to 16 were oriented in the x direction, analogous to the azimuthal direction used for the pipe geometry so in the following discussion, “azimuthal” refers to the x direction. The sensors were positioned in different locations relative to the semi-ellipsoidal defect shown underneath sensor 7 in Fig. 6.8b. Sensors 2 and 3 on the top array and 10 and 11 on the bottom array were positioned near where the greatest perturbation in B_z was expected, similar to position 1 in Fig. 6.9b. Sensors 1 and 4 (top) and 9 and 12 (bottom) were each 25 mm further from the defect where a smaller perturbation in B_z was expected (c.f. location 2 in Fig. 6.9b). Sensors 7 (top) and 15 (bottom) were positioned over the greatest change expected in B_x (c.f. location 1 in Fig. 6.9a), followed by sensors 6 and 8 (top) and 14 and 16 (bottom) each positioned 25 mm from the defect (c.f.

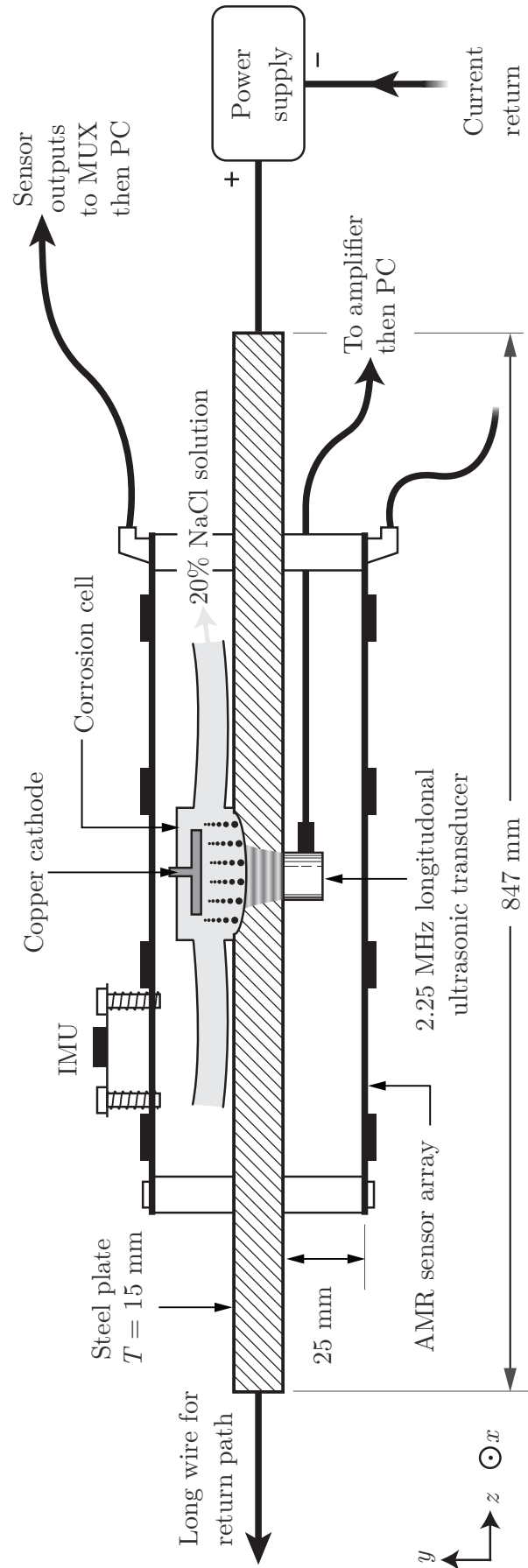


Figure 6.7: Schematic of electrochemically grown corrosion monitoring SHM experiment.

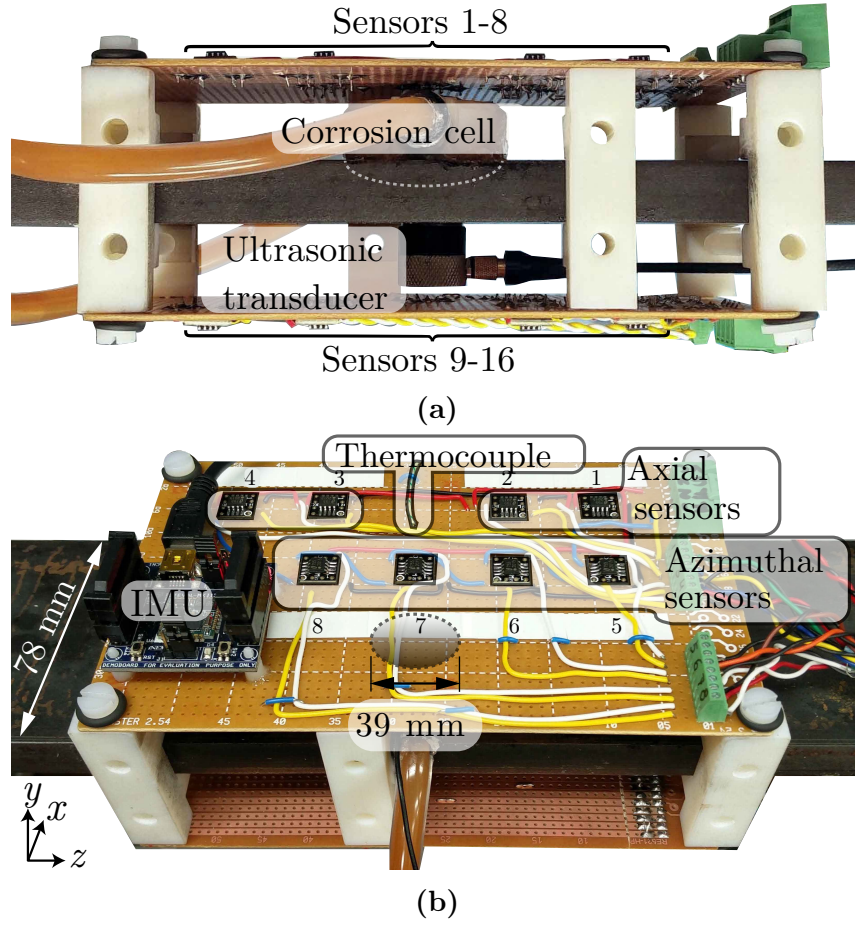


Figure 6.8: Photos of corrosion SHM experiment. (a) Side and (b) top profiles. Defect location below sensor 7 marked with dotted line.

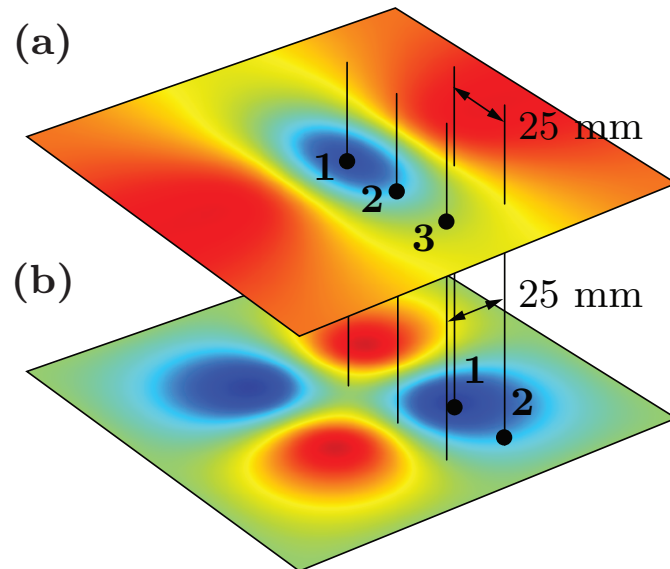


Figure 6.9: Schematic diagram showing sensor positioning relative to expected perturbation in (a) B_θ and (b) B_z due to defect. The numbers 1-3 are referred to in the text. Vertical lines to aid visualisation.

location 2 in Fig. 6.9a). Finally, sensors 5 (top) and 13 (bottom) positioned 50 mm from the defect were expected to measure the smallest change in B_x (c.f. location 3 in Fig. 6.9a).

A corrosion cell was created on the plate by 3D printing a plastic chamber and inserting a copper disk for the cathode. The corrosion cell was attached to the plate using epoxy, and a 20 % solution of NaCl electrolyte was pumped from a reservoir to prevent build-up of corrosion product. A current of 500 mA was impressed between the copper and the steel plate, which allowed removal of 500 μm of steel in approximately 5.5 h. The wall thickness was monitored by a 2.25 MHz longitudinal wave piezoelectric transducer permanently mounted underneath the corrosion cell. The experiment was carried out in 24 h segments as shown in Fig. 6.10. Firstly, the accelerated corrosion cell was activated until the maximum defect depth increased by 500 μm and then the magnetic field was then monitored for the remaining time, with each AMR sensor being interrogated once every 18 min with 25 s averaging time. The wall thickness and temperature corrected magnetic field were then averaged over the duration of the period in which the corrosion cell was deactivated, represented by the shaded segments in Fig. 6.10. The assumption that the wall thickness is unchanged over this averaging time is justified as corrosion growth is much slower in the field (severe rates rarely exceed 1 mm/yr (Santos et al. 2013) and most corrosion grows much slower than this (Caleyo et al. 2009)).

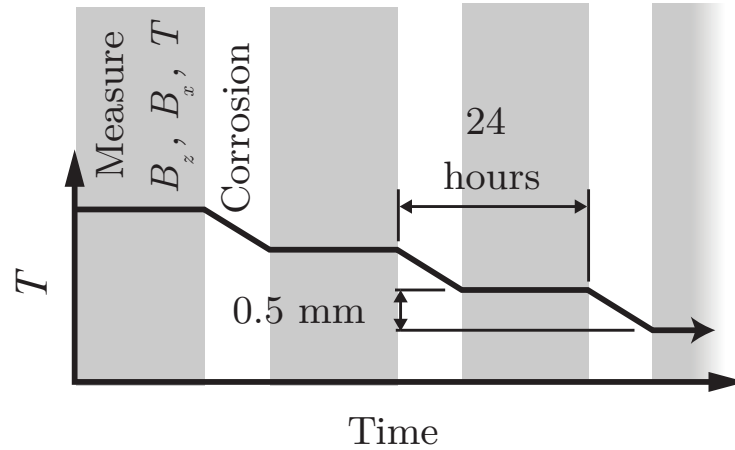


Figure 6.10: Methodology for SHM demonstration experiment. The thickness, T , and magnetic flux density are averaged over the shaded time segments.

In this experiment, step changes in the defect growth are measured over a limited time period which restricted the measurement time to a single day between

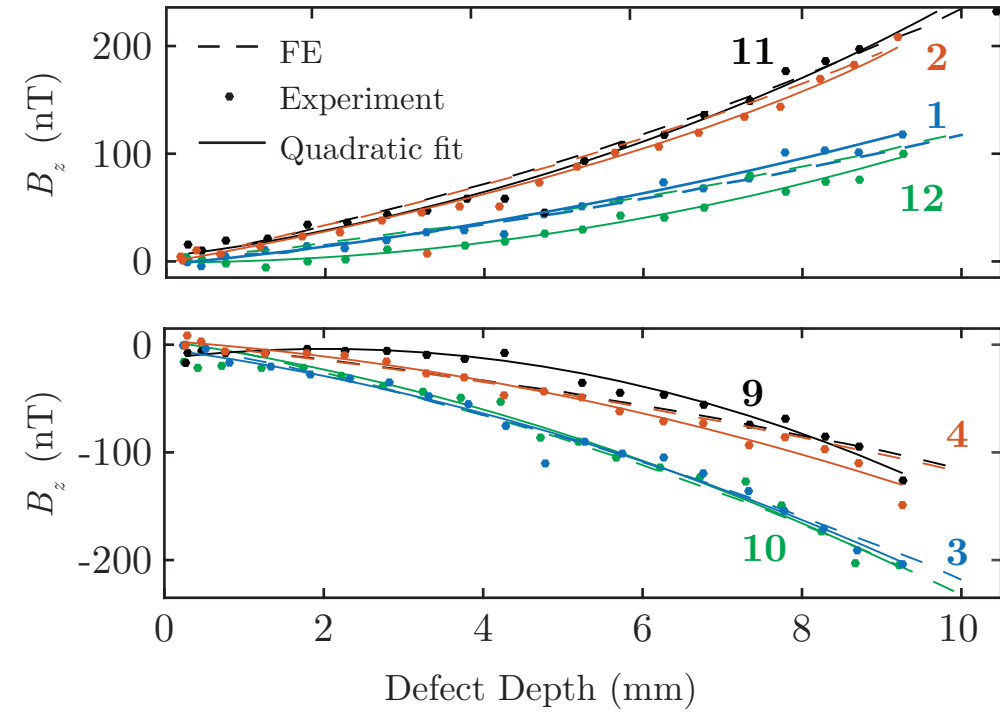
significant depth changes. Using wireless communications on permanently installed arrays in an industrial environment, it would be possible to take frequent readings which would enable more complex statistical detection methodologies. There would likely be sufficient data to monitor the rate of change of defect growth which would greatly enhance the sensitivity.

Potential interference due to movement of the current injection wires was reduced by fixing their position and ensuring the current return wire was sufficiently far from the sensor arrays. In addition, an Inertial Measurement Unit (IMU) containing tri-axial accelerometers, gyroscopes and magnetometers was mounted to the top array and used to record its orientation (Woodman 2009). In these experiments, the array orientation did not change; however, this measurement could be used to discount the changes in magnetic signal caused by sensor movement for situations in which perturbation of the sensor orientation is more likely.

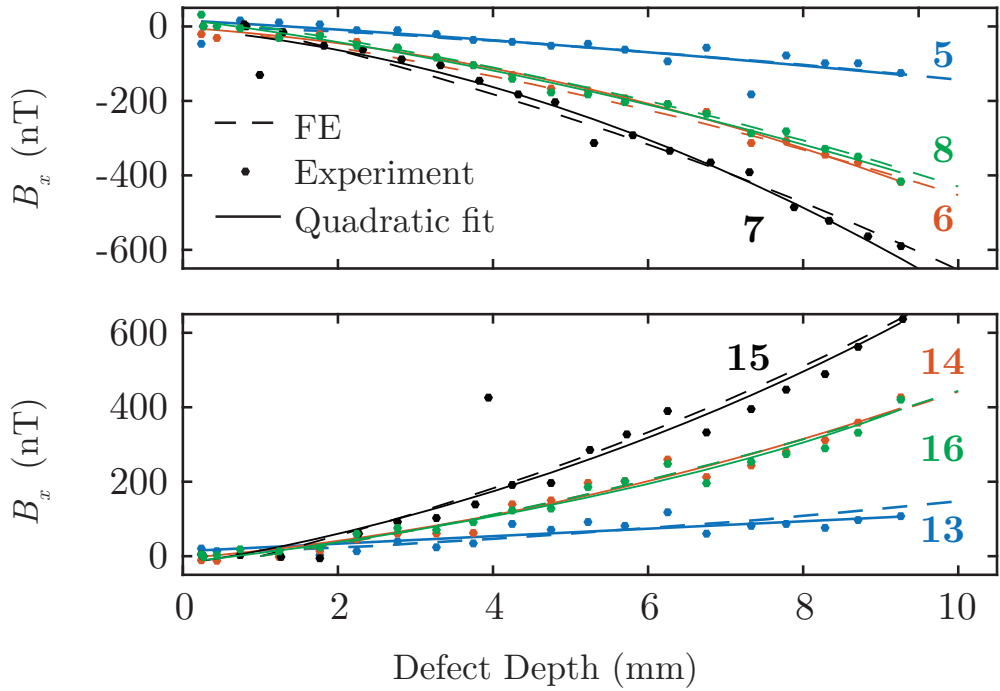
6.3.2 Results

Figure 6.11 shows how the perturbation in magnetic flux density caused by current deflection increases as the defect grows in 500 μm increments. The initial field measurement before corrosion growth formed the baseline signal, which was then subtracted from all subsequent measurements. In an undamaged state, the average baseline was 0 nT to 300 nT for the axially oriented sensors and around 13 μT for the azimuthally oriented sensors. There are equal numbers of sensors that measure a positive and a negative trend due to the positions of the sensors with respect to the signal distribution (Fig. 6.9), so the sensors that measure a positive change in the field have been plotted separately to those that display a negative trend for clarity. The axially oriented sensors on both sizes of the plate are oriented in the positive z direction, and the azimuthal sensors in the positive x direction which results in a 180° phase shift between the signal measured by sensors on opposite sides of the plate (i.e. 1 and 9, 2 and 10 etc.).

The sensors positioned closest to the defect measure the greatest change in field due to the corrosion growth, as the current deflection produces the strongest induced field in these locations; however, a discernible change in the magnetic field due to the defect growth can be observed for all sensors. The scatter in the readings at low thickness values suggests difficulty in detecting shallow defects, yet when the defect



(a)



(b)

Figure 6.11: (a) Axial and (b) azimuthal magnetic flux density change due to electrochemical corrosion growth on a pipe carrying 3 A current at 1 Hz. Solid markers are measured data, solid lines are quadratic curve fit and dashed lines are FE. Numbers shown next to data correspond to sensors described in text and shown in Fig. 6.8.

reaches a depth of 30 % of T (4.5 mm), the change in magnetic field is clear.

The sensors both on the near and far side of the plate show approximately the same amplitude change in B_z and B_x as a result of the defect growth. This demonstrates the ability to monitor the growth of both inner and outer wall defects which is possible due to the large skin-depth of the low-frequency current (~ 18 mm at 1 Hz). The change in B_x is approximately double that of B_z , suggesting a higher sensitivity; however, it must be stressed that the performance using the azimuthal sensors here is better than was predicted using the ROC of Fig. 6.3 as there were no significant environmental changes in the laboratory.

Model Validation

An FE model was created using COMSOL to represent the steel plate used in the experiment. The plate was 78 mm wide, 15 mm thick and 200 mm long (a shorter plate was modelled as the field perturbations are only of interest in the region local to the defect). The pipe was surrounded by a cylindrical air domain and magnetic insulation boundary conditions were applied to the external boundaries. This sets the tangential component of the magnetic potential to zero and acts a symmetry condition for the magnetic field. The diameter of the air domain was 6 times the width of the plate to ensure the boundary conditions did not restrict the path of the magnetic flux in the region of the defect. The model geometry is shown in Fig. 6.12.

The relative magnetic permeability was set to $\mu_r=100$. The defect was represented by a semi-ellipsoid 39 mm in diameter, based upon a measurement of the geometry of the real defect taken after the experiment was completed. A current was defined in the plate by imposing a 3 A feed at one end of the plate and a ground at the opposite end. A stationary solver was then used to solve Ampère's law at each FE node location. The model was solved for defect depths ranging from 0.5 mm to 10 mm in 0.5 mm intervals. The magnetic flux density was then extracted at the locations of the AMR sensors in the equivalent experiment, which were above and below the plate at 25 mm standoff as indicated in Fig. 6.8b. To aid the reader in visualising the physics, the magnetic field perturbation in B_z due to the defect is shown in Fig. 6.12. The FE results are plotted in Fig. 6.11 as solid lines which show very good agreement with the experimental results plotted as points. Note that

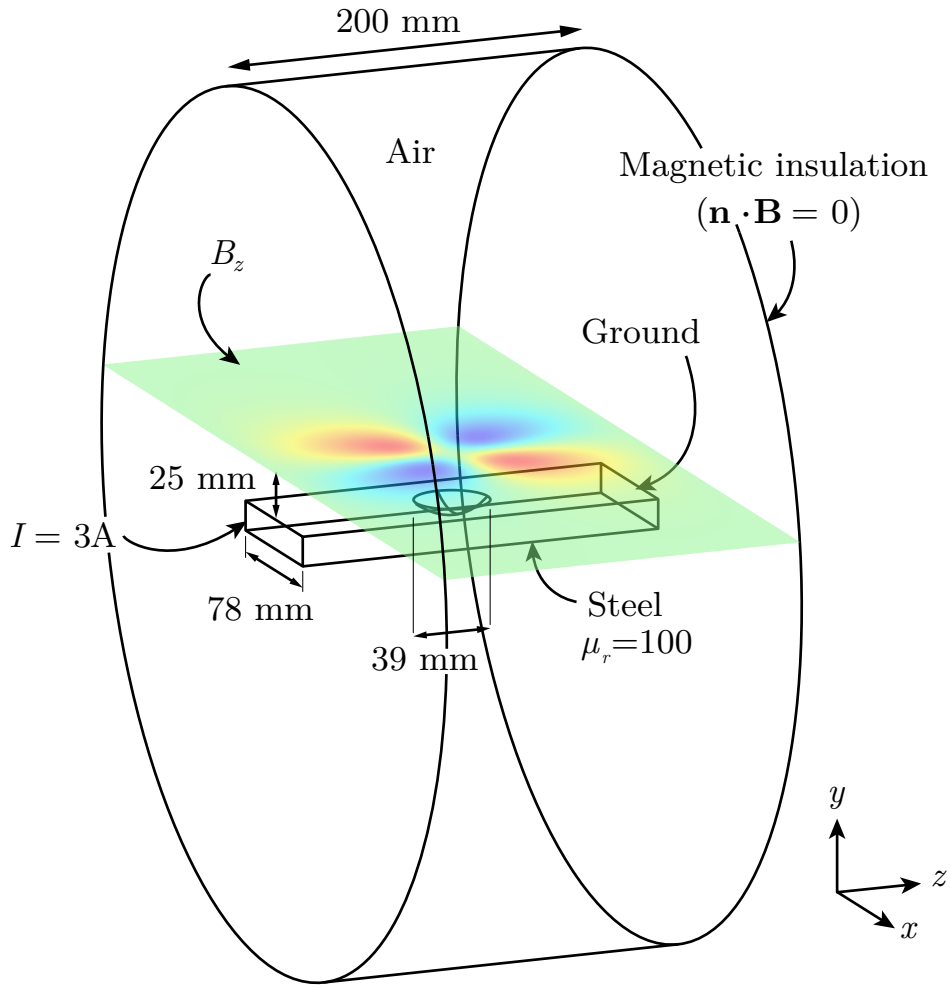


Figure 6.12: Schematic for FE model used to predict the perturbation due to current deflection from a growing defect in a plate. The colour gradient plot shows the expected perturbation in B_z .

some of the lines overlap due to the symmetry of the array and the defect signal.

6.4 Conclusions

Due to the availability of highly sensitive, low-cost sensors, current deflection has been suggested as a promising solution for monitoring CUI on unpiggable pipes. This chapter has outlined a flexible framework that allows the performance of current deflection SHM to be evaluated. Measurement of a real structure over repeated temperature cycles allowed the measurement accuracy to be ascertained, and a finite element model could then be used to predict the expected field perturbations due to current deflection around defects. This allows prediction of possible sensor con-

figurations for SHM on any pipe with any target defect with low time and resource costs.

As an example, the framework was applied to CUI monitoring on an ex-service 6" riser pipe. The results suggested that changes in the magnetic field of around 3 nT could be measured with axial or radial sensors with 90 % POD at <1 % PFA, whereas azimuthally oriented sensors get this performance for 10 nT signals due to the high-amplitude B_θ baseline signal. In this preliminary study, a simple monitoring strategy was employed in which a step change in sensor reading was equated to the detection of defect growth; however, more complex change detection methodologies would be employed in practice which exploit the availability of frequent sensor data to track defect growth over time and improve the sensitivity.

The results suggested that detection of $3T \times 3T \times \frac{T}{3}$ defects on an initially defect-free 6" pipe with 25 mm to 50 mm insulation/coating thickness would be possible using around 10 to 50 tri-axial sensors per meter of pipe and a few amperes of current. This is feasible due to the low sensor cost; however, a trial under industrial conditions would be required to determine true capabilities of the SHM method. In particular, the ability of the sensors to withstand tough conditions such as the splash zone without drift in the readings should be determined with further investigation.

The current deflection SHM of corrosion growth on a structure was demonstrated experimentally. Sensors on either side of the defective structure could measure the defect growth, confirming the technique would be able to use a sensor outside the pipe to measure damage on both the inner and outer wall. The results were also used to validate a numerical model with good agreement.

7 | Conclusions

7.1 Summary of Thesis

This thesis has documented the development of an electromagnetic NDE technique for the inspection and monitoring of pipes without the need to remove the pipe coating/insulation. Chapter 1 began by introducing the industrial motivation behind the work. There are millions of kilometers of pipelines carrying hydrocarbon fluids worldwide, the majority of which are made from carbon steel and are susceptible to time-dependent degradation e.g. corrosion and cracking. Inspection for this degradation is most routinely completed by In-Line Inspection (ILI) where a tool is inserted into the pipe where it is propelled by the fluid and is able to inspect the pipe condition. As ILI is not trivial, any pipe feature that could cause the tool to become stuck prevents its use. For these cases, which make up a significant proportion of pipes, occasional external inspection or permanent monitoring for damage is necessitated. This prompted a review of all the major techniques available for inspection and monitoring of these so-called “unpiggable” pipes.

Chapter 2 categorised each currently available NDE method by the underlying physics, with focus given to electromagnetic methods which had the most similarities to the technique being researched in this project. It was found that there were significant weaknesses that affected a number of the methods, particularly a lack of sensitivity at the standoff value associated with typical pipe insulation/coating thickness or an inability to detect internal defects. These weaknesses prompted the investigation of a technique which would be able to measure the perturbation in the induced magnetic field as a current (injected at remote locations) deflects around a defect. Advances in magnetic sensor technology and phase sensitive detection permit operation at low-frequencies, allowing detection of the very small field levels

associated with deflection around small (tens of mm diameter) corrosion defects on either the inner or outer pipe wall. This capability differentiates the technique from the similar methods of ACFM (which operates at tens of kHz and is sensitive to only surface-breaking defects) and NoPig (which has sensitivity only to relatively large defects due to the large standoff on the order of meters). Neither technique is used for health monitoring with permanently installed sensors.

Chapter 3 introduced a numerical model capable of predicting the signal distributions due to any defect geometry. An experiment used to measure current deflection signals around real pipe was also introduced, and the stability and repeatability of the measurements were quantified. The FE model was validated with scans of slot and semi-ellipsoidal defects, and was then used to investigate how a number of parameters such as the standoff affect the signal.

Chapter 4 considered how practical implementation of the current deflection method would differ from the laboratory environment or the scenarios considered in idealised numerical models. Nearby ferromagnetic objects, for example, may distort the induced magnetic field and degrade the sensitivity to defects. A regular amplitude variation was found to affect the magnetic field surrounding a seamless undamaged carbon steel pipe which had potential to mask defect signals. Further investigation revealed this to be due to magnetic property changes that occur during the pipe manufacture process.

As directional sensors are used to measure the perturbations in the field, it is essential to maintain stable sensor orientation during a scan otherwise the defect signal could become polluted by the large azimuthal component of the field arising from the injected current. To suppress this effect, it was proposed that the gradient of the magnetic field be measured using multiple sensors whose positions relative to one another are fixed.

Chapter 5 drew on both the numerical model for current deflection introduced in chapter 3, and the practical challenges discussed in chapter 4 to construct a framework that is capable of predicting the Receiver Operating Characteristics (ROC) that describe the sensitivity of the technique for defect detection by scanning. ROC are typically obtained from blind trials carried out on a number of test pieces containing realistic defects, which is resource and time intensive. The proposed framework circumvents this requirement by combining the scans of undamaged pipe with syn-

thetic damage growth and further contributions from general corrosion and sensor misalignment predicted by a validated FE model. The predicted ROC showed good potential for the current deflection technique to detect corrosion and crack damage.

Finally, chapter 6 outlined a similar framework that could be used to predict the performance of the technique when sensors are permanently installed outside the pipe insulation/coating in order to detect or monitor the growth of corrosion defects. The permanent installation of sensors permits much more frequent readings than one-off inspection which allows more advanced detection algorithms that give rise to an increased sensitivity. Although only a simple detection methodology was explored in this thesis, the current deflection technique showed great promise for structural health monitoring. This was proven by demonstrating monitoring of an electrochemically grown corrosion defect.

7.2 Key Contributions

The aim of this thesis was to explore the potential of an electromagnetic current deflection technique for NDE of unpiggable pipes and to analyse its capabilities for use as a screening technique by scanning outside the pipe, and in Structural Health Monitoring (SHM) using permanently installed sensors. In achieving this goal, a number of novel contributions have been made from an academic research perspective, and also from an industrial perspective. These contributions are summarised below:

Review of techniques for inspection and monitoring coated/insulated pipes

Although there has been some effort to document the available NDE solutions for application coated and insulated pipes, much of the literature is promotional in nature and there has not yet been a publication that effectively summarises all available methods as was presented in this thesis. Chapter 2 outlines the features and limitations of NDE methods for difficult-to-inspect pipes and provides a useful introduction to a reader seeking a brief overview of existing techniques.

Understanding of considerations affecting performance of practical implementation

In the development of a new NDE technique, an understanding of the limitations on the sensitivity is essential. The studies presented in this thesis have elucidated a number of these limitations (pipe wall thickness variations, nearby ferromagnetic objects, pipe crossings, bends, shallow general corrosion and sensor orientation and magnetic noise from seamless pipes). The results have provided understanding on how the current deflection technique should be developed for specific inspection or monitoring scenarios.

Numerical model for prediction of current deflection signals

A numerical model has been created that is able to predict the perturbations in the magnetic field from any arbitrary defect size and inspection or monitoring configuration. Due to the commercial availability of the FE software used to create the model, the description in section 3.2 could be used to reconstruct the model with little difficulty. This would prove invaluable in the design of future practical deployments of the current deflection technique.

Framework to evaluate performance of NDE scanning

A framework for the quantitative prediction of the performance of defect detection by scanning using the current deflection technique has been developed. The framework is flexible as the contribution to the signal from the defect is separated from contributions originating from other sources; this simplifies future development. The framework would be useful in determining the capabilities of current deflection NDE for a given industrial test scenario.

Framework to evaluate performance of SHM

Analysis of the sensitivity of current deflection technique as a permanent monitoring solution has been made possible via the development of a framework that combines the quantification of the measurement noise from monitoring an undamaged structure over multiple temperature cycles with the solution of a validated FE model that predicts the response to defect growth.

7.3 Comparison with Competing NDE Techniques

The final aim of the thesis was to determine whether or not the technique has significant strengths in comparison to existing methods and if so, to determine the next steps in the development of method.

In 2013, Santos and Filho reviewed technologies for the inspection of insulated riser pipe (Santos et al. 2013) where coating at the splash zone could not be removed. They concluded that best practice would be periodic inspection with SLOFEC beginning from both above and below the splash zone, combined with guided wave monitoring from above the splash zone. PEC was an alternative to SLOFEC, but it had poorer detection performance, only finding defects with a diameter greater than 60 mm when the pipe had 15 mm coating thickness whereas SLOFEC could detect all defects greater than 60 mm diameter with metal loss ranging from 10 % to 80 %. The potential advantage of PEC in measuring remnant thickness was not realised in this study as the reported results were inaccurate; however, it should be noted that PEC has been successfully used for detection of defects under insulation in many other cases (Sophian et al. n.d.). In comparison to SLOFEC, the current deflection technique has potential to detect smaller diameter defects with 15 mm coating thickness. The expected sensitivity is comparable to PEC (e.g. 10 % wall thinning detected on pipes with 10 mm to 100 mm coating thickness (Lai et al. 2015)). The scanning speeds achievable using SLOFEC are likely quicker than would be possible using current deflection; however, the equipment is heavy due to the need to magnetically saturate the pipe. Furthermore, the upper limit on coating thickness was around 15 mm whereas current deflection could potentially function on thicker coatings (Santos et al. 2013).

In 2012, Liu and Kleiner performed a review of available NDE technologies for inspection of water pipes (Z. Liu 2012). Water pipes are generally smaller diameter than petrochemical pipes, and the lower value of the pipe contents often means lower-cost techniques are preferred in contrast to petrochemical pipes. Nevertheless, the paper presents a useful overview of available methods. Of the electromagnetic methods applicable for unpiggable pipes, PEC was found to give accurate and repeatable results.

PEC and SLOFEC can be seen as the direct competitors for the current deflec-

tion technique, as both are grounded in electromagnetism, and are targeted towards corrosion detection on insulated pipes and are applicable without the removal of coating, whereas the other methods discussed in chapter 2 have alternative primary use-cases. To this end, current deflection NDE offers significant potential benefits over SLOFEC and PEC. The theoretical sensitivity is comparable, but current deflection NDE requires only inexpensive magnetic sensors and two access points for the current injection unlike the heavy equipment required by SLOFEC. PEC is an established technique for detection of corrosion under insulation; however, it has high power requirements, limited measurement accuracy at the upper standoff limit (tens of mm) and gives an average wall thickness measurement over a footprint which is typically 25 mm to 100 mm in diameter (Z. Liu 2012; Nestleroth, Davis, and Flamberg 2006). PEC cannot distinguish inner and outer-wall defects, unlike the current deflection technique which could utilise the skin-effect to differentiate either case. SLOFEC and PEC are currently only offered in scanning systems, whereas current deflection has potential for SHM using permanently installed sensors. It is clear with respect to the aim of the thesis, that current deflection NDE has potential advantages over competing methods capable of detecting defects on insulated pipe.

7.4 Direction of Future Work

This thesis has explored two potential applications of the current deflection NDE technique: defect screening by scanning and structural health monitoring. Future work could focus on expanding either or both of these applications. Although, in both cases, the signal arises from deflection of an injected current around a defect, a different set of practical challenges must be overcome in order for the technique to be successful. In this section, the potential for future developments will be highlighted.

Defect Screening by Scanning

NDE scanning involves physically moving the sensors to map the magnetic perturbations from defects; therefore, the stability of sensors is critical. This research suggested that alignment will be the limiting factor for the performance of the technique. A potential solution was explored in sections 4.7 and 5.2.4 where a gradiometer was formed synthetically by post-processing scan data acquired with well-aligned

sensors; however, future development of the technique should focus on testing and validating this principle using hardware-formed gradiometers. Similarly in section 4.6, the effect of sensor movement during acquisition was explored by post-processing model or scan data which should also be studied using a prototype scanning system. After measuring the magnetic field of a number of real, defect-free pipes in an industrial setting using a hardware gradiometer, the framework presented in chapter 5 could be used in conjunction with FE to achieve a more realistic estimate of the technique performance and to inform of the target areas for further development.

Further development of current deflection scanning would focus on improving the detection algorithm, which was relatively simple in this research. Some suggestions were given in section 5.3. Section 4.5 discussed how magnetic scans of seamless pipes would be difficult due to interference from variations in the material properties. A number of algorithms have been developed for MFL that claim to effectively suppress this interference. Future research could attempt to apply these algorithms to current deflection scans to improve detection performance on seamless pipe.

Structural Health Monitoring

Chapter 6 showcased the potential for current deflection as an SHM solution due to the high sensitivity and low cost of magnetoresistive sensors. Many of the practical challenges faced by current deflection scanning could be avoided as the sensors positions are fixed permanently. As with the scanning mode, it would be essential to control the sensors orientation in order to maximise sensitivity. The next step in the development of current deflection SHM should therefore be to quantify the signal stability in an industrial setting, after which the results could be used with the framework from chapter 6 to give a more realistic estimate of the sensitivity. In the monitoring experiments, an Inertial Measurement Unit (IMU) was used to monitor the sensor orientation, which stayed constant in the controlled laboratory environment. If a variation in sensor orientation were found in an industrial setting, future work could explore whether the IMU data could be used to compensate for orientation changes. The performance of SHM could be improved by making full use of the additional data made available by frequent sensor readings by using more advanced change detection methodologies.

A well established SHM technique is guided wave ultrasound. Guided wave

methods achieve the best results only when applied to long sections of pipe free from features such as tees, valves or circumferential welds. With permanent immobile sensors, SHM of some complex features without moving parts may be possible using the current deflection technique by employing baseline subtraction methods, so long as a current can be injected into the feature and the practical limitations of the technique are considered, such as the presence of nearby ferromagnetic objects (note that the monitoring of pipe features was not considered in this work). Guided waves can be attenuated by insulation coating, whereas the coating would not affect current deflection measurements. A relatively large amount of the coating should be removed in order to position the guided wave bracelet; whereas current deflection, in its most primitive form, requires only a pair of single attachment points to the pipe which may be made possible by exploiting the existing infrastructure (e.g. connections to the pipe for testing cathodic protection).

In addition to the issues specific to either monitoring or scanning, there lie a number of development opportunities for both the scanning and SHM techniques that were out of the scope of this thesis. For example:

- Multi-frequency or pulsed excitation could be used to exploit the skin-effect and allow higher sensitivity for surface-breaking defects, as well as an ability to locate defects on either the inner or outer pipe surface (similar to NoPig (Krivoi 2008)).
- The AMR sensors selected were the optimum choice when designing the experimentation; however, newer sensor technology is continually being developed which could offer improved performance and tri-axial sensing. Frequent reviews of sensor technology would optimise future developments.
- For the feasibility studies presented in this thesis, equipment size and measurement time was not a primary concern. Miniaturisation of the electronics and optimisation of the acquisition time should be a focus of future development. In particular, achieving simultaneous sensor interrogation would enable more rapid acquisition speeds in comparison to the multiplexing method used with the phase-sensitive detection in the current experiments, especially when using large arrays.

- It is important that the current can be injected into the pipe at distant locations with minimal coating removal. One possible solution would be to exploit existing connections with the pipe such as testing posts for cathodic protection currents. It would be crucial to investigate the best way to achieve the current injection in future work.
- Ultimately, whether or not the current deflection method receives further development will depend on its performance and cost relative to competing NDE methods. This thesis has shown that the expected performance is comparable to its competitors; however, a cost-benefit analysis would be invaluable in deciding which specific applications of the technique offer the best value.

List of Publications

- [A] Jarvis, R., Cawley, P., and Nagy, P. B. (2016a). “Current deflection NDE for the inspection and monitoring of pipes”. In: *NDT and E International* 81, pp. 46–59.
- [B] Jarvis, R., Cawley, P., and Nagy, P. B. (2016b). “Current deflection NDE for pipeline inspection and monitoring”. In: *42nd Annual Review of Progress in Quantitative Nondestructive Evaluation*. Vol. 1706. Minneapolis, MN: AIP Publishing, p. 160002.
- [C] Jarvis, R., Cawley, P., and Nagy, P. B. (2017a). “Performance evaluation of a magnetic field measurement NDE technique using a model assisted Probability of Detection framework”. In: *NDT & E International* 91, pp. 61–70.
- [D] Jarvis, R., Cawley, P., and Nagy, P. B. (2017b). “Permanently Installed Corrosion Monitoring using Magnetic Measurement of Current Deflection”. In: *Structural Health Monitoring (to be published)* 16.
- [E] Li, Z., Dixon, S., Cawley, P., Jarvis, R., and Nagy, P. B. (2017). “Study of metal magnetic memory (MMM) technique using permanently installed magnetic sensor arrays”. In: *43rd Annual Review of Progress in Quantitative Nondestructive Evaluation*. Atlanta, GA, p. 110011.
- [F] Li, Z., Dixon, S., Cawley, P., Jarvis, R., Nagy, P. B., and Cabeza, S. (2017). “Experimental studies of the magneto-mechanical memory (MMM) technique using permanently installed magnetic sensor arrays”. In: *NDT & E International*.

- [G] Li, Z., Jarvis, R., Nagy, P. B., Dixon, S., and Cawley, P. (2017). “Experimental and simulation methods to study the Magnetic Tomography Method (MTM) for pipe defect detection”. In: *NDT & E International* 92, pp. 59–66.

Bibliography

- Achterbosch, G. G. J. and Broderick, M. (2003). “NoPig - A New Technique in Pipeline Integrity”. In: *22nd World Gas Conference*. Tokyo.
- Afzal, M., Polikar, R., Udpa, L., and Udpa, S. (2001). “Adaptive noise cancellation schemes for magnetic flux leakage signals obtained from gas pipeline inspection”. In: *2001 IEEE International Conference on Acoustics, Speech, and Signal Processing. Proceedings (Cat. No.01CH37221)*. Vol. 5. IEEE, pp. 3389–3392. ISBN: 0-7803-7041-4.
- Afzal, M. and Udpa, S. (2002). “Advanced signal processing of magnetic flux leakage data obtained from seamless gas pipeline”. In: *NDT & E International* 35.7, pp. 449–457.
- Agthoven, R. van and Quakkelsteijn, H. (2007). “Different Solutions To Inspect Platform Risers”. In: *PPSA Aberdeen Seminar*, pp. 1–6.
- Alleyne, D., Pavlakovic, B., Lowe, M., and Cawley, P. (2004). “Rapid, Long Range Inspection of Chemical Plant Pipework Using Guided Waves”. In: *Key Engineering Materials* 270-273, pp. 434–441.
- Altman, D. G. and Bland, J. M. (2005). “Standard deviations and standard errors.” In: *BMJ (Clinical research ed.)* 331.7521, p. 903.
- American Petroleum Institute (2007). *API 5L Specification for line pipe*.
- Amineh, R. K., Ravan, M., Sadeghi, S. H., and Moini, R. (2008). “Using AC Field Measurement Data at an Arbitrary Liftoff Distance to Size Long Surface-breaking Cracks in Ferrous Metals”. In: *NDT & E International* 41.3, pp. 169–177.
- Arkulis, M. B., Baryshnikov, M. P., Misheneva, N. I., and Savchenko, Y. I. (2009). “On problems of applicability of the metal magnetic-memory method in testing the stressed-deformed state of metallic constructions”. In: *Russian Journal of Nondestructive Testing* 45.8, pp. 526–528.

- ASTM A106 / A106M - 14 Standard Specification for Seamless Carbon Steel Pipe for High-Temperature Service* (2014). West Conshohocken, PA.
- Atherton, D. (1995). "Remote field eddy current inspection". In: *IEEE Transactions on Magnetics* 31.6, pp. 4142–4147.
- Augustyniak, M. and Usarek, Z. (2015). "Discussion of Derivability of Local Residual Stress Level from Magnetic Stray Field Measurement". In: *Journal of Non-destructive Evaluation* 34.3, p. 21.
- Basseville, M., Nikiforov, I. V., et al. (1993). *Detection of abrupt changes: theory and application*. Vol. 104. Prentice Hall Englewood Cliffs.
- Beiki, M., Clark, D. a., Austin, J. R., and Foss, C. a. (2012). "Estimating source location using normalized magnetic source strength calculated from magnetic gradient tensor data". In: *Geophysics* 77.6, J23.
- Beugen, P. van (2009). "Pipeline Technology Conference 2009". In: *4th Pipeline Technology Conference*, p. 2.
- Bönisch, A. (2000). "Magnetic Flux and SLOFEC Inspection of Thick Walled Components". In: *15th WCNDT*. Rome.
- Bradley, I. (2009). *TNK-BP Experience with MTM*.
- Bresing, K.-H. and Sommer, B. (2015). *Steel Tube and Pipe Manufacturing Processes*. URL: http://www.smrw.de/files/steel%7B%5C_%7Dtube%7B%5C_%7Dand%7B%5C_%7Dpipe.pdf (visited on 02/09/2015).
- British Stainless Steel Association (2015). *Tolerances to BS EN 10297-2 for seamless stainless steel tubes*. URL: <http://www.bssa.org.uk/topics.php?article=423> (visited on 02/06/2015).
- British Standard (2014). *BSI Standards Publication Welded steel tubes for pressure purposes - Technical delivery conditions Part 7 : Stainless steel tubes*.
- Brondel, D., Edwards, R., Hayman, A., Hill, D., and Semerad, T. (1994). "Corrosion in the Oil Industry". In: *Oilfield Review*, pp. 4–18.
- Burkhardt, G. L., Crouch, A. E., and Fisher, J. L. (2006). *System and method using a collapsable coil for inspection of pipelines having internal restrictions*. URL: <http://www.google.co.uk/patents/US7154264>.
- Burkhardt, G. L., Goyen, T. H., Parvin, A. J., Peterson, R. H., and Tennis, R. F. (2008). "Small Diameter Remote Field Eddy Current Inspection for Unpiggable

- Pipelines". In: *ASME International Pipeline Conference*. Vol. 2. Calgary, Canada: American Society of Mechanical Engineers, pp. 41–44.
- Burrows, S., Fan, Y., and Dixon, S. (2014). "High temperature thickness measurements of stainless steel and low carbon steel using electromagnetic acoustic transducers". In: *NDT & E International* 68, pp. 73–77.
- Caleyo, F., Velázquez, J., Valor, A., and Hallen, J. (2009). "Probability distribution of pitting corrosion depth and rate in underground pipelines: A Monte Carlo study". In: *Corrosion Science* 51.9, pp. 1925–1934.
- Carboni, M. and Cantini, S. (2012). "A Model Assisted Probability of Detection approach for ultrasonic inspection of railway axles". In: *18th World Conference on Nondestructive Testing* April, pp. 16–20.
- Cawley, P., Lowe, M. J. S., Alleyne, D. N., Pavlakovic, B., and Wilcox, P. D. (2003). "Practical long range guided wave testing: applications to pipes and rail". In: *Materials Evaluation* 61.1, pp. 66–74.
- Cheng, W. (2012). "Pulsed Eddy Current Testing of Carbon Steel Pipe Wall-thinning Through Insulation and Cladding". In: *Journal of Nondestructive Evaluation* 31.3, pp. 215–224.
- Clark, R., Boyle, J. L., Douglas Jr, T. M., and LaMacchia, B. W. (2009). *HI-RAIL VEHICLE-BASED RAIL INSPECTION SYSTEM*.
- COMSOL (2017). *COMSOL Multiphysics*. URL: <http://www.uk.comsol.com/> (visited on 01/14/2014).
- COMSOL AB Stockholm, S. (2017). *AC/DC Module User's Guide*. URL: http://www.comsol.eu/doc/4.3.2.189/pdf/ACDC%5C_Module/ACDCModuleUsersGuide.pdf (visited on 08/09/2017).
- Corcoran, J. and Nagy, P. B. (2016). "Compensation of the Skin Effect in Low-Frequency Potential Drop Measurements". In: *Journal of Nondestructive Evaluation* 35.4, p. 58.
- Crouse, B. (2014). *Pulsed Eddy Current Inspection*. URL: <https://www.nde-ed.org/EducationResources/CommunityCollege/EddyCurrents/AdvancedTechniques/pulsedecinspection.htm> (visited on 09/12/2014).
- DeGarmo, E. P., Black, J. T., and Kohser, R. A. (2003). *Materials and Processes in Manufacturing*. Wiley, p. 1168. ISBN: 0471656534.

- Díaz-Michelena, M., Cobos, P., and Aroca, C. (2015). “Lock-in amplifiers for AMR sensors”. In: *Sensors and Actuators, A: Physical* 222, pp. 149–159.
- Dobson, J. (2015). “Guided wave monitoring of pipelines”. PhD thesis. Imperial College London.
- Dubov, A. (2007). *Metal Magnetic Memory (MMM) Method - A New Direction in Technical Diagnostics*. URL: <http://www.energodiagnostika.com/article-about-mmm-method.html> (visited on 08/27/2014).
- Dubov, A. (2016). “Principal Features of Metal Magnetic Memory Method and Inspection Tools As Compared To Known Magnetic NDT Methods”. In: *ECNDE*, pp. 1–5.
- Edalati, K., Rastkhah, N., Kermani, A., Seiedi, M., and Movafeghi, A. (2006). “The use of radiography for thickness measurement and corrosion monitoring in pipes”. In: *International Journal of Pressure Vessels and Piping* 83.10, pp. 736–741.
- EN 16407 Parts 1 and 2: Newly published European standards for the in-service digital and film radiography of pipes.*
- Energy Workforce (2014). *Alternating Current Field Measurement (ACFM)*. URL: <http://www.energyworkforce.net/?p=35> (visited on 05/30/2014).
- Foster-miller, R. T., Foster-miller, W. L., and Vradis, G. (2004). “Robotic Inspection System for Unpiggable Pipelines”. In: *Proceedings of IPC2004*. Calgary, Alberta, Canada: ASME.
- Fücsök, F., Müller, C., and Scharmach, M. (2005). “Measuring of the Reliability of NDE”. In: *The 8th International Conference of the Slovenian Society for Non-Destructive Testing*. Portoroz, pp. 173–180.
- Fúra, V., Petrucha, V., and Platil, A. (2016). “Construction of an AMR magnetometer for car detection experiments”. In: *IOP Conference Series: Materials Science and Engineering* 108, p. 012028.
- Galvagni, A. and Cawley, P. (2014). “Reliable Identification of Damage Growth Using Guided Wave SHM Systems”. In: *EWSHM - 7th European Workshop on Structural Health Monitoring*. Ed. by V. Le Cam, L. Mevel, and F. Schoefs. IFFSTTAR, Inria, Université de Nantes. Nantes, France.
- Gan, F., Tian, G., Wan, Z., Liao, J., and Li, W. (2016). “Investigation of pitting corrosion monitoring using field signature method”. In: *Measurement* 82, pp. 46–54.

- Gang, Y., Yingtang, Z., Zhining, L., Hongbo, F., and Guoquan, R. (2016). “Detection of ferromagnetic target based on mobile magnetic gradient tensor system”. In: *Journal of Magnetism and Magnetic Materials* 402, pp. 1–7.
- Georgiou, G. A. (2006). *Research Report 454 - Probability of Detection (PoD) curves*. Tech. rep. Jacobi Consulting Limited, p. 8.
- Guo, J., Zeng, L., and Liu, B. (2011). “High-quality image reconstruction from exterior helical cone-beam CT data for NDE of industrial pipelines”. In: *Insight - Non-Destructive Testing and Condition Monitoring* 53.10, pp. 534–541.
- Haith, M. I. (2017). “Radiographic imaging of subsea pipelines”. EngD Thesis. Imperial College London.
- Han, W. (2008). “A new denoising algorithm for MFL data obtained from seamless pipeline inspection”. In: *Russian Journal of Nondestructive Testing* 44.3, pp. 184–195.
- Harcourt, D. C. and Sperry, E. G. (1935). *Rail flaw detector mechanism*. URL: <https://www.google.co.uk/patents/US2077812?dq=sperry+rail%7B%5C%7Dhl=en%7B%5C%7Dsa=X%7B%5C%7Dved=0ahUKEwj0o8GJ3oHYAhUoJcAKHbLCAfEQ6AEIYjAI>.
- Hobbs, C. (1997). “Obtaining a clearer picture of corrosion using non-destructive testing”. In: *Anti-Corrosion Methods and Materials* 44.4, pp. 232–235.
- Honarvar, F., Salehi, F., Safavi, V., Mokhtari, A., and Sinclair, A. N. (2013). “Ultrasonic monitoring of erosion/corrosion thinning rates in industrial piping systems.” In: *Ultrasonics* 53.7, pp. 1251–8.
- Janošek, M., Platil, A., and Vyhnánek, J. (2016). “Simple estimation of dipole source z-distance with compact magnetic gradiometer”. In: *IOP Conference Series: Materials Science and Engineering* 108, p. 012025.
- Jarvis, R., Cawley, P., and Nagy, P. B. (2016). “Current deflection NDE for the inspection and monitoring of pipes”. In: *NDT and E International* 81, pp. 46–59.
- Jarvis, R., Cawley, P., and Nagy, P. B. (2017a). “Performance evaluation of a magnetic field measurement NDE technique using a model assisted Probability of Detection framework”. In: *NDT & E International* 91, pp. 61–70.
- Jarvis, R., Cawley, P., and Nagy, P. B. (2017b). “Permanently Installed Corrosion Monitoring using Magnetic Measurement of Current Deflection”. In: *Structural Health Monitoring (to be published)* 16.

- Jiles, D. (1988). "Review of magnetic methods for nondestructive evaluation". In: *NDT International* 21.5, pp. 311–319.
- Jiles, D. (1998). *Introduction to Magnetism and Magnetic Materials, Second Edition*. CRC Press, p. 568. ISBN: 0412798603.
- Jiles, D. (1999). "Theory of the magnetomechanical effect". In: *Journal of Physics D: Applied Physics* 32, pp. 1945–1945.
- Jogschies, L. et al. (2015). "Recent developments of magnetoresistive sensors for industrial applications". In: *Sensors (Switzerland)* 15.11, pp. 28665–28689.
- Jones, R. E., Simonetti, F., Lowe, M. J. S., and Bradley, I. P. (2012). "Use of Microwaves for the Detection of Water as a Cause of Corrosion Under Insulation". In: *Journal of Nondestructive Evaluation* 31.1, pp. 65–76.
- Khodayari-Rostamabad, A., Reilly, J. P., Nikolova, N. K., Hare, J. R., and Pasha, S. (2009). "Machine learning techniques for the analysis of magnetic flux leakage images in pipeline inspection". In: *IEEE Transactions on Magnetics* 45.8, pp. 3073–3084.
- Kim, D.-K. et al. (2013). "Development of MFL system for in-pipe robot for unpiggable natural gas pipelines". In: *2013 10th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*. IEEE, pp. 51–54. ISBN: 978-1-4799-1197-4.
- Knopp, J. S., Aldrin, J. C., Lindgren, E., and Annis, C. (2007). "Investigation of a model-assisted approach to probability of detection evaluation". In: *AIP Conference Proceedings* 894.2007, pp. 1775–1782.
- Kolesnikov, I. (2014). "Magnetic Tomography Method (MTM): A Remote Non-destructive Inspection Technology for Buried and Sub Sea Pipelines". In: *OTC Arctic Technology Conference*. Offshore Technology Conference. ISBN: 9781613993552.
- Krivoi, G. S. (2008). "NoPig: An above-ground inspection technique for non-piggable pipelines". In: *Oil Gas European Magazine* 34.03, pp. 122–124.
- Krivoi, G. S. (2007). "NoPig: A New Inspection Technique for Non-piggable Pipelines". In: *Pipeline Technology Conference*. Hannover Messe, p. 7.
- Laenen, C., Salazar, G., and Topp, D. (2007). "Application of the ACFM inspection method for the inspection of internal tank welds". In: *IV Conferencia Panamericana de END*. Buenos Aires.

- Lai, S., Chen, D., Chen, H., and Fu, Y. (2015). “Pulsed Eddy Current Testing of Inner Wall Flaws in Pipe under Insulation”. In: *Procedia Engineering* 130, pp. 1658–1664.
- Laursen, P., D’Zurko, D., Vradis, G., and Swiech, C. (2010). “Robotic Inspection of Unpiggable Natural Gas Transmission and Distribution Pipeline”. In: *8th International Pipeline Conference*. Calgary, Canada: ASME, pp. 407–410. ISBN: 978-0-7918-4420-5.
- Leinov, E., Lowe, M. J., and Cawley, P. (2016). “Ultrasonic isolation of buried pipes”. In: *Journal of Sound and Vibration* 363, pp. 225–239.
- LeTessier, R., Coade, R., and Geneve, B. (2002). “Sizing of cracks using the alternating current field measurement technique”. In: *International Journal of Pressure Vessels and Piping* 79.8-10, pp. 549–554.
- Lewis, A. M. (1991). “The modelling of electromagnetic methods for the nondestructive testing of fatigue cracks”. PhD thesis. University College London.
- Lewis, A. M., Michael, D. H., Lugg, M. C., and Collins, R. (1988). “Thin-skin electromagnetic fields around surface-breaking cracks in metals”. In: *Journal of Applied Physics* 64.8, p. 3777.
- Li, Y., Yan, B., Li, D., Li, Y., and Zhou, D. (2016). “Gradient-field pulsed eddy current probes for imaging of hidden corrosion in conductive structures”. In: *Sensors and Actuators A: Physical* 238, pp. 251–265.
- Li, Z., Dixon, S., Cawley, P., Jarvis, R., and Nagy, P. B. (2017). “Study of metal magnetic memory (MMM) technique using permanently installed magnetic sensor arrays”. In: *43rd Annual Review of Progress in Quantitative Nondestructive Evaluation*. Atlanta, GA, p. 110011.
- Li, Z., Dixon, S., Cawley, P., Jarvis, R., Nagy, P. B., and Cabeza, S. (2017). “Experimental studies of the magneto-mechanical memory (MMM) technique using permanently installed magnetic sensor arrays”. In: *NDT & E International*.
- Li, Z., Jarvis, R., Nagy, P. B., Dixon, S., and Cawley, P. (2017). “Experimental and simulation methods to study the Magnetic Tomography Method (MTM) for pipe defect detection”. In: *NDT & E International* 92, pp. 59–66.
- Liao, K., Yao, Q., and Zhang, C. (2011). “Principle and Technical Characteristics of Non-contact Magnetic Tomography Method Inspection for Oil and Gas Pipeline”.

- In: *International Conference on Pipelines and Trenchless Technology*. Beijing, China: ASCE, pp. 1039–1048.
- Liu, C., Dobson, J., and Cawley, P. (2017). “Efficient generation of receiver operating characteristics for the evaluation of damage detection in practical structural health monitoring applications”. In: *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 473.2199.
- Liu, Z. (2012). “State-of-the-Art Review of Technologies for Pipe Structural Health Monitoring”. In: *Structural Health Monitoring* 12.6, pp. 1987–1992.
- Lowe, M., Alleyne, D., and Cawley, P. (1998). “Defect detection in pipes using guided waves”. In: *Ultrasonics* 36.1-5, pp. 147–154.
- Lugg, M. C. (2004). “Alternating current field measurement”. In: *ASNT Nondestructive Testing Handbook, Vol. 5 Electromagnetic Testing*. 3rd ed. ASNT, pp. 247–269. ISBN: 0471420298.
- Lugg, M. C. (2012). “The First 20 Years of the AC field Measurement Technique”. In: *18th World Conference on Nondestructive Testing*. April. Durban, South Africa, p. 7.
- Lugg, M. C. and Topp, D. (2006). “Recent Developments and Applications of the ACFM Inspection Method and ACSM Stress Measurement Method”. In: *EC-NDT*. Berlin, pp. 1–14.
- Mao, B., Lu, Y., Wu, P., Mao, B., and Li, P. (2014). “Signal processing and defect analysis of pipeline inspection applying magnetic flux leakage methods”. In: *Intelligent Service Robotics* 7.4, pp. 203–209.
- McKirdy, D. M. and Lewis, A. M. (1993). “ACFM Above a Hemispherical Pit in an Aluminum Block”. In: *Review of Progress in Quantitative Nondestructive Evaluation*, pp. 265–270.
- Michael, D. H., Lewis, A. M., McIver, M., and Collins, R. (1991). “Thin-skin electromagnetic fields in the neighborhood of surface-breaking cracks in metals”. In: *Proc. R. Soc. London, Ser. A* 434.1892, pp. 587–603.
- Mirzoev, A., Mirzoev, A., Mashurov, S., and Sibila, J. (2016). “A Comprehensive Approach To Integrity Of Non-Piggable Pipelines Based On Combined DCVG / CIPS / MTM Survey”. In: *Pipeline Technology Journal* 1.08, pp. 20–26.
- Mitra, M. and Gopalakrishnan, S. (2016). “Guided wave based structural health monitoring: A review”. In: *Smart Materials and Structures* 25.5, p. 053001.

- Müller, C. et al. (2009). “Progress in Evaluating the Reliability of NDE Systems - Paradigm Shift”. In: *DGZfP Proceedings BB 116-CD: 4th European-American Workshop on Reliability of NDE, 24-26 June 2009, Berlin, Germany*, pp. 1–10.
- Nagy, P. B. (2011). “Electromagnetic NDE”. Course Notes.
- Nagy, P. B. (2012a). *ACFM online monitoring of TIG welding of austenitic stainless steel pipes - Phase 1 Report*. Tech. rep. University of Cincinnati, pp. 1–28.
- Nagy, P. B. (2012b). “Electromagnetic Nondestructive Evaluation”. In: *Ultrasonic and Electromagnetic NDE for Structure and Material Characterization: Engineering and Biomedical Applications*. Ed. by T. Kundu. 1st ed. Boca Raton, FL: CRC Press. Chap. 3, p. 890. ISBN: 1439836639.
- Nestleroth, J. B. and Davis, R. J. (2007). “Application of eddy currents induced by permanent magnets for pipeline inspection”. In: *NDT & E International* 40.1, pp. 77–84.
- Nestleroth, J. B., Davis, R. J., and Flamberg, S. (2006). *Innovative Sensor for Pipeline Crawlers: Rotating Permanent Magnetic Inspection*. Tech. rep. December. Columbus Ohio.
- Oceaneering International (2017). *Oceaneering International*. URL: <http://www.oceaneering.com/>.
- Ong, P. S., Patel, V., and Balasubramanyan, A. (1997). “Quantitative characterization of corrosion under insulation”. In: *Journal of Nondestructive Evaluation* 16.3, pp. 135–146.
- Plotnikov, Y., May, A., Nath, S., and Wang, C. (2008). *Pulsed eddy current pipeline inspection system and method*.
- Quarini, J. and Shire, S. (2007). “A Review of Fluid-Driven Pipeline Pigs and their Applications”. In: *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* 221.1, pp. 1–10.
- Raad, J. de, Bouma, T., and Bonisch, A. (2002). “Rapid corrosion screening in up to 30 mm wall thickness for plates and pipe”. In: *Insight* 44.2, pp. 97–103.
- Rail Inspection (2017). URL: <https://www.nde-ed.org/AboutNDT/SelectedApplications/RailInspection/RailInspection.htm> (visited on 12/11/2017).
- Rice, S. O. (1951). “Reflection of electromagnetic waves from slightly rough surfaces”. In: *Communications on Pure and Applied Mathematics* 4.2-3, pp. 351–378.

- Sadr, A. and Okhovat, R. (2016). "Extracting the region of interest from MFL signals". In: *Turkish Journal of Electrical Engineering and Computer Sciences* 24.2, pp. 427–434.
- Saka, M., Tohmyoh, H., Suzuki, T., and Ahmed, S. R. (2006). "Potential Drop Imaging Technique for Sensitive NDE of Small Surface Cracks". In: *12th A-PCNDT*, pp. 10–13.
- Santhosh Lukose (2010). "Detecting Corrosion Under Insulation (CUI) in Piping with Profiler System". In: *Inspectioneering Journal* 16.4, pp. 4–6.
- Santos, R. W. F. and Filho, M. P. (2013). "Evaluation of Technologies for Inspection of Riser Splash Zone". In: *OTC Brasil*. Offshore Technology Conference. ISBN: 978-1-61399-287-6.
- Saunderson, D. H. (1988). "The MFE tank-floor scanner - A case history - IET Conference Publication". In: *Non-Destructive Evaluation, IEE Colloquium on*. London: IET, pp. 811–812.
- Schneider, R. W. and Smith, C. H. (1999). *Low Magnetic Field Sensing with GMR Sensors, Part 2: GMR Sensors and Their Applications / Sensors*. URL: <http://www.sensorsmag.com/sensors/electric-magnetic/low-magnetic-field-sensing-with-gmr-sensors-part-2-gmr-senso-929>.
- Sensitec MagnetoResistive Sensors (2011). *AFF755B MagnetoResistive Field Sensor Data Sheet*.
- Shi, Y., Zhang, C., Li, R., Cai, M., and Jia, G. (2015). "Theory and Application of Magnetic Flux Leakage Pipeline Detection". In: *Sensors* 15.12.
- Singer, J. R. (2013). *Method and Apparatus for Magnetic Response Imaging*.
- Singer, J. R., Stevick, G., and King, D. (2013). "Detecting and Monitoring Corrosion under Insulation in Piping". In: *Mat. Corr.* 52.10, pp. 8–10.
- Slessarev, D., Sukhorukov, V., and Belitsky, S. (2006). "Magnetic In-Line Inspection of Pipelines : Some Problems of Defect Detection , Identification and Measurement". In: *ECNDE*. Paris, pp. 1–5.
- Sloan, R. N. (2001). "Pipeline Coatings". In: *Control of Pipeline Corrosion*. Ed. by A. W. Peabody. 3rd ed. Houston, Texas: NACE International. Chap. 2, pp. 7–20. ISBN: 1575900920.

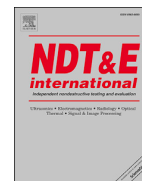
- Sohn, H. (2007). “Effects of environmental and operational variability on structural health monitoring”. In: *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 365.1851.
- Song, Q., Ding, W., Peng, H., Shuai, J., and Wang, B. (2017). “A new magnetic testing technology based on magnetic gradient tensor theory”. In: *Insight (to be published)*.
- Sophian, A., Tian, G., and Fan, M. “Pulsed Eddy Current Non-destructive Testing and Evaluation: A Review”. In: *Chinese Journal of Mechanical Engineering* 30.
- Spier Hunter Limited (2014). *Stress Concentration Tomography*. URL: <http://www.speirhunter.com/files/SCT%20official%20Brochure.pdf> (visited on 09/11/2014).
- Sposito, G. (2009). “Advances in Potential Drop Techniques for Non-Destructive Testing”. PhD thesis. Imperial College London, p. 189.
- Stanford Research Systems (2011). *Model SR830 DSP Lock-In Amplifier*. Sunnyvale, California.
- Stefanita, C.-G. (2008). “Barkhausen Noise as a Magnetic Nondestructive Testing Technique”. In: *From Bulk to Nano*. 1st ed. Berlin, Heidelberg: Springer. Chap. 2, pp. 19–40. ISBN: 978-3-540-70547-5.
- Stone, M. (2009). “Wall Thickness Distributions for Steels in Corrosive Environments and Determination of Suitable Statistical Analysis Methods”. In: *4th European-American Workshop on Reliability*.
- Stutzke, N. A., Russek, S. E., Pappas, D. P., and Tondra, M. (2005). “Low-frequency noise measurements on commercial magnetoresistive magnetic field sensors”. In: *Journal of Applied Physics* 97.10, 10Q107.
- Suárez-Ántola, R. and Suárez-Bagnasco, D. (2014). “The Physical Foundations of the Magnetic Memory Method of NDT”. In: *Segundas Jornadas Técnicas de la Asociación Uruguaya de Ensayos No Destructivos*.
- Swets, J. (1983). “Assessment of NDT systems-Part I: The relationship of true and false detections.” In: *Materials Evaluation* 41.11, pp. 1294–1298.
- Teitsma, A. (2004). *Remote Field Eddy Current Inspection of Unpiggable Pipelines*. English. Tech. rep. Pittsburgh, PA, and Morgantown, WV: Gas Technology Institute (US), pp. 1–42.

- Temperature & Climatic Test Chambers - Weiss Technik UK* (2017). URL: <http://weiss-uk.com/products/temperature-and-climatic-testing/temperature-and-climatic-test-chambers> (visited on 06/21/2017).
- TWI ltd. (2002). *Guidelines for use of statistics for analysis of sample inspection of corrosion*. Ed. by HSE Health & Safety Executive. Cambridge: HSE Health & Safety Executive, p. 8.
- UK Research Centre in NDE* (2017). URL: <https://www.rcnde.ac.uk/> (visited on 06/28/2017).
- Vyhnanek, J., Janosek, M., and Ripka, P. (2013). “Low frequency noise of anisotropic magnetoresistors in DC and AC-excited metal detectors”. en. In: *Journal of Physics: Conference Series* 450.1, p. 012031.
- Wang, Z., Yao, K., Deng, B., and Ding, K. (2010). “Theoretical studies of metal magnetic memory technique on magnetic flux leakage signals”. In: *NDT & E International* 43.4, pp. 354–359.
- Willcock, S. (1985). “An investigation of the magnetic properties of high tensile steels”. PhD thesis. Durham University.
- Willcock, S., Tanner, B., and Mundell, P. (1987). “The magnetic properties of seamless steel pipe”. In: *Journal of Magnetism and Magnetic Materials* 66.1, pp. 153–157.
- Wilson, J. W. and Tian, G. Y. (2007). “Pulsed electromagnetic methods for defect detection and characterisation”. In: *NDT & E International* 40.4, pp. 275–283.
- Wold, K. and Sirnes, G. (2007). *Fsm Technology - 16 Years Of Field History-Experience, Status And Further Developments*.
- Woodman, O. J. (2009). *An introduction to inertial navigation*. Tech. rep. 3B. Cambridge: University of Cambridge, pp. 961–2. arXiv: ISSN1476–2986.
- Wu, J. et al. (2017). “A Lift-Off-Tolerant Magnetic Flux Leakage Testing Method for Drill Pipes at Wellhead.” In: *Sensors (Basel, Switzerland)* 17.1.
- Yin, W., Hao, X., Peyton, A., Strangwood, M., and Davis, C. (2009). “Measurement of permeability and ferrite/austenite phase fraction using a multi-frequency electromagnetic sensor”. In: *NDT & E International* 42.1, pp. 64–68.
- Zscherpel, U. et al. (2006). “Radiographic Evaluation of Corrosion and Deposits in Pipelines: Results of an IAEA Co-ordinated Research Program”. In: *European Conference on NDT*. Berlin.



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Experimental studies of the magneto-mechanical memory (MMM) technique using permanently installed magnetic sensor arrays

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ABSTRACT

The magneto-mechanical memory (MMM) method, that is often referred to as the metal magnetic memory method, has been reported to be a non-destructive testing technique capable of quantifying stress concentrations and detecting defects in ferromagnetic materials. The underlying mechanism behind MMM has been explained in the literature, but the sensitivity to stress concentration has not been satisfactorily investigated. In this paper, both the normal and tangential components of the stress-induced MMM signal were measured by permanently installed magnetic sensor arrays on specimens made from three grades of L80 alloy steel and 20 other structural steels; tests were also carried out on a pipe made from the 4140-L80 steel. As expected, the stress history affects the MMM signal, but the experimental results show that significant irreversible change of magnetization always occurs only in the first cycle of loading regardless whether the deformation is purely elastic or partially plastic. If the peak stress level is increased at a given point during cycling, the immediately following next cycle acts as a new “first” cycle at that peak stress level and causes additional significant irreversible change of magnetization, but there is no evidence that plastic deformation might build up a cumulative magnetization. The MMM effect is very small in the steel samples tested, indicating that it will not be useful in field applications. In un-notched specimens the irreversible change in magnetization caused a proportional change in the measured external magnetic field on the order of only 5–10 A/m, while in the case of notched specimens the leakage field was on the order of 30–60 A/m.

1. Introduction

Internal or external corrosion in pipelines is unavoidable, and compromises the structural integrity of the pipeline [1]. The pressure and bending stresses that the pipe experiences will result in stress concentrations in corroded areas due to geometric wall thinning. The ability to detect and quantify a stress concentration zone (SCZ) or detect micro-defect growth, can in principle enable one to predict the location of mechanical failure and evaluate the residual life of pipelines [2]. There is a range of well-established non-destructive testing (NDT) methods used in pipeline inspection, such as radiography, ultrasonic testing, eddy current testing and magnetic flux leakage (MFL) pipeline pigs [3]. The magneto-mechanical memory (MMM) technique, which is also referred to as the metal magnetic memory technique [4–7], is promoted as a passive, non-contact NDT method, that uses measurement of the residual magnetic leakage field (RMLF) above a pipe to detect regions of stress

concentration or defects [5,8–12].

Ferromagnetic materials exhibit intrinsic remanent magnetization left behind after the applied magnetic field is removed. This magnetic memory effect is widely exploited in magnetic storage devices and can be also exploited for the purposes of nondestructive materials characterization. Of particular interest in this study was magnetic memory of the mechanical deformation history of ferromagnetic materials that can be directly related to remaining strength and service life of fracture critical components. The underlying physical phenomenon behind such magnetic memory of a mechanical origin is the so-called magneto-mechanical effect [6,13,14], in which the application of stress in a ferromagnetic material causes the rearrangement of magnetic domains, thereby causing a change in the magnetization of the material. The MMM method is generally rather weak and perceivable only in the absence of strong applied magnetic fields. Therefore these NDE techniques require high detection sensitivities commonly encountered in residual magnetic flux

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leakage measurements. Jiles and Atherton laid down the foundation of NDE based on the elastic magneto-mechanical effect [13,14], which shows that the largest change in RMLF is always in the very first elastic loading cycle. Then, further cycling at the same stress level has no significant effect on the RMLF signal. Dubov reported stronger cumulative elastic and plastic magneto-mechanical effects that he called the “magnetoelastic” effect [5] and “magnetoplastics” [6], respectively. These effects were reported to manifest themselves in an irreversible increase of RMLF in the presence of a weak external field, as shown in Fig. 1. Dubov postulated that cyclic plastic strain has a cumulative effect, so that the RMLF increases right up to point of failure. This effect would make defects producing stress concentrations in heavily loaded structures progressively easier to detect as failure approaches, and could be a very attractive approach for NDT. However, before basing an inspection procedure on the method, it is necessary to determine the strength of the effect in the materials of interest. The magneto-mechanical effect is sensitive to the microstructure of the ferromagnetic material, meaning that mechanical cyclic softening or strengthening can be observed on different materials [15].

A potentially significant advantage of the MMM technique as a means to locate stress concentration or monitor defects is that the signal intensity is not as significantly affected by the stand-off as other techniques such as ultrasound or eddy current inspection [3,16]. This could allow the technique to be applied for detection of corrosion under insulation or in buried pipes at significant stand-off [17]. The MMM technique has been implemented as a periodic screening inspection tool by measuring RMLF distribution on the outer surface of a specimen [18]. It has been reported to be capable of evaluating the degree of stress concentration [19–22], indicating the deformation stage [23–26], and monitoring fatigue crack propagation [27–29].

Recent publications have suggested that the MMM technique has low reliability when used for stress assessment if the formation conditions of the remanence state are not taken into account [30–32]. Different formation conditions may cause significant variation in remanent magnetization. The RMLF produced due to stress concentration depends on many factors, such as the initial magnetic state [33], the external background magnetic field [34,35], the chemical composition and microstructure of the material [15,35] and the load history [36]. In most MMM experiments in the published literature, the chemical composition of samples was known in advance, and the samples were usually demagnetized prior to the application of stress. As the source of excitation in the

MMM technique, the background magnetic field only changes the MMM signal magnitude, and does not change the profile of the response curves. The load history has a more complex influence on the MMM signal, due to the hysteresis of the magneto-mechanical effect [13,36].

During site trials, the MMM technique has been shown to detect defects in some instances, but has failed in other trials [37]. It is interesting to note that diagrams of the form of Fig. 1 are often presented in a schematic form in papers on the MMM technique [5,6,38], rather than being illustrated with real experimental data. In this paper we evaluate the sensitivity of the MMM technique using permanently installed monitoring systems on some steel alloys commonly used in pipeline applications. The primary question this study raises is whether the magnetic memory exhibited by some common Grades of L80 pipe steel conforms to the relatively weak magneto-mechanical effect predicted by Jiles and Atherton [13,14] or to the empirical observations of a stronger cumulative magnetoplastic effect reported by Dubov [6] and others. Both effects occur in the presence of weak external magnetic fields such as the natural geomagnetic field (30–50 A/m).

In this paper, dog-bone specimens were prepared from representative materials and tensile testing was carried out. In addition, four point bending tests were performed on a pipe specimen. Both the normal and tangential components of the stress-induced RMLF just above the specimen surface were measured by means of permanently installed magnetic sensor arrays. Two types of notches were machined in the dog-bone specimens to introduce local stress concentration. The variations of the MMM signal during elastic and plastic deformation during the loading process under different strength biasing magnetic fields were investigated. Tests were also carried out on a pipe made from one of the materials in four point bending in order to investigate whether similar effects were seen in geometries more representative of industrial practice.

2. Experimental set-ups and samples

2.1. Specimen preparation

Samples were prepared from three different grades of L80 alloy steel [39], which are commonly used for pipelines in the petrochemical industry, and from 20 other structural steels [40–45]. The chemical composition and mechanical properties of these steels are shown in Tables 1 and 2 in the Appendix, respectively. The 5 mm thick, flat, dog-bone shape specimens were machined from pipes of various diameters and wall thicknesses or plates of various lengths and widths, with the dimensions shown in Fig. 2.

One 450 mm long pipe specimen was prepared for a four point bending test. The material of the pipe specimen was 4140-L80 with outer diameter 60.32 mm and wall thickness 4.83 mm.

2.2. Experimental instrumentation

An Instron 1185 testing machine, whose load error is $\pm 0.5\%$, was used to carry out the tensile tests on the dog-bone specimens and a Testometric 100 kN FS machine was used to carry out the four point bending test on the pipe specimen. To reduce the influence of surrounding ferromagnetic materials, the specimen clamps for the tensile test and the loading cells for the bending test were made of non-magnetic stainless steel.

The normal and tangential components of the stress-induced RMLF, which are known as the MMM signal, were measured by two permanently installed magnetic sensor arrays. Each magnetic sensor array consists of 16 channels (8 normal channels and 8 tangential channels) of AMR sensors AFF755B, whose resolution is 0.0016 A/m and sensitivity is 15 (mV/V)/(kA/m) [46].

For the dog-bone samples, two linear AMR sensor arrays were fixed on the sides of the specimen surface to isolate magnetic fields originating inside the specimen. The 16 channels of AMR sensors were labeled 1 to

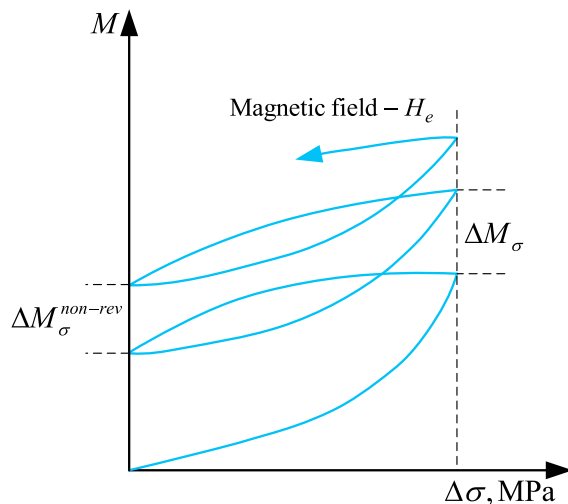


Fig. 1. Schematic representation of the magnetoelastic effect action mechanism (after [6]): ΔM_e and $\Delta M_{\sigma}^{non-rev}$ are variations of residual magnetization under load and after its relief, respectively, $\Delta\sigma$ is the variation of thermal stress and H_e is the external magnetic field.

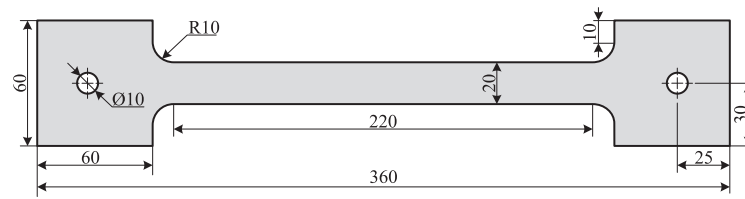


Fig. 2. Geometry and dimensions of the dogbone specimen (units: mm).

16 and fixed on two 3D printed ABS plastic sensor holders, as shown in Fig. 3. The tangential magnetic field sensors were marked by odd numbers (blue colour), while the normal ones were marked by even numbers (orange colour). Here, the “normal magnetic field” component is in the direction normal to the specimen surface, while the “tangential magnetic field” is in the direction parallel to the specimen surface in the length direction of the sample. The tangential and normal magnetic field sensors were placed alternately in the length direction. The designations f and b represent the front face and back face, respectively.

Two ring AMR sensor arrays were fixed on the outer surface of the pipe specimen, as shown in Fig. 4. The tangential magnetic field sensors were marked by odd numbers (blue colour), while the normal ones were marked by even numbers (orange colour). Here, the “normal magnetic field” component is in the direction normal to the pipe surface, while the “tangential magnetic field” is in the direction parallel to the specimen surface in the axial direction of the pipe. The tangential and normal magnetic field sensors were placed alternately in the circumferential direction.

An electrical circuit was designed to control the 32 channels of AMR sensors, as shown in Fig. 5. In Fig. 5, the shape of the AMR sensor arrays can be either linear or ring and the corresponding specimen is either a dog-bone sample or pipe sample. The AMR sensors were powered by a constant voltage power supply. The multiplexer, which consists of 4×16 channels, was divided into two groups and controlled by a Pico data logger to switch the differential outputs of the AMR sensors into a two channel amplification circuit. The amplified voltages were captured by the Pico data logger and then sent to a PC for post processing.

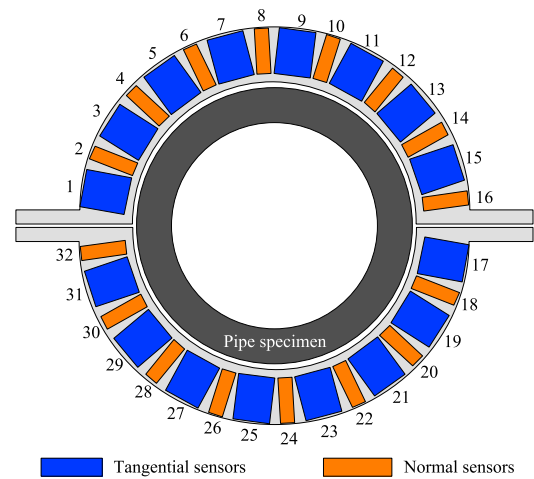


Fig. 4. Schematic diagram of the configuration of the ring AMR sensor arrays. The tangential magnetic field sensors were marked by odd numbers (blue colour), while the normal ones were marked by even numbers (orange colour). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Experimental procedure

Five experiments were conducted in this study. Firstly, one 4140-L80 dog-bone specimen was chosen to study the elastic magneto-mechanical

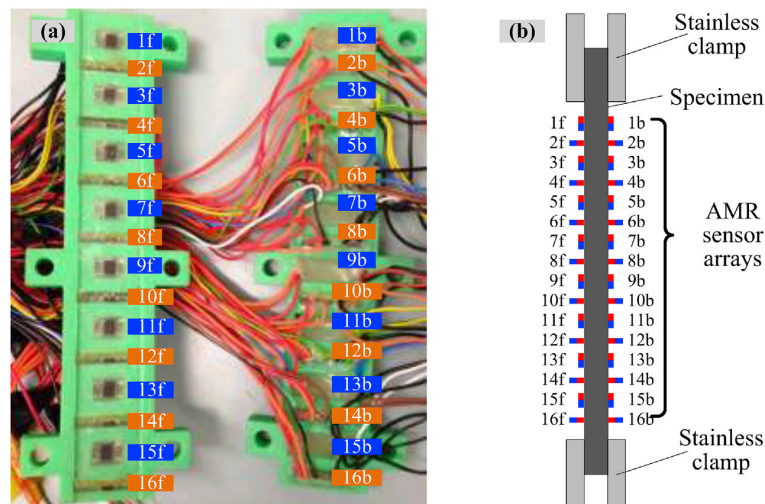


Fig. 3. (a) Photograph and (b) schematic diagram of the configuration of two AMR sensor arrays. The tangential magnetic field sensors were marked by odd numbers (blue colour), while the normal ones were marked by even numbers (orange colour) in (a). The designations f and b represent the front face and back face of the sample, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

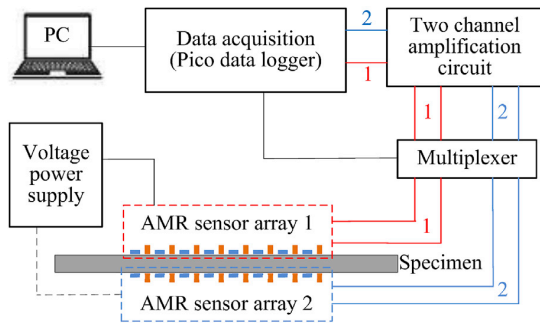


Fig. 5. Schematic diagram of hardware circuit.

effect described by Jiles and Atherton [13,14]. Secondly the strength of the plastic magneto-mechanical effect on three kinds of L80 dog-bone specimens was checked under plastic deformation. Next, two types of notches were machined on 4140-L80 dog-bone specimens in order to investigate whether the effects were stronger in the presence of localized change of the sort that would be of interest to detect. Some pipelines are routinely inspected by 'pigging' using the magnetic flux leakage (MFL) technique and this leaves significant remnant magnetization [47]. It was therefore also of interest to investigate whether the presence of remnant magnetization affected the MMM measurements.

It should also be remembered that the geometry of the dog-bone sample used should produce a stronger MMM signal than would be observed in a pipe specimen for the same level of applied stress. This is because one would expect the magnetic return path in a pipe geometry to reduce the amount of magnetic flux leakage when compared to the dog-bone sample shape. Therefore, a four point bending test was carried out on a pipe specimen to study the elastic magneto-mechanical effect.

These experiments were carried out at room temperature and in the presence of the Earth's magnetic field (horizontally northward 15.12 A/m and vertical component perpendicular down to the Earth's surface 35.81 A/m). Before testing, all the specimens were demagnetized by a Magnaflux L-10 coil to eliminate any magnetization generated during machining.

3.1. Magnetization change under elastic load

To study the elastic magneto-mechanical effect, a 4140-L80 dog-bone specimen was loaded to 250 MPa (about 45% of the yield strength). Instead of loading the specimen direct to 250 MPa, the load was increased in three steps:

- (1) Two load and unload cycles from 0 to 100 MPa with readings taken at 10 MPa steps, without demagnetizing between cycles.
- (2) Two load and unload cycles from 0 to 180 MPa with readings taken at 10 MPa steps, without demagnetizing.
- (3) Two load and unload cycles from 0 to 250 MPa with readings taken at 10 MPa steps, without demagnetizing.

By increasing the load in steps, the magnetization change due to first loading cycle and further cycling at the same stress level can be clearly distinguished. Two linear AMR sensor arrays as shown in Fig. 3 were fixed on both sides of the dog-bone specimen using brass screws. The lift-off distance between AMR sensors and the specimen surface was 1 mm.

3.2. Magnetization change under plastic load

Three types of L80 dog-bone specimens were used to study the plastic magneto-mechanical effect based on the mechanical properties given in Table 2:

- (1) 4140-L80 cycled up to 20% strain in 5% steps, without demagnetizing.
- (2) 9CR-L80 cycled up to 0.5% strain in 0.1% steps, without demagnetizing.
- (3) 13CR-L80 cycled up to 0.5% strain in 0.1% steps, without demagnetizing.

The MMM signal was measured by the same linear AMR sensor arrays simultaneously when applying the load. To measure the strain, four strain gauges were used to make a Wheatstone bridge. One strain gauge was attached on the specimen surface and the other three were used as references. A photograph of the AMR sensor array and strain gauge configuration is shown in Fig. 6.

3.3. Notched samples

In order to produce local stress concentration during loading, two types of notches were machined in the center of two 4140-L80 dog-bone specimens labeled A and B, respectively. Specimen A was machined with two semi-cylindrical notches on the face surfaces, as shown in Fig. 7(a). Specimen B was machined with two semi-cylindrical notches on the side surfaces, as shown in Fig. 7(b). The dimensions of the notches are listed in Table 1.

The MMM signal from the notched samples was measured using the same linear AMR sensor arrays as already described, in the following steps:

- (1) Demagnetize the dog-bone specimen.
- (2) Measure the MMM signal with no load at different levels of biasing magnetic field, which was generated by a Helmholtz coil, as shown in Fig. 8. The Helmholtz coil, with a diameter of 300 mm, was placed horizontally and in the East-West direction.
- (3) Demagnetize the specimen.
- (4) Increase the load in 50 MPa steps to a nominal average stress of approximately 600 MPa and then unload in 50 MPa steps. Take magnetic measurements at each load step.
- (5) Demagnetize the specimens.
- (6) Repeat the measurement of the MMM signal with no load at different levels of biasing magnetic field.

3.4. Side notched sample with remanent magnetization

The same side notches as shown in Fig. 7 (b) were machined on a new

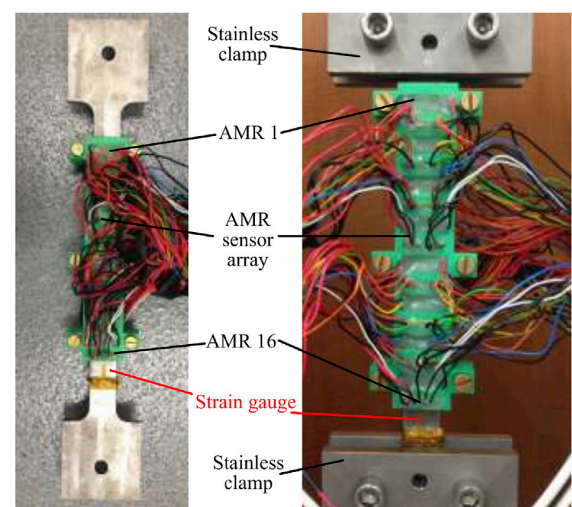


Fig. 6. Photograph of AMR sensor array and strain gauge configuration for plastic tests.

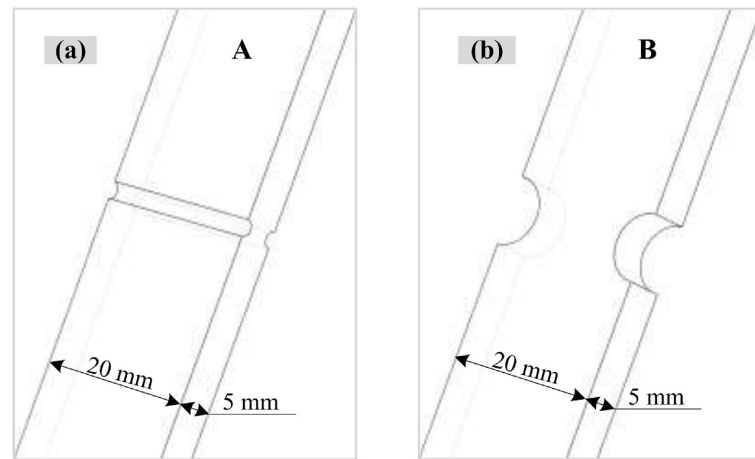


Fig. 7. Schematic diagram of two types of notches in the center of 4140-L80 dog-bone specimens. (a) Notches on face surfaces of specimen A and (b) notches on side surfaces of specimen B.

Table 1
Dimensions of two types of notches.

	Notch type	Notch diameter (mm)	Notch depth (mm)
Specimen A	Face-notched	2	1
Specimen B	Side-notched	8	4

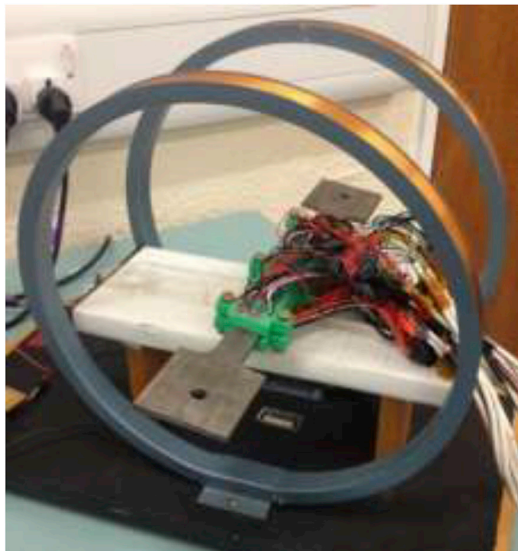


Fig. 8. Helmholtz coil generates different levels of magnetization.

4140-L80 dog-bone sample labeled as “C”. To study the influence of remanent magnetization on the MMM signal, the sample was demagnetized and then put into a magnetizing solenoid coil to obtain a remanent magnetization of approximately 300 A/m in the sample. The solenoid coil, which has a diameter and length of 65 mm and 330 mm respectively, is constructed from 1000 turns of 28 gauge, insulated copper wire. The DC resistance of the solenoid coil was $157 \Omega \pm 5\%$. After magnetization, the dog-bone sample was loaded in 50 MPa steps to a nominal average stress of approximately 600 MPa and then unloaded in 50 MPa steps. Magnetic measurements were taken at each load step.

3.5. Magnetization change of pipe sample under a four point bending test

A four point bending test was performed on a pipe specimen to study the stress-induced RMLF in the magnetic return path of a pipe geometry. A schematic diagram of the four point bending test is shown in Fig. 9. The span distances of L_1 , L_2 and L_3 are the same ($L_1 = L_2 = L_3 = 100$ mm). To reduce stress concentration at the loading points, four aluminum sheets (4 mm thick) were inserted into the contacting area between the rollers and the pipe sample. One pair of strain gauges (pair I) were placed in the center part of the pipe sample, with one on the top and the other one on the bottom; another pair of strain gauges (pair II) were placed near the left supporting roller.

The flexural stress in the four point bending test can be estimated from simple beam theory [48], the maximum stress when a 50 kN load was applied at each loading roller being 462 MPa. Instead of loading the specimen direct to this maximum stress, the load was increased in three steps:

- (1) Two load and unload cycles from 0 to 154 MPa with readings taken at 10 MPa steps, without demagnetizing between cycles.
- (2) Two load and unload cycles from 0 to 308 MPa with readings taken at 10 MPa steps, without demagnetizing between cycles.
- (3) Two load and unload cycles from 0 to 462 MPa with readings taken at 10 MPa steps, without demagnetizing between cycles.

By increasing the load in steps, the magnetization change due to the first loading cycle and further cycling at the same stress level can be clearly distinguished. Two ring AMR sensor arrays as shown in Fig. 4 were fixed on the outer surface of the pipe specimen using brass screws. The lift-off distance between the AMR sensors and the pipe surface was 1 mm.

3.6. Tests on wider variety of steels with side notches

Having completed the extensive tests above on 4140-L80 steel, a representative test was then carried out on a further 20 steels in order to see whether the same trends were seen. The same side notches as shown in Fig. 7(b) were machined in dog-bone specimens made from these steels. The notched samples were tested in the following steps:

- (1) Demagnetize;
- (2) Increase load in steps ($\leq 5\%$ yield strength) to a nominal average stress of approximately 10% above the yield stress yield strength and take magnetic measurements at each load step;

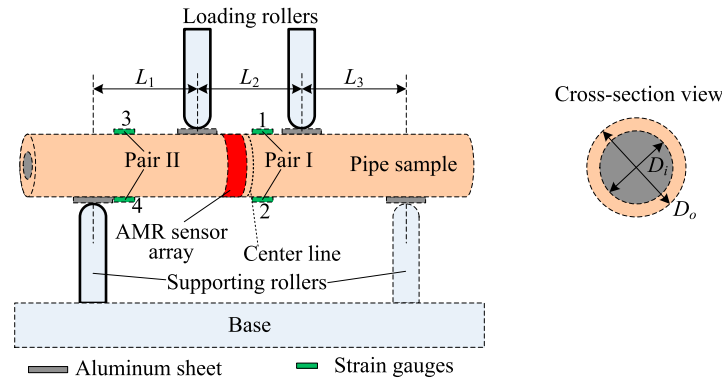


Fig. 9. Schematic diagram of the four point bending test. $L_1 = L_2 = L_3 = 100$ mm, and the maximum force loaded at each roller is 50 kN.

- (3) Unload in steps ($\leq 5\%$ yield strength) and repeat magnetic measurements at each step.

4. Experimental results and analysis

4.1. Magnetization measurement under elastic load

Our goal was to selectively measure the magnetic field produced by sources inside the specimen by suppressing the magnetic field originating from external sources. Based on the experimental results, it was found that the tangential magnetic field signal does not vary significantly in the area tested, and so to summarize the data for each loading test, the tangential field data from each side of the sample is averaged, as shown in Eq. (1).

$$H_{\text{tangential}} = \frac{\sum H_{nf} + \sum H_{nb}}{\text{number of tangential sensors}} \quad (1)$$

The normal field varies approximately linearly along the length direction and is strongest towards the ends of the sample as expected; the

normal field data from the 4 outermost sensors is presented, as shown in Eq. (2). The normal field measured by sensors closer to the specimen center show small variations during the loading process; data from these sensors have lower SNR and are therefore not used in this summary data.

$$H_{\text{normal}} = \frac{(H_{2f} - H_{16f}) + (H_{2b} - H_{16b})}{4} \quad (2)$$

To present the experimental data more clearly, the raw data was compressed according to Eqs. (1) and (2). After this, the magnetization change during six load cycles can be obtained. It was found that the results on repeat loading cycles to the same maximum load were almost identical to those of the first cycle. The solid and dashed lines indicate the loading and unloading steps, respectively. An irreversible change is seen in initial loading to a given load, while subsequent unloading and reloading gives reversible changes. This finding on the elastic magneto-mechanical effect is completely consistent with that obtained by Jiles and Atherton [13,14], but the effect is small (about 10 A/m maximum compared with the Earth's magnetic field ~ 40 A/m).

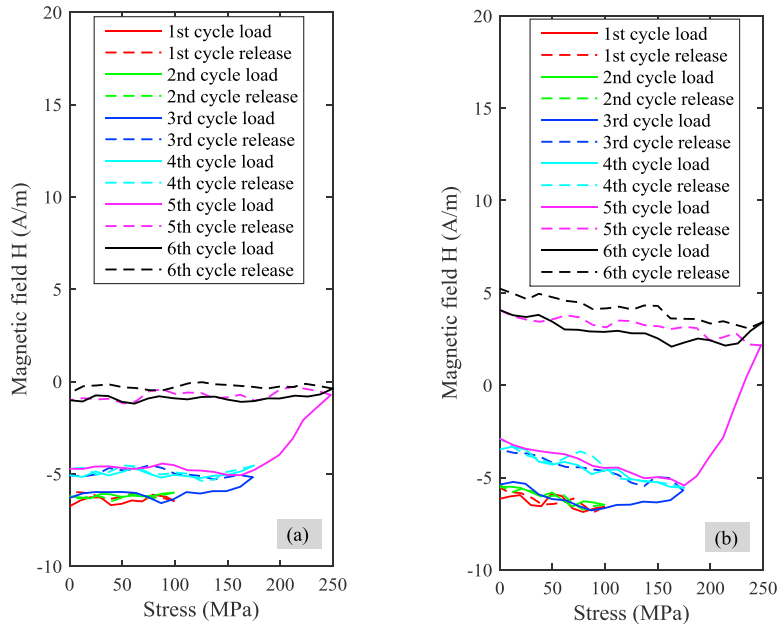


Fig. 10. (a) Tangential and (b) normal magnetic field change of 4140-L80 dog-bone sample measured during elastic testing. The solid and dashed lines indicate the loading and unloading steps, respectively.

4.2. Magnetization measurement under plastic load

The raw data of magnetization change during plastic tests was compressed according to Eqs. (1) and (2). The curves from repeat measurements at the same strain level were averaged due to the small signal levels. The magnetization change for the 4140-L80 sample during plastic deformation is shown in Fig. 11.

It can be seen that the profile of the tangential magnetic field is similar to that of the normal magnetic field. Likewise, the tangential and normal magnetic fields have similar profiles for the 9CR-L80 and 13CR-L80 samples, except that the signal amplitude is different. Due to the limited space available on the sample surface with the AMR sensors used, only the normal magnetic field was measured for the other two samples, and is shown in Fig. 12. From Figs. 11 and 12, it can be seen that the stress history affects the MMM signal, but the effects are small in these materials (about 10–20 A/m compared with the Earth's magnetic field of ~ 40 A/m in the lab), and the plastic deformation tends to reduce the MMM signal. The results show no evidence of the cumulative effect due to cyclic plastic strain reported by Dubov [6]. In this experiment, the plastic strain is essentially uniform along the sample length direction. Therefore it was decided that localized strain deformation would be introduced in the next stage of the experiments to further check the plastic magneto-mechanical effect.

4.3. Magnetization measurement of notched samples

By localizing the plastic strain the localized magnetization becomes easier to detect through the resulting RMLF. Fig. 13 presents the experimental results of the face notched sample at different biasing magnetic field before being loaded. The variation of the normal magnetic field at different axial positions is much more obvious than that observed for the tangential magnetic field. Therefore, only the normal field is presented in further results.

The magnetic signal of interest in Fig. 13 is surrounded by incoherent noise which makes analysis of the correlation with the controlled input parameters difficult. A matched filter was therefore proposed which takes advantage of the a-priori knowledge of the system, in order to suppress the noise that does not match the expected behavior of the signal. One must note the limitations of this approach, in that noise that matches the expected behavior of the signal will pass through the filter, and it is only applicable to simple situations with a known specimen geometry and loading process. The filter steps are outlined below:

- (1) The general slope of the data was removed as this is only related to the specimen geometry.

- (2) The average value of the field was subtracted, as the normal magnetic field on the specimen surface should have odd symmetry with a vanishing average.
- (3) The normal magnetic field data equidistant from the sample center were averaged with an inverted sign as the normal field produced by magnetization exhibits odd symmetry about the specimen center (due to the alternation of adjacent normal and tangentially oriented sensors, there was an offset equal to the array pitch between sensors above and below the sample center).

The peak to peak amplitude of the filtered magnetic field was then calculated on sensors 6–12, as these sensors were closest to the notch as shown in Fig. 3. After data processing, comparison of the peak to peak value of the normal magnetic field perturbation under different biasing magnetic fields can be obtained for both types of notched specimens, as shown in Fig. 14. The average value was subtracted as the expected normal magnetic leakage field caused by magnetization inside the specimen is zero. The cross markers are the measured data points and the solid line is the fitted line based on linear regression. As expected, the perturbation generated by the notch is proportional to the applied field, but it is much smaller in magnitude than the applied field. The test was repeated after the samples had been loaded to a nominal average stress of 600 MPa, and it was observed that the effect was increased but was still relatively small.

Fig. 14(a) shows that the slope of the fitted curves increases from 8.5% (before load) to 16.1% (after unloading from 600 MPa) for the face notched specimen, while for the side notched specimen the slope increases from 2.3% (before load) to 20.6% (after unloading from 600 MPa), as shown in Fig. 14(b). It can be seen that the plastic deformation and residual stress around the notches after loading will increase the remanent flux leakage. The effect of side notches is larger than that observed for face notches. This is because the side notches have a larger magnetization concentration length (8 mm) in the length direction of the sample, compared with that of face notches (2 mm), and the spatial resolution of normal magnetic sensors is 20 mm. Therefore the current AMR sensor arrays can capture larger RMLF signal for side notched samples than face notched samples.

The notched dog-bone specimens were also loaded and unloaded in 50 MPa steps. Fig. 15 shows the normal magnetic field of the face notched specimen at different loading and unloading steps, where the solid and dashed lines indicate the loading and unloading steps, respectively.

The normal component of magnetic field was used for data post-processing by using the filter steps 1–3 outlined previously. Here, the data from the original zero load case was subtracted from all other load cases, so that the remaining magnetic field profiles are only due to stress-

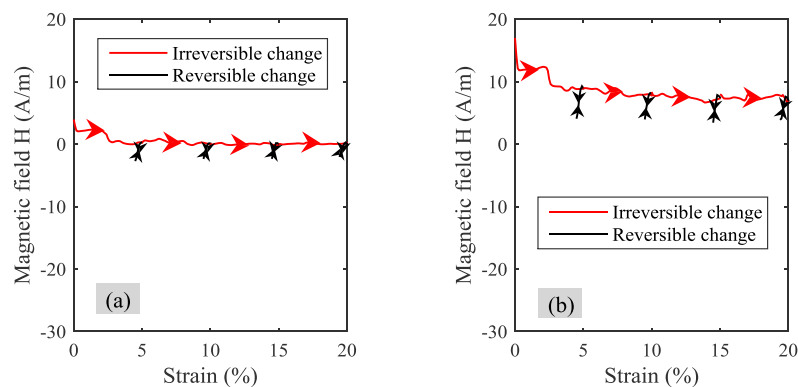


Fig. 11. (a) Tangential and (b) normal magnetic field change of 4140-L80 sample measured during plastic deformation.

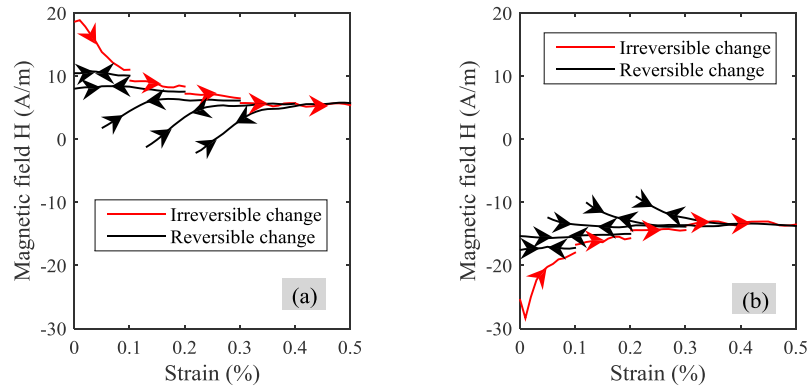


Fig. 12. Normal magnetic field change of (a) 9CR-L80 and (b) 13CR-L80 samples measured during plastic deformations.

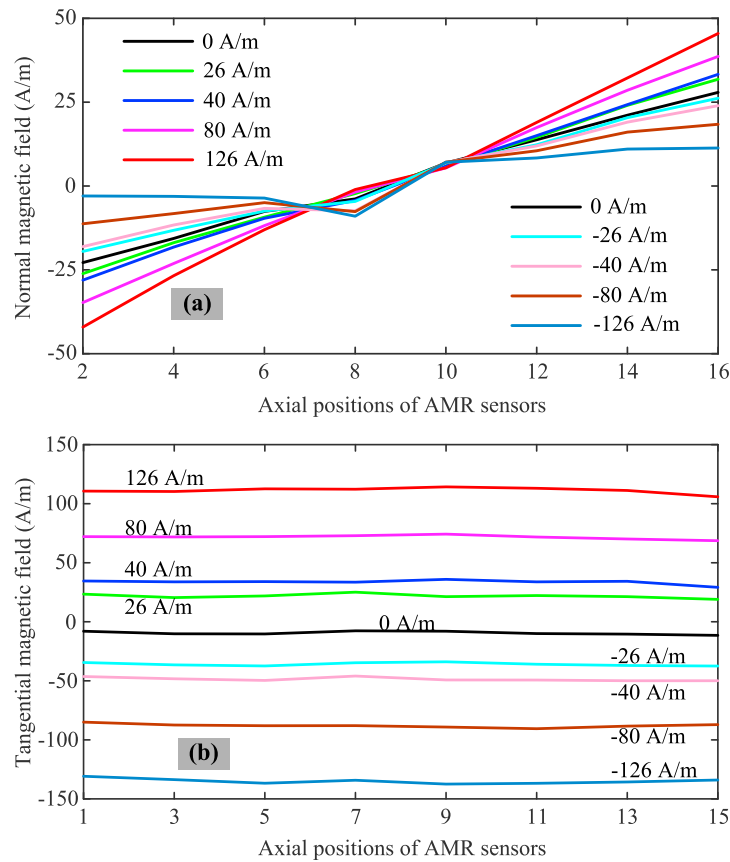


Fig. 13. Magnetic field measurement of face notched sample at different magnetization levels. (a) Normal magnetic field and (b) tangential magnetic field.

induced magnetization. The comparison of the normal magnetic field profiles of the two types of specimens during the loading and unloading steps is shown in Fig. 16.

When applying the load, plastic deformation and residual stress were generated around the notches. We have confirmed the presence of residual stresses of the order of 200 MPa predicted by finite element (FE) simulations via neutron diffraction measurements [49]. Fig. 16 indicates that there is a measurable effect, but again it is very small (about 6 A/m maximum compared with the Earth's magnetic field ~ 40 A/m) and does not vary monotonically with load. Further tests on different samples have

shown that the MMM signals detected are fairly reproducible for each alloy grade tested. The results presented here show no evidence of a cumulative plastic magneto-mechanical effect.

4.4. Magnetization measurement of side notched sample with remanent magnetization

Fig. 17 presents the normal magnetic field results of the side notched sample during the loading and unloading process, where the solid and dashed lines indicate the loading and unloading steps, respectively. The

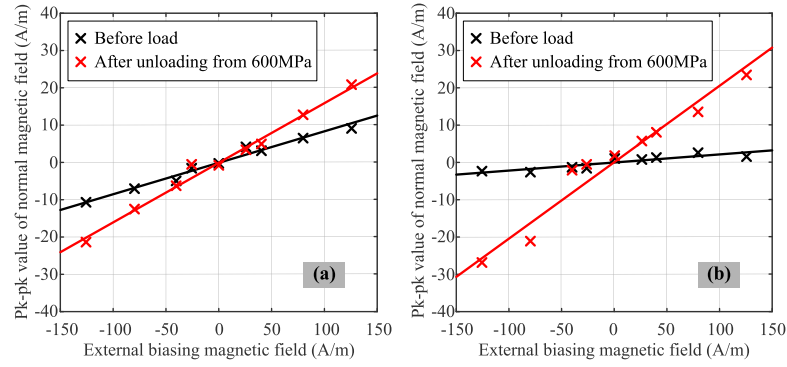


Fig. 14. Comparison of peak to peak amplitude of the normal magnetic field perturbation from notches as a function of external bias field for (a) the face notched specimen and (b) the side notched specimen.

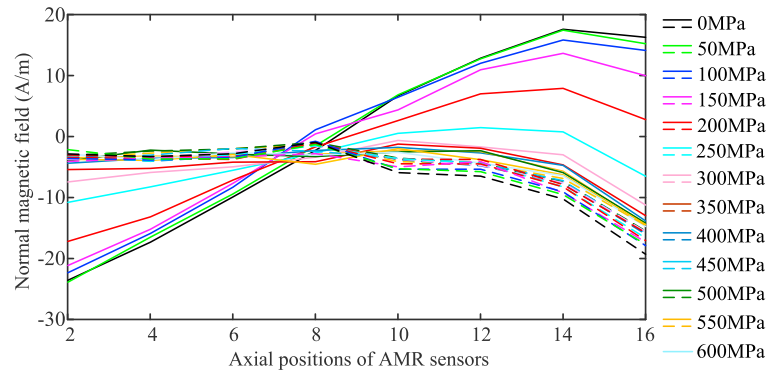


Fig. 15. Normal magnetic field measured at different loading and unloading steps of face notched sample. The solid and dashed lines indicate the loading and unloading steps, respectively.

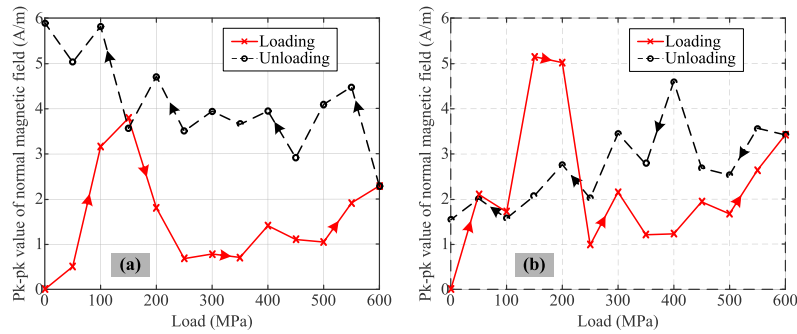


Fig. 16. Comparison of peak to peak amplitude of the normal magnetic field during loading and unloading steps for (a) face notched specimen and (b) side notched specimen.

dashed lines are overlapped because the magnetization change during unloading process is small.

Based on the matched filter outlined previously, the raw data of the normal magnetic field was processed. The relationship between the magnetization change and loading steps was calculated, as shown in Fig. 18.

It can be seen that the remanent magnetization has been significantly decreased with a small applied stress (about 150 MPa). Plastic deformation generated by the notches has a relatively small effect on the MMM signal, as described in the previous section. During the unloading process, there is a small increase in the normal magnetic field signal with decreasing load. Plastic deformation does not seem to build up a cumulative magnetization; rather, it tends to erase the magnetic memory.

4.5. Magnetization measurement of pipe sample under a four point bending test

Based on the experimental results, it was found that the tangential magnetic field signal does not vary significantly in the area tested. In order to suppress the magnetic field originating from external sources and summarize the data for each loading test, the averaged tangential magnetic field data from the whole circumferential direction of the pipe specimen is presented, as shown in Eq. (3).

$$H_{\text{tangential average}} = \frac{\sum (H_n - H_{n0})}{\text{number of tangential sensors}} \quad (n = 1, 3, \dots, 31) \quad (3)$$

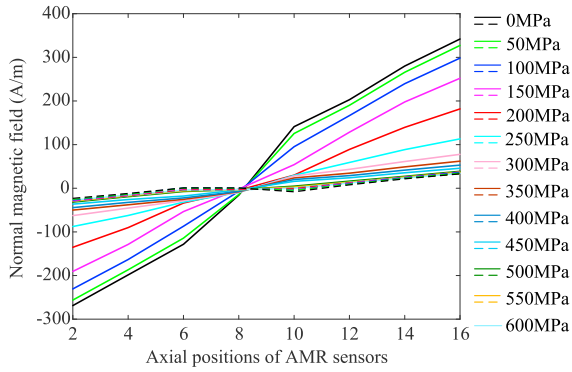


Fig. 17. Normal magnetic field measured at different loading and unloading steps with remanent magnetization. The solid and dashed lines indicate the loading and unloading steps, respectively.

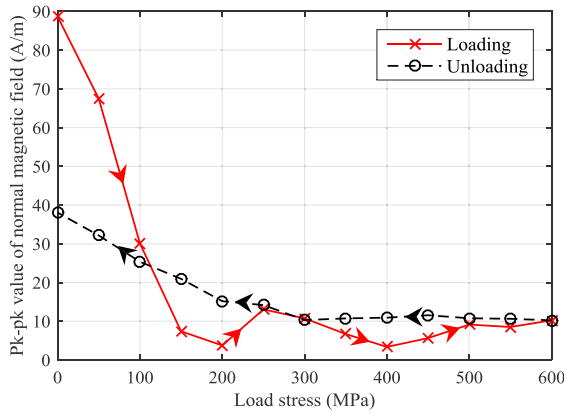
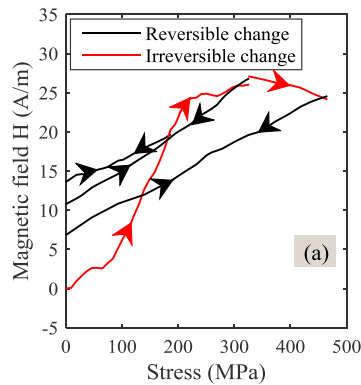


Fig. 18. Magnetization change during loading and unloading steps for a side notched sample with remanent magnetization.

where H_{n0} is the initial tangential magnetic field.

The normal field almost varies approximately sinusoidally along the circumferential direction of the pipe specimen. To average the normal magnetic field, three steps were used as follows:

- (1) The initial normal magnetic field was subtracted as this is related to the remnant magnetization.



- (2) The sum values of the top normal sensors ($\sum H_{top}$) and bottom normal sensors ($\sum H_{bottom}$) were calculated, respectively.
- (3) The averaged normal field is obtained by

$$H_{\text{normal average}} = \frac{\sum H_{top} - \sum H_{bottom}}{\text{number of normal sensors}} \quad (4)$$

To present the experimental data more clearly, the raw data was compressed according to Eqs. (3) and (4); after this, the magnetization change during six load cycles can be obtained. It was found that the results on repeat loading cycles to the same maximum load were almost identical to those of the first cycle. Therefore only the average results are presented in Fig. 19, the arrows indicating loading or unloading. An irreversible change is seen in initial loading to a given load, while subsequent unloading and reloading gives reversible changes. However the effect is small (about 25 A/m maximum compared with the Earth's magnetic field ~ 40 A/m).

The dog-bone sample should produce a stronger MMM signal than the pipe specimen for the same level of applied stress, but Fig. 19 shows that the magnetization change of the pipe specimen is about 25 A/m under 250 MPa stress, while the magnetization change of the dog-bone specimen is 10 A/m under 250 MPa stress as shown in Fig. 10. The reason for the larger magnetization change of the pipe specimen is due to the influence of the Testometric machine. There are two support arms of the machine that are made of ferromagnetic material. The gap between the pipe specimen and the arms is small (about 25 mm) so the pipe specimen was in the magnetic return path and the external bias magnetic field was reinforced, which caused a larger magnetization change under the same level of applied stress [13].

The MMM technique has been implemented as a periodic screening inspection tool and reported to be capable of measuring stress concentration and detecting defects. However, these results indicate that it will not be a useful technique in practice in the field for these steel alloys.

4.6. Variety of steels with side notches

Since complex tests conducted on full-scale pipes produced very similar results to those obtained by much simpler means on simple, small machined specimens, it was decided to investigate whether the cumulative magnetoplastic effect could be found in other materials on the side-notched dog-bone specimen shown in Fig. 7(b) with dimensions listed in Table 1. Specimens of each of 20 structural steels were prepared and loaded and unloaded in steps ($\leq 5\%$ yield strength). The normal component of magnetic field was processed using the filter steps 1–3 outlined previously in Section 4.3. Fig. 16 shows that the peak to peak amplitude of the magnetic field varies with load and this erratic behavior was seen in the tests on all the steels. Table 2 shows the maximum peak to peak amplitude for each steel; from Fig. 16(b), this is 5.2 A/m for the

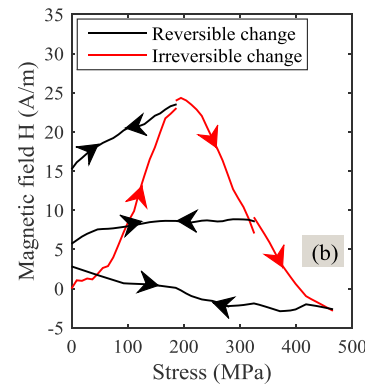


Fig. 19. (a) Tangential and (b) normal magnetic field change of pipe sample measured during bending test.

Table 2
Maximum magnetization change during loading and unloading of different steels.

Steel type	Amplitude of magnetic field (A/m)	Steel type	Amplitude of magnetic field (A/m)
1.0570	5.5	708M40	6.8
1.2083	4.2	EN9	8
1.2312	13	EN32	6.5
1.2343	14	EN42	8
1.2363	9	EN43	5.3
1.2379/ D2	7.3	EN45	6.4
1.2436	8.7	EN47	8.4
1.2510/ O1	10.1	S275	4.8
1.2767	10	S355J2+N	6
1.7131	6	X65	6.2
4140-L80	5.2	13CR-L80	19.3
9CR-L80	21		

4140-L80 steel.

Table 2 indicates that there are measurable MMM effects of the steels tested, but again they are very small (up to about 21 A/m maximum compared with the Earth's magnetic field ~ 40 A/m). The results presented here also show no evidence of a cumulative plastic magneto-mechanical effect on different steels tested.

5. Discussion

The primary question this study raised was whether the magnetic memory exhibited by common Grade L80 pipe steels and other structural steels conforms to the relatively weak magneto-mechanical effect predicted by Jiles and Atherton [13,14] or to the empirical observations of a stronger cumulative magnetoplastic effect reported by Dubov [6] and others. Both effects occur in the presence of weak external magnetic fields such as the natural geomagnetic field (30–50 A/m). In the case of the well understood ordinary magneto-mechanic effect, application of stress tends to release the pinned domain walls and thereby diminishes the magnetic hysteresis. This leads to an irreversible change of magnetization towards the anhysteretic equilibrium in the material at the prevailing external magnetic field level. This irreversible change towards the anhysteretic equilibrium value could be either positive or negative depending on the initial magnetization. If the material is in a demagnetized initial state, the change of magnetization will be positive, i.e., in the direction of the external magnetic field, because the initial magnetization curve of ferromagnetic materials always lies below the anhysteretic curve [50]. Movement of pinned domain walls is similar to dislocation motion under plastic deformation, but we will reserve the term “plastic” change to irreversible mechanical deformation. Most of the irreversible change of magnetization occurs in the first cycle of loading. However, the anhysteretic magnetization is also slightly stress dependent because of domain-wall bending, a phenomenon analogous to dislocation bending during elastic mechanical deformation, which leads to relatively small reversible changes of magnetization during the following cycles.

Let us consider cycling at the same stress level as earlier shown in Fig. 1. Regardless whether the first cycle is purely elastic or partially plastic, it is the only one that causes relatively large irreversible changes in magnetization. Subsequent fully elastic cycles cause only small reversible changes in magnetization due to the stress-dependence of the anhysteretic magnetization curve. If the peak stress level is increased at a given point during cycling, the immediately following next cycle will act as a new “first” cycle at that peak stress level and likely cause significant irreversible changes in magnetization. Further cycles up to the previous peak stress level are fully elastic and cause only relatively small reversible changes in magnetization. It is worth citing what Bozorth wrote about this critical issue in his seminal monograph on ferromagnetism [51]: “When H (magnetic field) is applied first and maintained constant, successive applications and release of σ (stress) cause unequal

changes in B (flux density) until the process has been repeated a number of times, thus for the ‘cyclic state’ the change in B produced by the stress is often considerably less than for the first application of the same stress.”

As described by Dubov [5,6], the so-called Metal Magnetic Memory method is based on a much stronger cumulative process of “self-magnetization” in ferromagnetic bodies. Such self-magnetization occurs when the strain-induced magnetization due to the inverse magnetostrictive effect (also known as Villari effect) is much stronger than the weak external magnetic field. Although there is little doubt that cumulative self-magnetization can occur in ferromagnetic materials when exposed to cyclic deformation in the presence of a weak external magnetic field, very little is known in the scientific literature about the magnitude of this “magnetoplastic” effect in engineering materials such as commonly used pipe steels. There is plenty of evidence that the Metal Magnetic Memory method can be exploited for flaw detection when it is used just like any other residual magnetic flux leakage technique to detect surface-breaking cracks or subsurface ones at shallow depths, though its selectivity is questionable as there are many competing influences on the magnetization of the material [52–54]. However, the use of this NDE method for quantitative materials characterization crucially depends on whether a cumulative process of self-magnetization occurs in typical engineering materials, such as pipe steels, an issue that is highly relevant from the points of view of both scientific research and engineering applications. The principal experimental results presented in Figs. 10–12, 18, and 19 clearly demonstrate that the behavior of the three common Grade L80 pipe steels (4140-L80, 9CR-L80, 13CR-L80) and twenty other structural steels tested in our study conforms to the weak magneto-mechanical effect predicted by Jiles and Atherton [13,14] and showed no indication of the cumulative magnetoplastic effect that is required for the MMM as described by Dubov et al. to be capable of reliably detecting small area of stress concentration. Distinguishing between these two competing magnetization mechanisms is rendered easy and unequivocal by the fact that in the former case cyclic loading erases rather than builds up the magnetic memory. In this study, the stress concentration is due to geometrical wall thinning that would occur due to corrosion or erosion; it may be that other mechanisms such as fatigue may involve local dislocation enhancement or porosity, which act as local pinning points for Bloch wall movement [55]. These local pinning points are magnetic dipoles which may increase self-magnetization.

6. Conclusions

The magneto-mechanical memory (MMM) signal on the surfaces of L80 and 20 other structural steel specimens was recorded by AMR sensor arrays. The results show evidence of the residual magnetic leakage field (RMLF) signal due to applied load and the presence of notches as would be expected. A matched filter was applied to the results in order to extract the small perturbation on the magnetic signal. The main conclusions are:

- The stress history affects the MMM signal, but the effects are small in the steel samples tested.
- An irreversible change is seen in the initial elastic loading to a given load, while subsequent unloading and reloading at the same elastic stress level gives reversible changes.
- There is no evidence that plastic deformation builds up a cumulative magnetization; rather, it tends to erase the MMM signal.
- The perturbation of the magnetic signal due to notches without load is proportional to the applied magnetic field. Plastic deformation and residual stress generated around the notches after loading will increase the remanent flux leakage, but it remains small.

The results presented here showed no indication of the cumulative magnetoplastic effect that is required for the MMM as described by Dubov et al. to be capable of reliably detecting small areas of stress concentration. These observations suggest that the MMM effect is very small in the different grades of L80 pipeline steels and other structural

steels that have been tested and it will not be a useful technique in practice in the field for these steel alloys.

Naturally, the absence of evidence for cumulative magnetization upon cyclic loading in our results does not constitute evidence of absence in general. Because of the obvious advantages of an NDE inspection method based on cumulative self-magnetization over other potential NDE methods available for assessment of remaining strength and service life, the NDE community cannot afford to give up on an opportunity like this. When a cumulative increase of RMLF is detected, special care will have to be taken to ascertain whether the effect is caused by increasing self-magnetization of the material or ordinary residual magnetic flux leakage caused by the nucleation and growth of otherwise undetectable microcracks. The influence of fatigue cracks (microcracks and macrocracks) on the MMM signal will be studied in further work. The 23 steels

tested here are the start of an open data base and we encourage other researchers working in this field to contribute their results in the hope of establishing the specific conditions (alloying, temper, microstructure, hardness, etc.) under which the Metal Magnetic Memory method based on a cumulative magnetoplastic effect might be used reliably for quantitative materials characterization or, if that turns out to be not feasible, at least for pre-screening before more sophisticated inspection.

Acknowledgements

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Appendix

The purpose of this appendix is to show the detailed chemical composition and mechanical properties of the steels used in the tests. The raw magnetic measurement data shown in Table 2 will be included in the electronic appendix upon publication.

Table 1
Chemical composition of steels used in this paper (wt%) [39–45].

	C	Mn	Mo	Cr	Ni	Cu	P	S	Si	V	other
4140-L80	0.38–0.43	0.75–1.0	0.15–0.25	0.8–1.1	≤0.25	≤0.25	≤0.025	≤0.025	≤0.35	≤0.3	Al<0.04
9CR-L80	≤0.15	0.3–0.6	0.9–1.1	8–10	≤0.5	≤0.25	≤0.02	≤0.01	≤1	–	–
13CR-L80	0.15–0.22	0.25–1	–	12–14	≤0.5	≤0.25	≤0.02	≤0.01	≤1	–	–
1.0570	≤0.20	1–1.6	≤0.08	≤0.3	≤0.3	–	≤0.035	≤0.035	≤0.55	0.02–0.15	–
1.2083	0.36–0.42	≤1.00	–	12.5–14.5	–	–	≤0.03	≤0.03	≤1.00	–	–
1.2312	0.35–0.45	1.4–1.6	0.15–0.25	1.8–2	–	–	≤0.03	0.05–0.1	0.3–0.5	–	–
1.2343	0.36–0.42	0.3–0.5	1.1–1.4	4.8–5.8	–	–	≤0.03	≤0.03	0.9–1.2	0.25–0.5	–
1.2363	0.95–1.05	0.4–0.8	0.9–1.2	4.8–5.5	–	–	≤0.03	≤0.03	0.1–0.4	0.15–0.35	–
1.2379/D2	1.45–1.6	0.2–0.6	0.7–1	11–13	–	–	≤0.03	≤0.03	–	0.7–1	–
1.2436	2–2.3	0.3–0.6	–	11–13	–	–	≤0.03	≤0.03	0.1–0.4	–	W 0.6–0.8
1.2510/O1	0.9–1.05	1–1.2	–	0.5–0.7	≤0.3	–	≤0.035	≤0.035	0.15–0.35	0.05–0.15	W 0.5–0.7
1.2767	0.4–0.5	0.2–0.5	0.15–0.35	1.2–1.5	3.8–4.3	–	≤0.03	≤0.03	0.1–0.4	–	–
1.7131	0.14–0.19	1–1.3	–	0.8–1.1	–	–	≤0.025	≤0.035	≤0.4	–	–
708M40	0.36–0.44	0.7–1	0.15–0.25	0.9–1.2	–	–	≤0.035	≤0.04	0.1–0.35	–	–
EN9	0.5–0.6	0.5–0.8	–	–	–	–	≤0.06	≤0.06	0.05–0.35	–	–
EN32	0.1–0.18	0.6–1	–	–	–	–	≤0.05	≤0.05	0.05–0.35	–	–
EN42	0.7–0.8	0.55–0.75	–	–	–	–	≤0.05	≤0.05	0.1–0.4	–	–
EN43	0.45–0.6	0.6–0.8	–	–	–	–	≤0.05	≤0.05	0.1–0.4	–	–
EN45	0.5–0.6	0.7–1	–	–	–	–	≤0.05	≤0.05	1.5–2	–	–
EN47	0.45–0.55	0.5–0.8	–	0.8–1.2	–	–	≤0.06	≤0.06	≤0.05	≥0.15	–
S275	≤0.25	≤1.6	–	–	–	–	≤0.04	≤0.05	≤0.05	–	–
S355J2+N	≤0.2	≤1.6	–	–	–	–	≤0.025	≤0.025	≤0.55	–	–
X65	0.04–0.16	1–1.6	–	–	–	–	≤0.035	≤0.035	≤0.55	–	–

Table 2
Mechanical properties of steels used in this paper [39–45].

Steel	Yield strength (MPa)	Ultimate strength (MPa)
4140-L80	552	689
9CR-L80	552	655
13CR-L80	552	655
1.0570	345	470–630
1.2083	486	495
1.2312	620	859
1.2343	350–550	650–880
1.2363	450	750
1.2379/D2	550	850
1.2436	450	860
1.2510/O1	597	668
1.2767	645	880
1.7131	420	550
708M40	525	775–925
EN9	355	700
EN32	330	430
EN42	483	924
EN43	325	618
EN45	376	615
EN47	368	852

Table 2 (continued)

Steel	Yield strength (MPa)	Ultimate strength (MPa)
S275	275	410
S355J2+N	355	470–630
X65	448	530

References

- [1] Liu X, Wang X. The research of oil and gas pipeline corrosion and protection technology. *Adv Pet Explor Dev* 2014;7:102–5.
- [2] Arora P, Singh PK, Bhasin V, Vaze KK, Pukazhendhi DM, Gandhi P, et al. Fatigue crack growth behavior in pipes and elbows of carbon steel and stainless steel materials. *Procedia Eng* 2013;55:703–9.
- [3] Garland PJ. The importance of non-destructive testing and inspection of pipelines. In: *Proceedings of 10th European conference on non-destructive testing* 2010, vol. 4. Curran Associates, Inc.; 2010. p. 2421–31.
- [4] Dubov AA. A study of metal properties using the method of magnetic memory. *Met Sci Heat Treat* 1997;39:401–5.
- [5] Dubov AA. Method of magnetic memory (MMM) of metal and inspection devices. Training handbook. Moscow: Energodiagnostika Co. Ltd; 2001.
- [6] Dubov A. Energy diagnostics - is a physical basis of the metal magnetic memory method. In: *19th world conference on non-destructive testing*; 2016.
- [7] International Institute of Welding. Non-destructive testing - Metal magnetic memory - Part 1: Vocabulary (standard No. ISO 24497–1).
- [8] International Institute of Welding. Non-destructive testing - Metal magnetic memory - Part 2: General requirements (standard No. ISO 24497–2).
- [9] International Institute of Welding. Non-destructive testing - Metal magnetic memory - Part 3: Inspection of welded joints (standard No. ISO 24497–3).
- [10] Dubov A, Kolokolnikov S. The metal magnetic memory method application for online monitoring of damage development in steel pipes and welded joints specimens. *Weld World* 2013;57:123–36.
- [11] Dubov A, Kolokolnikov S. Assessment of the material state of oil and gas pipelines based on the metal magnetic memory method. *Weld World* 2012;56:11–9.
- [12] Lin S, Wang W, Zhao C, Feng Z, Bi W, Jiang X. Application of metal magnetic memory method in long-distance oil and gas pipeline defects detection. In: *Proceedings of the international conference on pipelines and trenchless technology*. American Society of Civil Engineers; 2011. p. 973–80.
- [13] Jiles DC. Theory of the magnetomechanical effect. *J Phys D App Phys* 1995;28:1537–46.
- [14] Atherton DL, Jiles DC. Effects of stress on magnetization. *NDT Int* 1986;19:15–9.
- [15] Kaleta J, Zebracki J. Application of the villari effect in a fatigue examination of nickel. *Fatigue Fract Eng Mater Struct* 1996;19:1435–43.
- [16] Willcox M, Dawnes G. A review of common nondestructive tests. *Tube Pipe J* 2006;17:28–32.
- [17] Nowakowski A, Paszyk P. Metal magnetic memory method used for analyzing high-pressure gas pipelines. *AGH Drill Oil Gas* 2015;32:395–404.
- [18] Energodiagnostika Co. Ltd. Inspection devices for metal magnetic memory method, <http://www.mmmssystem.com/Categories/Devices.html>.
- [19] Roskosz M, Gawrilenko P. Analysis of changes in residual magnetic field in loaded notched samples. *NDT E Int* 2008;41:570–6.
- [20] Shi C, Dong S, Xu B, He P. Stress concentration degree affects spontaneous magnetic signals of ferromagnetic steel under dynamic tension load. *NDT E Int* 2010;43:8–12.
- [21] Roskosz M, Bieniek M. Evaluation of residual stress in ferromagnetic steels based on residual magnetic field measurements. *NDT E Int* 2012;45:55–62.
- [22] Wilson JW, Tian G, Barrans S. Residual magnetic field sensing for stress measurement. *Sens Actuat A Phys* 2007;135:381–7.
- [23] Dong L, Xu B, Dong S, Song L, Chen Q, Wang D. Stress dependence of the spontaneous stray field signals of ferromagnetic steel. *NDT E Int* 2009;42:323–7.
- [24] Leng J, Liu Y, Zhou G, Gao Y. Metal magnetic memory signal response to plastic deformation of low carbon steel. *NDT E Int* 2013;55:42–6.
- [25] Guo P, Chen X, Guan W, Cheng H, Jang H. Effect of tensile stress on the variation of magnetic field of low-alloy steel. *J Magn Magn Mater* 2011;323:2474–7.
- [26] Li X, Ding H, Bai S. Research on the stress-magnetism effect of ferromagnetic materials based on three-dimensional magnetic flux leakage testing. *NDT E Int* 2014;62:50–4.
- [27] Dong L, Xu B, Dong S, Chen Q, Dan W. Monitoring fatigue crack propagation of ferromagnetic materials with spontaneous abnormal magnetic signals. *Int J Fatigue* 2008;30:1599–605.
- [28] Li C, Dong L, Wang H, Li G, Xu B. Metal magnetic memory technique used to predict the fatigue crack propagation behavior of 0.45% C steel. *J Magn Magn Mater* 2016;405:150–7.
- [29] Huang H, Koamg S, Liu R, Liu Z. Investigation of magnetic memory signals induced by dynamic bending load in fatigue crack propagation process of structural steel. *J Nondestruct Eval* 2014;33:407–12.
- [30] Gorkunov ES. Different remanence states and their resistance to external effects. Discussing the so-called magnetic memory method. *Insight Non Destr Test Cond Monit* 2015;57:709–17.
- [31] Augustyniak M, Usarek Z. Discussion of derivability of local residual stress level from magnetic stray field measurement. *J Nondestruct Eval* 2015;34:1–9.
- [32] Usarek Z, Augustyniak B, Augustyniak M, Chmielewski M. Influence of plastic deformation on stray magnetic field distribution of soft magnetic steel sample. *IEEE Trans Magn* 2014;50:1–4.
- [33] Leng J, Xu M, Zhou G, Wu Z. Effect of initial remanent states on the variation of magnetic memory signals. *NDT E Int* 2012;52:23–7.
- [34] Huang H, Yao J, Li Z, Liu Z. Residual magnetic field variation induced by applied magnetic field and cyclic tensile stress. *NDT E Int* 2014;63:38–42.
- [35] Hu B, Li L, Chen X, Zhong L. Study on the influencing factors of magnetic memory method. *Int J Appl Electrom* 2010;33:1351–7.
- [36] Craik DJ, Wood MJ. Magnetization changes induced by stress in a constant applied field. *J Phys D Appl Phys* 1970;3:1009–16.
- [37] Arkulis MB, Baryshnikov MP, Misheneva NI, Savchenko YI. On problems of applicability of the metal magnetic-memory method in testing the stressed-deformed state of metallic constructions. *Russ J Nondestruct Test* 2009;45:526–8.
- [38] Wu D, Xu M, Li J. Study on physical mechanism of metal magnetic memory technique. *Appl Mech Mater* 2010;34–35:841–4.
- [39] Continental Alloys & Services. Alloy Steel, <http://www.contalloy.com/materials/alloy-steel>.
- [40] SteelNumber: European Steel and Alloy Grades, <http://www.steelnumber.com/index.php>.
- [41] West Yorkshire Steel. Steel Specifications, <https://www.westyorkssteel.com/steel-specifications/>.
- [42] Otai Special Steel. <http://www.astmsteel.com/>.
- [43] Woolman J, Mottram RA. The mechanical and physical properties of the British standard En steels (BS 970:1955): En 1 to En 20. Elsevier; 1964.
- [44] Woolman J, Mottram RA. The mechanical and physical properties of the British standard En steels (BS 970:1955): En 21 to En 39. Elsevier; 1964.
- [45] Woolman J, Mottram RA. The mechanical and physical properties of the British standard En steels (BS 970:1955): En 40 to En 363. Elsevier; 1964.
- [46] Sensitec GmbH. AMR magnetic field sensors, <http://www.sensitec.com/english/products/magnetic-field/aff755.html>.
- [47] Shi Y, Zhang C, Li R, Cai M, Jia G. Theory and application of magnetic flux leakage pipeline detection. *Sensors* 2015;15:31036–55.
- [48] Chan PH, Tshai KY, Johnson M, Li S. The flexural properties of composite repaired pipeline: numerical simulation and experimental validation. *Compos Struct* 2015;133:312–21.
- [49] Jiang WC, Woo W, Wan Y, Luo Y, Xie XF, Tu ST. Evaluation of through-thickness residual stresses by neutron diffraction and finite-element method in thick weld plates. *J Press Vess T ASME* 2017;139:031401.
- [50] Jiles DC, Atherton DL. Theory of ferromagnetic hysteresis. *J Magn Magn Mater* 1986;61:48–60.
- [51] Bozorth RM. Ferromagnetism. Hoboken: Wiley-IEEE Press; 1993.
- [52] Dubov AA. Comprehensive diagnostics of the bends of boiler and steam-line tubes. *Therm Eng* 2007;54:712–5.
- [53] Dubov AA. Experience with technical diagnostics of generator shroud rings at thermal plants. *Therm Eng* 2009;56:120–3.
- [54] Dubov AA. Diagnostics of steam turbine disks using the metal magnetic memory method. *Therm Eng* 2010;57:16–21.
- [55] Kobayashi S, Takahashi S, Kamada Y, Kikuchi H, Ara K. Magnetic minor hysteresis loops of compressively deformed transition-metal single crystals. *J Appl Phys* 2006;99:08H908.



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Experimental and simulation methods to study the Magnetic Tomography Method (MTM) for pipe defect detection

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ABSTRACT

The Magnetic Tomography Method (MTM), a passive Non-Destructive Testing (NDT) technique based on the magneto-mechanical effect, has been claimed to be able to detect defects at large (>1 m) stand-off distances. In this study, the MTM signal was studied experimentally on a 4140-L80 pipe sample, in which a flat bottom defect was electrochemically generated. The Residual Magnetic Leakage Field (RMLF) signal was recorded using an annular array of AMR sensors. The experimental results show perturbations due to the defect (about 12 dB above noise level) only when the AMR sensors were positioned at a very low stand-off. The presence of ferromagnetic objects near the sensors could cause perturbations many times larger than that from a defect (about 18 dB above the noise level). A Finite Element (FE) model validated the experimental results. The model showed that there is a significant risk of false indications due to foreign ferromagnetic objects when measuring at a large distance from the pipe.

1. Introduction

Pipelines provide the most efficient means to transport oil and gas so ensuring their safe and reliable operation is of utmost importance [1]. With environmental interaction and time-dependent degradation, pipelines are unavoidably subject to corrosion, so they must be periodically inspected to maintain safe operation [2]. A well-proven method for the routine inspection of pipelines uses In-Line Inspection (ILI) tools or smart pigs which utilize Non-Destructive Testing (NDT) techniques such as Magnetic Flux Leakage (MFL) and Ultrasonic Tools (UT) [2,3]. A large proportion of installed pipelines, however, have properties that restrict the use of pigging [4], so alternative means of inspection that are applied from outside the pipe are required. A range of externally applied techniques are available including Guided Wave Testing (GWT) [5–7], Eddy Current (EC) method [8–10] and Radiography [11,12].

Non-contact magnetic technology can be used for the inspection of metal pipelines where the ILI is difficult or impossible. The Magneto-Mechanical Memory (MMM) method, which is also referred to as the Metal Magnetic Memory method [13,14], has been applied to pipeline inspection by measuring the Residual Magnetic Leakage Field (RMLF) above a pipe [15,16]. The underlying physical phenomenon behind the MMM technique is the so-called magneto-mechanical effect [17], in

which stress concentration in a ferromagnetic material causes an amplification of magnetization change. The stress-induced magnetization is, however, a function of several inseparable variables and it is not possible to retrieve an invertible relationship between the local stress level and the RMLF signal [18,19]. The MMM technique has shown some false calls in site trials [20], indicating that it will be difficult to make it a reliable technique in practice.

The Magnetic Tomography Method (MTM) has been implemented predominantly in Russia for assessing the safety and integrity of ferromagnetic pipelines [21]. MTM is a passive NDT method which uses the “natural” magnetization of ferrous pipes by the Earth's magnetic field [21,22]. It is based on measurement of the distortions of RMLF that are due to the changes in the magnetization of a ferrous material when subjected to mechanical stress or corrosion. Practitioners of the technique claim that MTM does not measure the dimensions of geometric defects alone but also the stress caused by these defects (often labelled the stress-deformed condition of the pipe) [21]. It is claimed that the MTM technique can detect defects at very large stand-off distances [21–24]. However, the leakage magnetic field can be affected by various parameters such as nearby ferromagnetic materials, remanent magnetization left during prior magnetic flux leakage detection, and interference from surrounding high power transmission lines [22]. Li et al. used a

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Table 1
Chemical Composition of 4140-L80 steel (wt.%) [27].

	C	Mn	Mo	Cr	Ni	Cu	P	S	Si	V	Al
Min	0.380	0.750	0.150	0.800	–	–	–	–	–	–	–
Max	0.430	1.000	0.250	1.100	0.250	0.250	0.025	0.025	0.350	0.300	0.040

Table 2
Mechanical properties of 4140-L80 steel [27].

	Yield strength (MPa)	Tensile strength (MPa)	Elongation
Min	552	689	–
Max	655	–	20%

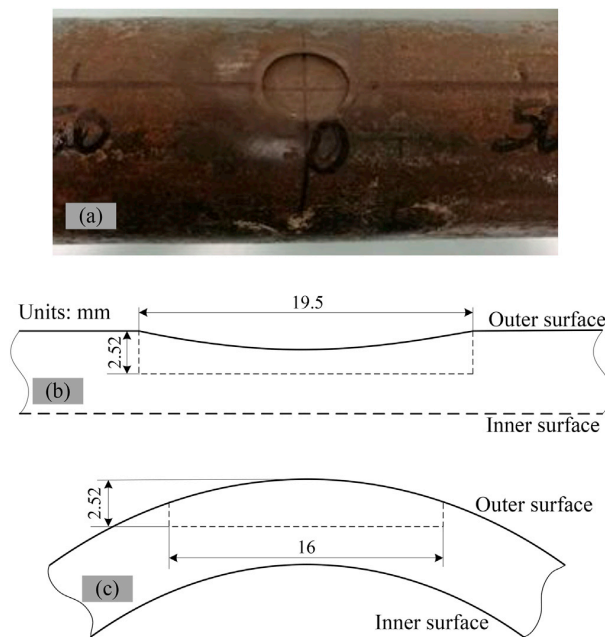


Fig. 1. Flat bottom hole with oval shape cross section generated by electrochemical method. (a) Photograph in top view and schematic diagrams in (b) front view and (c) side view.

model based on magnetic dipole theory to predict the Ground Magnetic Leakage Field (GMLF) that would be measured above a buried pipe. The model did not consider the remainder of the ferromagnetic pipe surrounding the magnetized region that would affect the path of the magnetic flux [25]. A revision of the model with the pipe material included found that the GMLF would be significantly lower than the original prediction [26].

In this paper, the MTM technique will be studied by experiments and Finite Element (FE) simulation. The perturbation of the magnetic field surrounding a pipe due to the defect and ferromagnetic objects was assessed. In Section 2, the experimental setup is introduced. The methodology is outlined and the experimental results of magnetic perturbation due to a flat bottom defect are given in Section 3. Studies of the influence of nearby ferromagnetic objects completed with a validated FE model follow in Section 4. Initially, the FE model is introduced in Section 4.1 then validated by experiments in Section 4.2. Section 4.3 analyzes the false call risk due to surrounding ferromagnetic objects and Section 5 concludes the paper.

2. Experimental setup

A 480 mm long pipe sample made from 4140-L80 alloy steel [27],

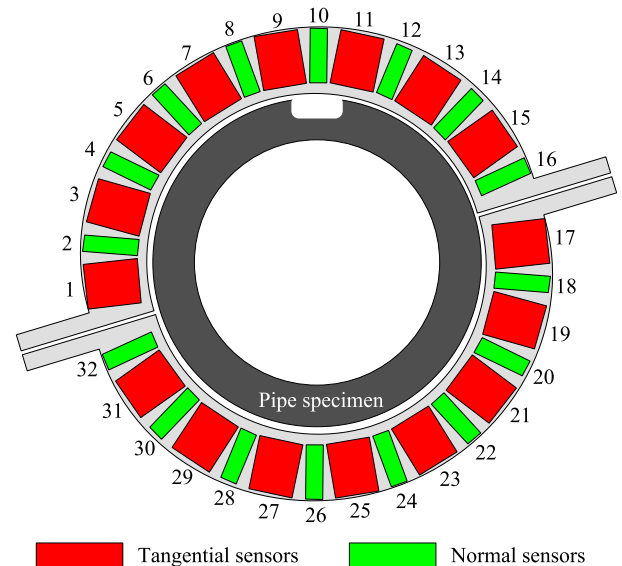


Fig. 2. Configuration of the ring AMR sensor arrays. The tangential magnetic field sensors were marked by odd numbers (red), while the normal ones were marked by even numbers (green).

which is commonly used for pipelines in the petrochemical industry, was used. Its chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. The outer diameter and the wall thickness of the pipe sample are 60.32 mm and 4.83 mm, respectively.

For the purpose of studying pipe corrosion, a flat bottom defect with oval shape cross section was generated in the outer surface of a pipe sample using an electrochemical method [28], as shown in Fig. 1. The long and short axes of the oval defect are 19.5 mm and 16 mm, respectively and the defect depth is 2.52 mm.

The normal and tangential components of magnetic field of the pipe sample were measured by two ring magnetic sensor arrays on the outer surface of the pipe. Each magnetic sensor array consists of 16 channels (8 normal channels and 8 tangential channels) of AMR sensors AFF755B, of

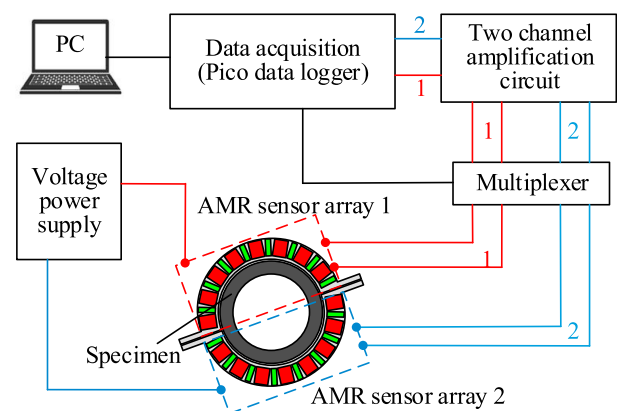


Fig. 3. Schematic diagram of the hardware circuit.

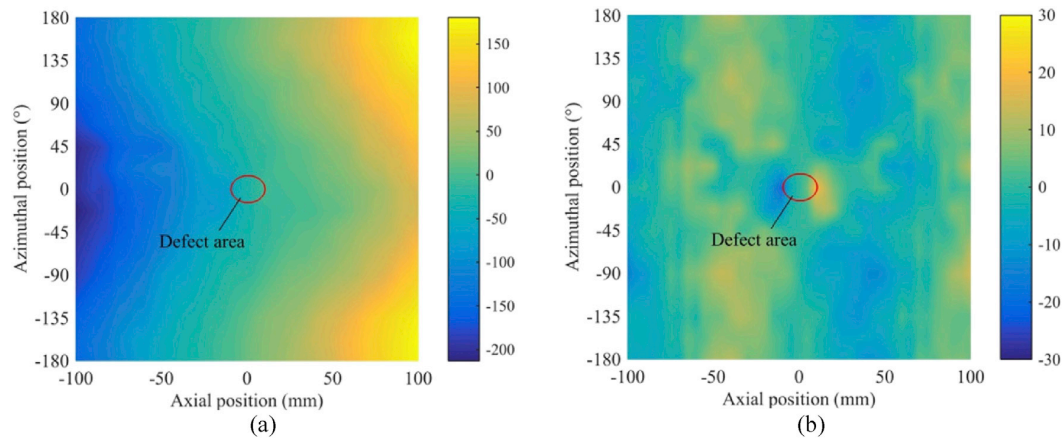


Fig. 4. (a) Normal magnetic field distribution with array at 1 mm stand-off after linear interpolation when the pipe sample was placed vertically (aligned with the maximal component of the geomagnetic field) with the defect northward. (b) After application of matched filter.

which the resolution is 1.6 mA/m and the sensitivity is 15 (mV/V)/(kA/m) [29]. Here, the normal component is normal to the specimen surface, while tangential means parallel to the specimen surface in the axial direction of the pipe. The AMR sensors were fixed using two 3D printed ABS plastic sensor holders, as shown in Fig. 2. The tangential magnetic field sensors were marked by odd numbers (red), while the normal ones were marked by even numbers (green). The tangential and normal magnetic field sensors were placed alternately in the circumferential direction. After fixing the two sensor holders using brass screws, the stand-off distance between AMR sensors and the pipe surface was 1 mm. To study the influence of the stand-off distance of the AMR sensors, another pair of holders was produced to give a 20 mm stand-off distance of the sensors from the pipe.

An electrical circuit was designed to control the 32 channels of AMR sensors, as shown in Fig. 3. The AMR sensors were powered by a constant voltage power supply. The multiplexer, which consists of 4×16 channels, was divided into two groups and controlled by a Pico data logger to switch the differential outputs of the AMR sensors into a two-channel amplification circuit. The amplified voltages were captured by the Pico data logger and then sent to a PC for post processing.

3. Experiments

3.1. Experimental methodology

The leakage magnetic field measured by MTM is due to the natural magnetization of the stressed or corroded pipe under the Earth's magnetic field [21,22]. For this reason, the experiments were carried out at room temperature and in the presence of the Earth's magnetic field. Magnetic measurements were taken in the middle of the lab away from ferromagnetic materials.

Firstly, to study the influence of the strength and direction of the Earth's magnetic field, the pipe specimen was placed in three positions:

- (1) Horizontal and in the west-east direction with defect upward;
- (2) Horizontal and in the south-north direction with defect upward;
- (3) Vertical direction with defect northward.

Magnetic measurements were taken using the ring AMR sensor arrays shown in Fig. 2 with a stand-off distance 1 mm. The total scanning length along the axial direction of the pipe sample was 400 mm with 5 mm axial resolution.

3.2. Results and analysis

The results presented in this section are associated with measurements when the pipe sample was placed vertically with the defect northward, as this was the configuration that resulted in the largest perturbations in the magnetic field surrounding the pipe. This was consistent with the estimated geomagnetic field from survey data at the test location value being maximal in this direction with a vertical component of 36 A/m [30]. The profiles shown have been linearly interpolated for visual clarity [31]. Fig. 4 presents the interpolated magnetic field measured using the ring AMR sensor arrays at 1 mm stand-off distance. Some perturbation at the defect location could be seen in both the normal and tangential signals, but the change was always larger in the normal field so only this component is presented here.

The magnetic signal of the defect in Fig. 4(a) is dominated by the signal due to the pipe geometry which makes analysis of the correlation with the controlled input parameters difficult. In previous work, a matched filter was successful in taking advantage of the a-priori knowledge of the system to suppress the noise that does not match the expected behavior of the signal [32]. A similar approach was therefore applied here. One must take care in the interpretation of the filtered data as a limitation with this approach is that noise that matches the expected behavior of the signal will pass through the filter. The filter is also applicable only to simple situations with a known specimen geometry. The filter steps for the scanning results of each normal AMR sensor are outlined below:

- (1) The general slope of the data for each normal AMR sensor was removed as this is only related to the specimen geometry.
- (2) The average value of the field was subtracted, as (when considering just the fields of which the source is inside the pipe) the signal in the normal magnetic field on the specimen surface should have odd symmetry with a vanishing average.
- (3) The normal magnetic field data equidistant from the sample center were averaged with an inverted sign as the normal field produced by magnetization exhibits odd symmetry about the defect center (which is halfway along the sample length).

The processed data after matched filtering is shown in Fig. 4(b). These data show the passive RMLF in the configuration where the pipe is maximally aligned with the geomagnetic field. The defect is expected at the origin of the figure as indicated by red line. The perturbation of the defect from both the normal and tangential magnetic field signal is about

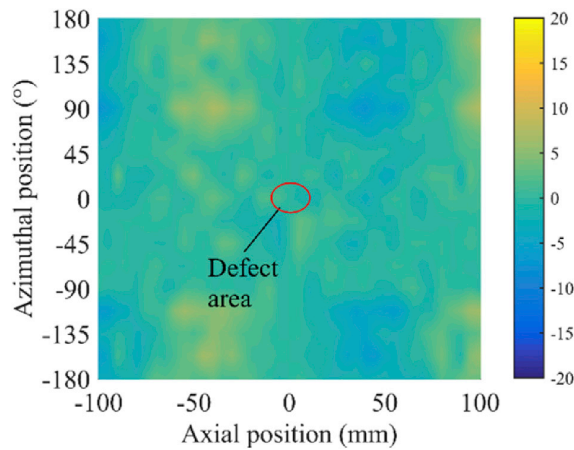


Fig. 5. Normal magnetic field component with array at 20 mm stand-off.

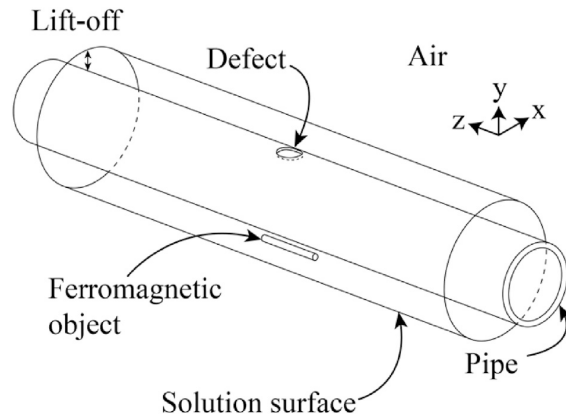


Fig. 6. Schematic diagram of the FE model showing the solution surface at 20 mm stand-off and a ferromagnetic rod located at 10 mm stand-off and 180° from the defect.

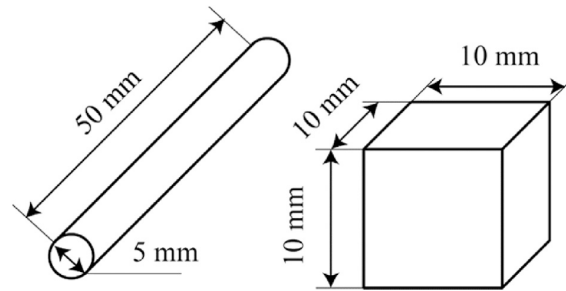


Fig. 7. Geometry and dimensions of the iron cube and rod.

12 dB above the noise level. The measurement was repeated with the pipe in the west-east direction and the south-north direction where the RMLF from the defect appeared visible but was about 8 dB above the noise level. The experiment was repeated with the array at 20 mm stand-off. The results in Fig. 5 show that even after the application of the matched filter, the defect is still not at all distinguishable from the surrounding noise.

4. Finite element simulation

4.1. Model overview

FE modelling is an effective tool that allows efficient and cost-effective investigation into the parameters that affect the RMLF signal such as defect morphology and other sources of magnetic perturbation. Fig. 6 shows a schematic diagram of the FE model built in COMSOL. The pipe dimensions match those given in Fig. 1. A background magnetic field of $19 \mu\text{T} \cdot \hat{e}_y + 45 \mu\text{T} \cdot \hat{e}_z$ was defined to emulate the level measured in the laboratory [30]. The pipe remanent magnetization was $120 \text{ A/m} \cdot \hat{e}_z$ and the relative magnetic permeability was $\mu_r = 100$. A volume of air was defined outside of the pipe sufficiently large enough not to artificially restrict the path of the magnetic flux.

A primary use case for MTM is to measure buried pipes where the environment immediately surrounding the pipe may contain objects that could influence the measured magnetic field. Nearby ferromagnetic material could cause distortion of the magnetic flux due to its high magnetic permeability, which may result in signals similar in shape to those from defects. An iron rod and a cube with volume of 1 cm^3 , shown in Figs. 6 and 7, were defined in the FE model to represent objects that may be found nearby the pipe such as a nail, nut or bolt. A remanent magnetization was defined such that the field just outside the object matched the level measured using a Gauss meter with the equivalent geometry in the laboratory. The relative magnetic permeability of the object was $\mu_r = 900$.

4.2. Validation of model

Fig. 8 shows signals predicted by FE from the defect discussed in Section 2 and the rod in comparison to the equivalent experiment where the rod was positioned 90° azimuthally from the defect, the sensor stand-off is 1 mm and the rod is at 30 mm stand-off. Fig. 8(c) shows the axial line passing through the defect signal at 0° in black, and through the rod signal at 90° in red. The matched filter has been applied to both experimental and simulated data with the array at 1 mm stand-off. The sharp peaks in the defect signal are due to the small distance between the sensors and defect, and there is a good overall agreement between the FE and experiment for the defect signal. The gradient of the rod measurement is also in good agreement with FE near the zero-crossing and the signal amplitudes are similar; however, the increased width of the peaks in the experimental signal is likely due to incoherent noise that matches the characteristics of the matched filter and is therefore not suppressed.

To provide additional model validation, the annular AMR sensor arrays with two different sensor stand-off distances were used to measure the magnetic field surrounding the pipe sample when a rod and cube (Fig. 7) were present near the sensor array. The objects, cut from mild steel samples, were placed at two distances from the outer surface of the pipe sample and oriented 0°, 90° and 180° from defect, as shown in Fig. 9. The squares at 12, 6 and 9 o'clock show the positions of the foreign ferromagnetic objects, which can be either the rod or the cube.

Fig. 10 shows the magnetic field distribution measured by the ring AMR sensor arrays with 20 mm stand-off distance when the rod was aligned with the pipe axis 10 mm from the pipe and directly above the defect (Fig. 10(a and b)), and 50 mm from the pipe and 90° offset from the defect (Fig. 10(c and d)). In each case, there is good agreement between the FE and experiment.

In Fig. 10(a and b), the defect signal is completely masked by the signal caused by flux concentration of the ferromagnetic rod. When the rod was placed between the pipe sample and the AMR sensors in this configuration, the magnetic signal from the rod is about 18 dB greater than the noise signal. It can be seen in Fig. 10(c and d) that the perturbations in the magnetic field resulting from distortion by the ferromagnetic rod when aligned with the pipe axis are larger than the defect signal.

Fig. 11 shows the configuration of Fig. 10(a and b) with a cube in

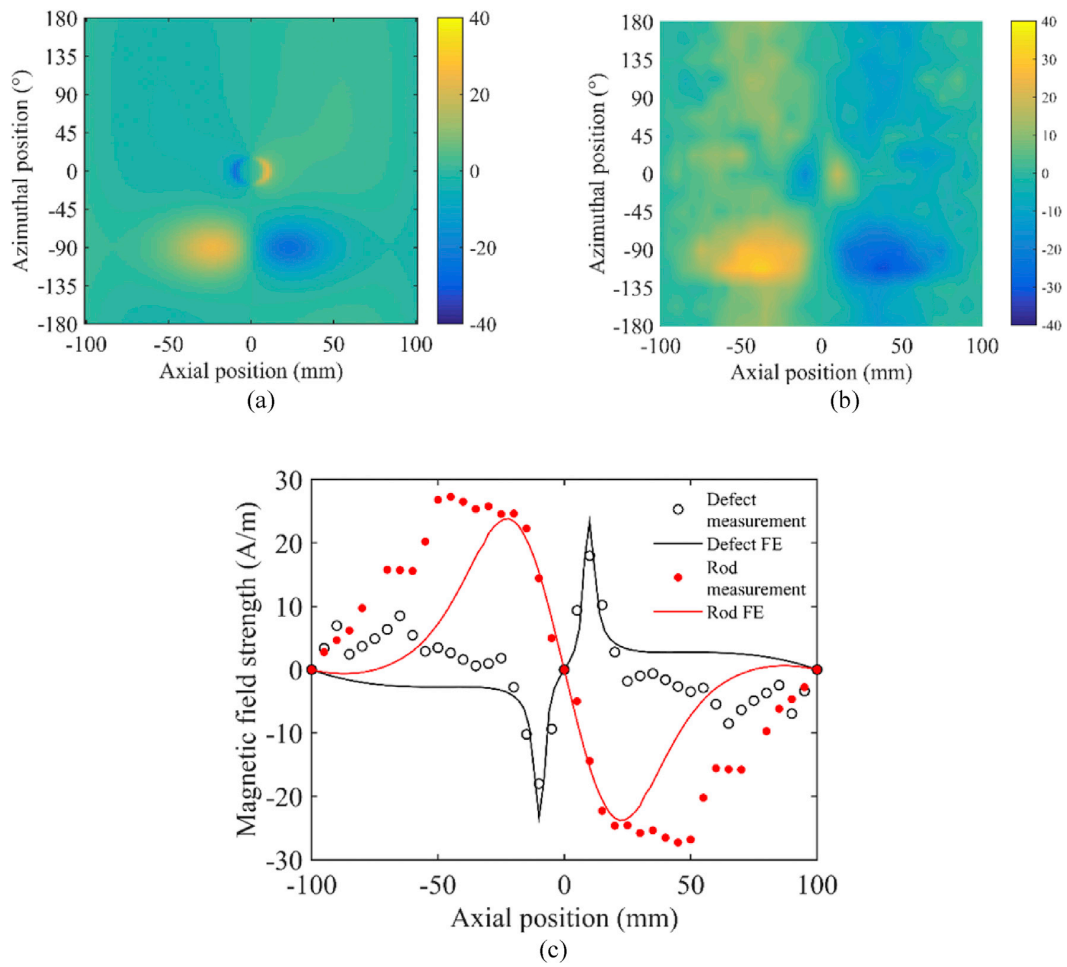


Fig. 8. Magnetic field profile at 1 mm stand-off from pipe with a mild steel rod positioned 90° azimuthally and 30 mm radially away from a flat-bottomed defect. 2D profiles of (a) FE and (b) interpolated experimental data. (c) Axial lines bisecting the maximum perturbation of the signals due to the defect and the rod.

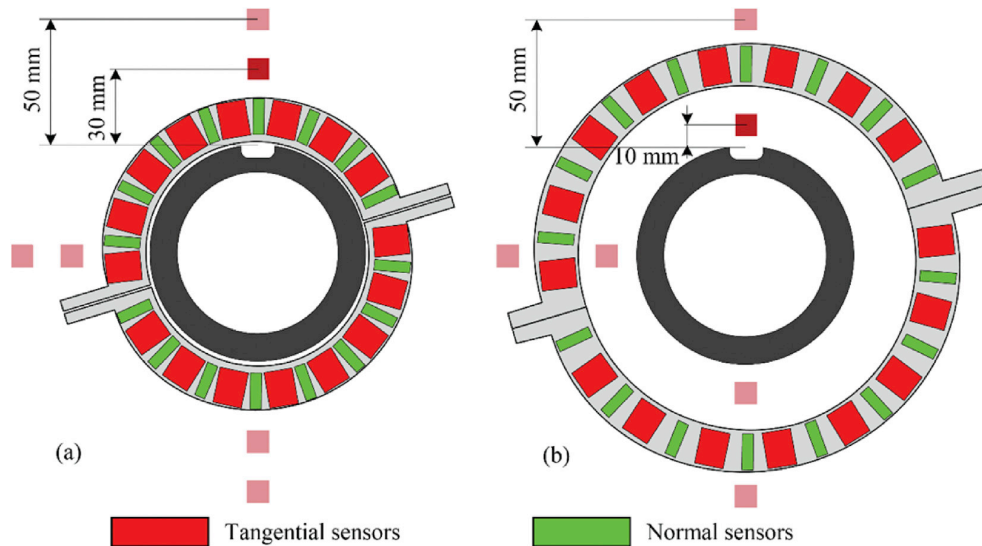


Fig. 9. Configuration of the nearby ferromagnetic objects by using ring AMR sensor arrays with (a) 1 mm and (b) 20 mm sensor stand-off distance, respectively. Only one object was in place in a given test.

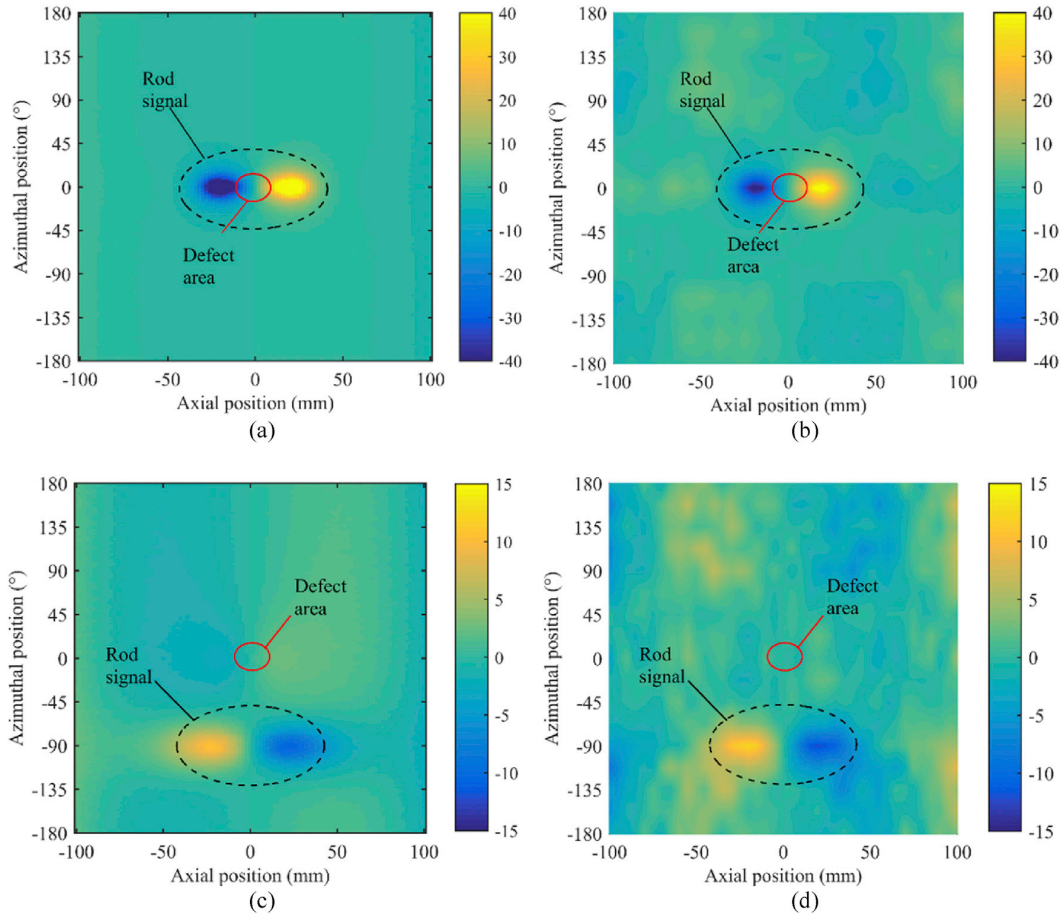


Fig. 10. Normal magnetic field distributions at 20 mm stand-off. (a) Modelled and (b) measured when rod aligned with the pipe axis was 10 mm away from the pipe surface and oriented 0° from the defect; (c) modelled and (d) measured when rod was 50 mm away from the pipe surface and oriented 90° from the defect.

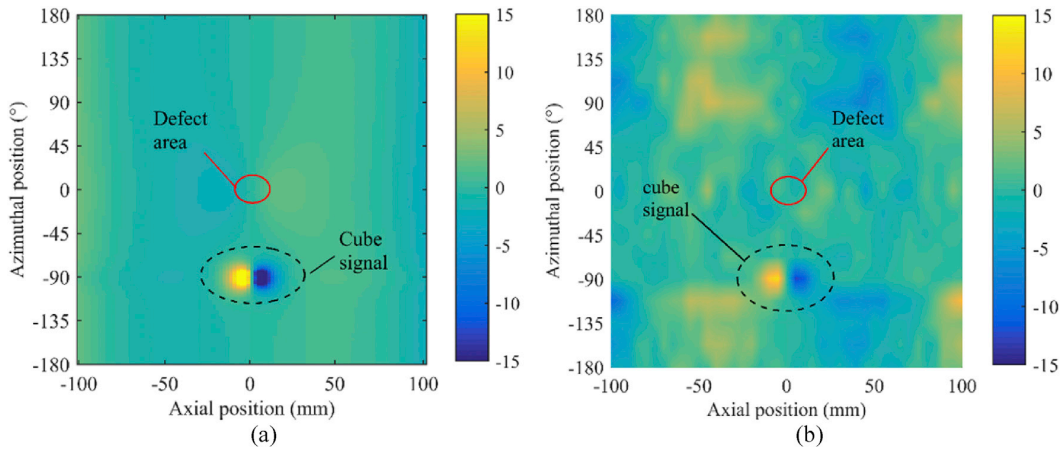


Fig. 11. (a) FE prediction and (b) measurement of normal magnetic field distribution at 20 mm stand-off with 1 cm³ iron cube 10 mm from the pipe and 90° from the defect.

place of the rod and offset from the defect by 90°. The spatial distributions of the defect and cube signals show good agreement between FE and measurement. The apparent higher amplitude in the FE is due to the uncertainty in the cube magnetization and the sampling locations of the measurement before interpolation not being exactly on the rod signal peaks, which are localized to a small area. At the same stand-off, the cube

signal is about 5 times smaller than that due to the rod due to the demagnetizing factors for different geometries [33].

4.3. False call risk of ferromagnetic objects

Having validated the FE model for both the defect and ferromagnetic

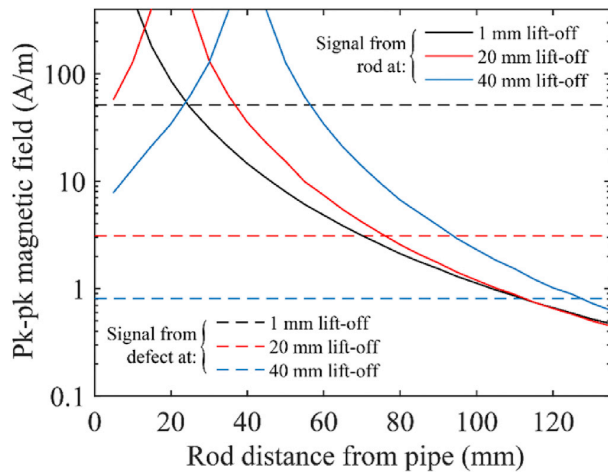


Fig. 12. Peak-to-peak magnetic field signals predicted for an annular sensor array located at 1 mm (black) 20 mm (red) and 40 mm stand-off. Solid lines: perturbation from 5 mm diameter, 50 mm long ferromagnetic rod. Dashed lines: signal from ~18 mm diameter, 2.5 mm deep defect matching dimensions of electrochemical corrosion used in experiment.

object signals in multiple cases, it could then be used to accurately predict the level of perturbation in the magnetic field due to such objects in different configurations. The model was used to predict the likelihood of such objects resulting in false calls. Fig. 12 shows the peak-to-peak perturbation in the magnetic field caused by the 5 mm diameter, 50 mm long rod ($\mu_r = 900$) of Fig. 7, aligned parallel to the pipe axis and at varying radial distance from the pipe. The solid lines show the peak-to-peak amplitude of the signal caused by the rod, predicted on a cylindrical surface which represents an annular array with high sensor density performing a scan along the pipe axis at stand-off distances of 1 mm, 20 mm and 40 mm. The peak-to-peak magnetic field perturbation caused by a flat-bottomed defect representing the corrosion patch used in the experimental studies is plotted as horizontal dashed lines for comparison. The crossing points of the solid and dashed lines of the same color represent the radial distance from the pipe that an array would be positioned to measure equal amplitude signals from the defect and from the ferromagnetic rod.

The array-rod separation is then plotted against array stand-off using black markers in Fig. 13(a). These data represent the minimum radial distance from the array that the ferromagnetic rod would need to be positioned to cause a signal perturbation equal to or smaller than the

amplitude of the defect signal. Plotted in red are the distances where the rod signal is exactly 6 dB below the defect amplitude for various values of array stand-off. Between these two lines, the rod signal is less than 6 dB below the defect signal, so represents some false call risk. The data has been fitted via linear interpolation for clarity. Fig. 13(b) shows the same data, but with the stand-off extrapolated to 1 m to demonstrate the risk of false calls for the stand-off distances reported in some practical MTM tests [21–24].

These figures illustrate that when performing a scan with low stand-off, nearby ferromagnetic objects are unlikely to cause false calls as the magnetic indication from a defect is of a much higher amplitude than the signal from any ferromagnetic object that is not in the immediate vicinity of the sensor. For example, if performing a scan at 5 mm stand-off, foreign objects like a nail or bolt etc. similar in dimensions to the modelled rod would need to be closer than 28 mm from the sensor to cause an indication like the defect signal. However, as the array stand-off is increased, the defect signal diffuses and reduces in amplitude meaning that magnetic flux distortion and/or remanent magnetization from ferromagnetic objects can equal the defect signal amplitude even if they are distant from the array. When the array stand-off is 40 mm, a nail closer than 88 mm would cause a magnetic indication with amplitude greater than the defect signal. The interfering distance increases approximately twice as quickly as the array stand-off which implies that when measuring 1 m from the pipe, ferromagnetic objects nearly 2 m from the sensor pose a risk of false indications.

The pipe used for the present test was not subject to external stress, though it should be noted that practitioners of the MTM technique suggest that the RMLF signal from a defect could be enhanced by repeated stress cycling of the pipe. If this were true and the signal could increase multiple orders of magnitude, the interfering distance for ferromagnetic objects and false call rate may decrease significantly, however, recent work suggests that this does not universally occur [20,32,34]. Bending tests completed on this pipe sample did not significantly change the defect signal [32], and work is ongoing to determine whether the effect is material specific.

5. Conclusions

MTM signals due to residual magnetic flux leakage from corrosion defects in a pipe measured by sensor arrays at different stand-offs were predicted by FE and validated by experiments. The effect of nearby ferromagnetic objects was also predicted and measured. The results suggest that the RMLF from corrosion defects could be detectable and are unlikely to suffer interference from such objects when the sensors are at a low stand-off where the defect signals are relatively large and localized. As the stand-off increases and the defect signal spreads out and reduces in

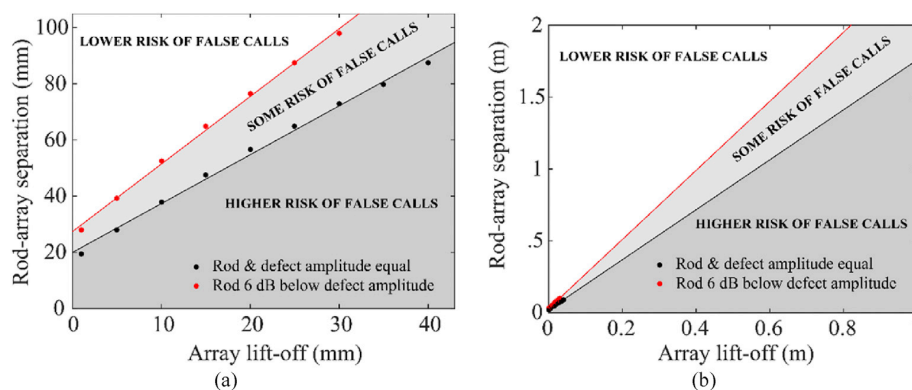


Fig. 13. Interfering distance for a 5 mm diameter, 50 mm long ferromagnetic rod to produce a magnetic perturbation similar in peak-to-peak amplitude to a 20 mm × 16 mm × 2.5 mm corrosion patch. Solid lines are linear best fit to data. Higher risk of false calls when rod signal > defect signal, some risk when within 6 dB. (b) shows (a) extrapolated to 1 m stand-off.

amplitude, there is an increasing risk of interference from nearby ferromagnetic objects. For example, a signal from an object like a bolt 2 m from the measuring sensors could result in a signal similar to an 18 mm diameter, 2.5 mm deep (approximately 50% of the wall thickness) defect when the sensor array is 1 m from the pipe. The weak signals from defects at large stand-offs and the possibility of interference from relatively remote ferromagnetic objects such as bolts, nuts etc. are likely causes of the high false call rates seen in some trials of the technique.

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References

- [1] Van Ness Feldman LLP. Natural gas pipeline safety and reliability: an assessment of progress. <http://www.ourenergypolicy.org/wp-content/uploads/2015/11/pipelinesafety.pdf>; 2015.
- [2] Vanaei HR, Eslami A, Egbewande A. A review on pipeline corrosion, in-line inspection (ILI), and corrosion growth rate models. *Int J Pres Ves Pip* 2017;149: 43–54.
- [3] Beller M, Reber K. Tools, vendors, services: a review of current in-line inspection technologies. In: Tiratsoo J, editor. Pipeline pigging and integrity technology. third ed. Houston: Clarion Technical Publishers; 2003. p. 357–74.
- [4] Steinvorte T. Unpiggable pipelines, in oil and gas pipelines: integrity and safety handbook. first ed. Hoboken: John Wiley & Sons, Inc; 2015. p. 545–54.
- [5] Lowe MJS, Alleyne DN, Cawley P. Defect detection in pipes using guided waves. *Ultrasonics* 1998;36(1–5):147–54.
- [6] Alleyne DN, Pavlakovic B, Lowe MJS, Cawley P. Rapid, long range inspection of chemical plant pipework using guided waves. *Key Eng Mat* 2004;270–273:434–41.
- [7] Honarvar F, Salehi F, Safavi V, Mokhtari A, Sinclair AN. Ultrasonic monitoring of erosion/corrosion thinning rates in industrial piping systems. *Ultrasonics* 2013; 53(7):1251–8.
- [8] Silva IC, Santos YT, Batista LS, Farias CT. Corrosion inspection using pulsed eddy current. In: 11th European conference on non-destructive testing; 2014.
- [9] De Raad JA, Bouma T, Bönsch A. Rapid corrosion screening in up to 30 mm wall thickness for plates and pipe. *Insight* 2002;44(2):97–103.
- [10] Li Y, Yan B, Li D, Li Y, Zhou D. Gradient-field pulsed eddy current probes for imaging of hidden corrosion in conductive structures. *Sens Actuat A-Phys* 2016; 238:251–65.
- [11] Ekinci S, Bas N, Aksu M, Yildirim A, Bingöldag M, Kurtcebe T, et al. Corrosion and deposit measurements in pipes by radiographic techniques. *Insight* 1998;40(9): 628–31.
- [12] Edalati K, Rastkhah N, Kermani A, Seiedi M, Movafeghi A. The use of radiography for thickness measurement and corrosion monitoring in pipes. *Int J Pres Ves Pip* 2006;83(10):736–41.
- [13] Dubov AA. A study of metal properties using the method of magnetic memory. *Met Sci Heat Treat* 1997;39(9):401–5.
- [14] Dubov A. Energy diagnostics - is a physical basis of the metal magnetic memory method. In: 19th world conference on non-destructive testing; 2016.
- [15] Dubov A, Kolokolnikov S. The metal magnetic memory method application for online monitoring of damage development in steel pipes and welded joints specimens. *Weld World* 2013;57(1):123–36.
- [16] Lin S, Wang W, Zhao C, Feng Z, Bi W, Jiang X. Application of metal magnetic memory method in long-distance oil and gas pipeline defects detection. In: The international conference on pipelines and trenchless technology; 2011.
- [17] Jiles DC. Theory of the magnetomechanical effect. *J Phys D Appl Phys* 1995;28(8): 1537–46.
- [18] Hu B, Li L, Chen X, Zhong L. Study on the influencing factors of magnetic memory method. *Int J Appl Electron* 2010;33(3–4):1351–7.
- [19] Augustyniak M, Usarek Z. Discussion of derivability of local residual stress level from magnetic stray field measurement. *J Nondestruct Eval* 2015;34(3):1–9.
- [20] Arkulis MB, Baryshnikov MP, Misheneva NI, Savchenko YI. On problems of applicability of the metal magnetic-memory method in testing the stressed-deformed state of metallic constructions. *Russ J Nondestruct Test* 2009;45(8): 526–8.
- [21] Transkor Group Inc. Magnetic Tomography Method (MTM) safety programs for underground and underwater pipelines. 2013. <http://transkorgroup.com/safety-programs>.
- [22] Janega G, Grigil V, Kolesnikov I. NYSEARCH's validation program of Transkor's Magnetic Tomography Method of pipe inspection. *Pipeline Gas J* 2011;238(6): 30–1.
- [23] Kolesnikov I. Magnetic Tomography Method (MTM) - a remote non-destructive inspection technology for buried and sub sea pipelines. In: Offshore technology conference; 2014.
- [24] Liao K, Yao Q, Zhang C. Principle and technical characteristics of non-contact Magnetic Tomography Method inspection for oil and gas pipeline. In: International conference on pipelines and trenchless technology; 2011.
- [25] Li C, Chen C, Liao K. A quantitative study of signal characteristics of non-contact pipeline magnetic testing. *Insight - Non-Destruct Test Condit Mon* 2015;57(6): 324–30.
- [26] Jarvis R. Current deflection NDE for pipeline inspection and monitoring. Unpublished doctoral thesis. London: Department of Mechanical Engineering, Imperial College London; 2017.
- [27] Continental Alloys & Services. Alloy steel; <http://www.contalloy.com/materials/alloy-steel>.
- [28] Gajdacs A, Cegla F. High accuracy wall thickness loss monitoring. *AIP Conf Proc* 2014;1581(1):1687–94.
- [29] Sensitec GmbH. AMR magnetic field sensors; <http://www.sensitec.com/english/products/magnetic-field/aff755.html>.
- [30] National Centers for Environmental Information. Magnetic field calculators; <https://www.ngdc.noaa.gov/geomag-web/#igrfwmm>.
- [31] Brooks RA, Weiss GH, Talbert AJ. A new approach to interpolation in computed tomography. *J Comput Assist Tomo* 1978;2(5):577–85.
- [32] Li Z, Dixon S, Cawley P, Jarvis R, Nagy PB. Experimental studies of the magneto-mechanical memory (MMM) technique using permanently installed magnetic sensor arrays. Manuscript submitted for publication. *NDT&E Int*. 2017.
- [33] Pugh BK, Kramer DP, Chen CH. Demagnetizing factors for various geometries precisely determined using 3-D electromagnetic field simulation. *IEEE T Magn* 2011;47(10):4100–3.
- [34] Arkulis MB, Misheneva NI, Savchenko YI. Studying magnetic stray field at the surface of elastostrained extensive object. *Russ J Nondestruct Test* 2016;11(52): 623–6.