Magnetic Flux Leakage System for External Robotic Inspection of Oil and Gas Pipelines

by

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Abstract

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Pipelines transport invaluable energy resources such as crude oil and natural gas over long distances. The integrity of the piping system in terms of safety of the process is then of high importance. However, pipes are prone by time to defects that may degrade their properties and lead to failures. Particularly, wall thinning is a serious anomaly that threatens aging pipelines. Therefore, their inspection plays a critical role to prevent the collapse of the system. Magnetic Flux Leakage (MFL) is by far the most effective technique of nondestructive evaluation for robotic diagnosis of ferromagnetic pipes. This work follows a novel approach to control such problem and assess the condition of the pipe by measuring with a good precision the wall radial thickness based on calibrated curves of reference and using an MFL diagnostic system tool. The proposed technique is generic and can be applied systematically for pipes with different sizes and material properties. It represents an advancement over the current conventional practices which require multiple physical experiments to generate empirical reference curves. Such procedures are cumbersome, time consuming and in consequence costly. The MFL sensing tool will be placed at the end-effector of a mobile robot platform devoted for external pipe inspection in a desert environment. It is based on permanent magnets producing a strong magnetic field that locally magnetizes and saturates the sample in question. At areas where there is metal loss, the magnetic flux flowing in the pipe leaks from the wall, which is detected by a Hall effect sensor and compared to the reference curve to estimate the wall thickness.
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Chapter 1

Introduction

1.1 Pipeline Inspection

Every human creation since the beginning of the world is susceptible by nature to gradually get damaged or destroyed due to the surrounding environment that interacts with its material composition. One example is pipelines used for the transportation of goods, which consist of sections of pipe made of metal (e.g., steel, cast iron, or aluminum) equipped with pumps, valves and other control devices to carry liquids mostly usually over long distances.

In the petrochemical industry particularly, pipelines play an important role in transporting crude and refined petroleum, fuels - such as oil, natural gas and biofuels - and other different type of fluids. These energy resources are considered to be very valuable and precious keeping important utilities in continuous service. Therefore, an uninterrupted supply and provision is necessary while ensuring the integrity of the piping system with respect to the process, the business, the safety and the environment. Figure 1.1 shows a photograph depicting a section of a pipeline related to the Trans-Alaska Pipeline System.

Unfortunately, steel pipes are prone by time to defects such as corrosion, cracks and dents, as long as the duration of being in service. Figure 1.2 illustrates some anomalies in pipelines through an image of a corroded pipe (Figure 1.2a) and a crack in the wall (Figure 1.2b). Hence, pipeline inspection plays a great role in maintaining the working process and preventing catastrophic failures. This can be achieved by monitoring and diagnosing regularly the “health” or status of the pipeline and intervening preventively in
Figure 1.1: An Elevated Section of the Trans-Alaska Pipeline System [1]

Figure 1.2: Illustrations of some Anomalies in Steel Pipelines

A defect (or anomaly) in energy pipeline is a growing issue considering the several thousands of miles of aging pipelines. It alters the original configuration of the steel pipe and can occur by time due to corrosion (commonly known as rust) or outside forces, which may degrade the metal until a spill or release happens. Prior to failure, some form of anomalies can be manifested such as the change in the wall thickness due to the metal loss by internal or external corrosion, a deformation in the pipe wall due to pitting caused by local corrosions, a crack (known also as surface breaking) defined as the separation of metal, dents or gouges caused by mechanical means.
Corrosion is an electrochemical reaction that is continuous and virtually unstoppable by nature, which requires an effective monitoring. Here comes the role of pipeline inspection to ensure the safety of the transmission pipelines and prevent accidents using advanced technologies. The inspection can be carried out internally or externally using specially adapted pieces of machinery and tools that provide data on the condition of the pipelines in order to assess the health and integrity of the steel conduits. Smart PIGs (or Pipeline Inspection Gauges) are diagnosis devices that travel inside the pipeline and perform their function without stopping the flow of the product. For external inspection, there exist robotic pipe crawlers that climb on the tube surface and robotic platform with gripper housing clamshell.

Mainly, there are two techniques to test the integrity of pipelines and that by using the destructive or the nondestructive evaluations. The destructive testing techniques are not preferred because they use hydrostatic process that disrupts the normal operation of the pipeline. However, the nondestructive testing (NDT) techniques detect flaws that may lead potential failures without causing any damage, providing information on the integrity of the pipeline as well as a measure of its current state of safety. The magnetic flux leakage method is one of the most promising NDT techniques.

1.2 The Magnetic Flux Leakage Method

The Magnetic Flux Leakage (MFL) is an electromagnetic method of nondestructive testing used to detect and evaluate defects in metallic pipelines like corrosions, pittings and metal losses. It is a noncontact method that uses powerful magnetic field which can be generated by permanent magnets or electromagnets and which is governed by Maxwell’s equations. The flux lines distribution can be accurately represented using modern numerical modeling (like the finite element method package ANSYS) showing the strength and direction of the magnetic field.

When a magnet is placed next to the pipe surface, most of the flux lines pass through
the wall since the steel has much higher magnetic permeability than the surrounding free space, which creates a path for the magnetic flux to flow through the wall. Hence, most of the flux lines are concentrated in the pipe wall while few propagate in the media around the pipe.

A defect characterized by a local decrease in the thickness of the pipe wall due to metal loss causes the phenomenon of flux leakage at this region. The flux leaks from both the inner and outer surfaces of the pipe. The concept of magnetic flux leakage can be illustrated as follows. We consider a perfect specimen (defect-free) of a ferromagnetic pipe’s wall, as shown in Figure 1.3a, subjected to a strong magnetic field, uniformly distributed. The magnetic flux lines flow inside the wall and travel axially through it in straight lines between the two magnetic poles. On the other hand, an identical specimen with a triangular defect in the wall, for instance, as shown in Figure 1.3b, is subjected to the same magnetic field. In this case, the magnetic flux flowing through the pipe tends to leak from its wall in the vicinity of the defect. This is what is known as the magnetic flux leakage phenomenon.

![Figure 1.3: Pipe’s Wall Specimens Subjected to a Uniform Magnetic Field](image)

1.3 Framework and Objectives

This work is part of a research project for designing and constructing a mobile robotic platform devoted for external inspection of industrial aboveground pipelines that transport crude oil and natural gas. This task will be carried out remotely using an integrated acoustic and MFL diagnostic system. The robot is aimed to operate in a severe environ-
ment characterized by a harsh and rugged ground, without the need of stopping the flow of the product in the pipeline, which explains the fact of opting for the external robotic inspection over the internal PIGs. A CAD representation of the mobile robotic platform is given by Figure 1.4.

![Mobile Robotic Platform for External Pipeline Inspection](image)

Figure 1.4: Mobile Robotic Platform for External Pipeline Inspection

The current work is concerned with the part of the MFL examination system and it is interested particularly in the problem of detecting and evaluating the wall thinning defects that could alter the surface of pipelines due to corrosion or erosion. This type of defect is a serious problem because even slight changes in the wall thickness can affect the ability of the pipe to operate properly and withstand the flow pressure. The main objective is to develop and implement a method that allows to measure with a high accuracy the radial wall thickness of ferromagnetic pipes using the MFL technique and a numerical method tool, which is the finite element method (FEM) combined with the computer-aided engineering simulation software ANSYS.

Although the problem of wall thickness measurement sounds trivial, it is not the case in reality. This work deal with such problem differently in comparison with the conventional current practices which demand a great amount of effort and time. It follows a method
developed in our Robotics & Intelligent Systems Lab at Rice University that has not been concretely implemented yet. The next section presents a review of the literature to see how this problem was approached over the years.

1.4 Literature Review on the Problem of Wall Thickness Measurement of Pipelines

The wall thickness measurement of steel pipelines with the MFL technique has been in development since the eighties. In 1985, Stanley et al. developed a device for indicating the wall thickness of ferromagnetic pipes by utilizing the induced saturation value of the magnetic flux [4], which is considered as the earliest rigorous application. They used electric coils excited by DC current to generate and detect the axial flux leakage.

In another publication in the field of NDT [5], Stanley described a magnetic method consisting in measuring the wall thickness and detecting flaws in ferromagnetic tubes and plates. The method employed solid-state sensors that are able to identify material losses from eccentricity, erosion and corrosion.

Weinbaum [6] presents a nondestructive inspection tool for coiled tubing oilfield tubulars testing. The system uses a magnetizing coil to saturate the pipe. The inspection head includes multiple sensors for detecting defects, in particular, wall thickness transducers that measure magnetic flux density corresponding to a specific tubular wall thickness.

Zhang and Yan [7] described a MFL-based technique for the detection of pipes reduction. They developed a device composed of a detector array with 32 Hall effect sensors for measuring the magnetic flux density. They revealed the influence of some factors on thickness measurement to select the optimal excitation conditions of the detector. A measuring calibration is then given to establish the relationship between the wall thickness and the output of the sensors.

Standen and Pike [8] presents a wall thickness and ovality measuring device combining
fiber-optical transducers and MFL principles. The wall thickness tool is based on permanent magnets used in a steel shell of split, hinged configuration and contained in an aluminum housing.

The work conducted until this point in academia for pipe wall thickness measurements with MFL uses empirical calibrations to obtain calibration curves of reference plotting the axial component of the MFL signal versus the true wall thickness. These calibrations are conducted in a laboratory environment for a particular pipe sample with specific size (inner and outer diameters) and material property. Consequently, new calibration experiments have to be produced for a new sample with different dimensions and magnetic permeability. Such procedure is tedious, time consuming and expensive.

For these reasons, Dutta and Ghorbel [9] proposed a method that accurately estimates the amount of wall reduction in steel pipes based on the axial MFL signal readings without the need of the long empirical calibrations. They suggested to model mathematically the relation between the wall thinning and the axial MFL signal in the region of interest using Maxwell’s equations. The problem is solved by the FEM with accounting for the geometrical constraints and material properties of the magnetizing device and the pipe under inspection.

This method is considered novel and generic since it can be applied with any MFL-based inspection setup. In fact, Dutta and Ghorbel worked with two types of magnetizing devices, internal and external, to validate the proposed technique. They used the FEM package COMSOL Multiphysics for system modeling and analysis. Because of the cylindrical symmetry of the considered models, the problems were dealt with as axisymmetric, i.e., having a symmetry about an axis of rotation. Therefore, the modeling process became much like as it is conducted in a two-dimensional environment by considering only the plane composed of the axial and radial directions of the corresponding cylindrical coordinate system and defining the element behavior as axisymmetric.
1.5 Contributions

The current work exploits the method developed by Dutta and Ghorbel to design an MFL sensing tool for wall thickness measurements aimed to be carried by the end-effector (gripper housing clamshell) of the external mobile robotic platform (of Figure 1.4) used for pipeline inspection and diagnosis. The proposed design of the MFL tool is modeled with the different parts composing the system (the pipe and the surrounding air) in the advanced numerical analysis package with the FEM, ANSYS. This software does not require deriving the magnetostatic mathematical model of the system using Maxwell’s equations, which is actually done by Dutta and Ghorbel. The system modeling is conducted in two different ways: axisymmetrically and in a three-dimensional (3-D) environment. The axisymmetric models are valid only for geometries that have a cylindrical symmetry with respect to an axis of rotation, the case that Dutta and Ghorbel was limited to. The 3-D simulations represent an additional improvement to their work providing more flexibility in modeling by accounting for nonuniform pipe’s wall thinning all over the circumference of the cylindrical pipe, that may have different shapes at the edges, in addition to nonaxisymmetric magnetization by the source of the magnetic field.

Owning a well-characterized magnetizing device represents another advantage over Dutta and Ghorbel’s work in terms of minimizing the time, effort and expenses of generating wall thickness calibration curves. Due to the fact of having a parametric model, each time there is a steel pipe with some new characteristics, we only need to change the pipe parameters in our model. New simulations will be executed in a systematic way allowing to obtain the wall thickness reference curve for that specific pipe.

1.6 Outline of the Thesis

The next content of the thesis is organized as follows: Chapter 2 introduces the relevant theory of magnetostatics using Maxwell’s equations applied to the system, and addresses
the magnetic modeling using the finite element method and the numerical tool ANSYS. Chapter 3 presents the problem of wall thickness measurements of oil and gas pipelines and the procedure followed here to solve such problem by designing an MFL sensing system and using the tools introduced in Chapter 2. Chapter 4 describes the MFL experimental prototype that is built for the pipe inspection applications and as validation of the proposed method. Finally, Chapter 5 summarizes and discusses the work and contributions carried out in this research project introducing future steps based on this work.
Chapter 2

Magnetostatics and Finite Element Analyses

The adopted method for the measurement of wall thickness of energy pipelines based on magnetic flux leakage depends on the behavior of the ferromagnetic specimen itself when it undergoes an external applied magnetic field. The resultant magnetic field distribution obey the physical laws of magnetostatics governed by Maxwell’s equations.

This chapter presents briefly the relevant theory of magnetostatics using Maxwell’s equations, and describes the modeling and analysis of a magnetostatic problem using the finite element method applied within the package ANSYS.

2.1 Theory of Magnetostatics and Maxwell’s Equations

Magnetostatics is the branch of electromagnetics that study magnetic fields produced by steady time invariant currents. A magnetization current as in permanent magnets is produced by moving charges which undergo translational motion if magnetic dipoles are not uniformly distributed. When a large number of charges exists as continuous flow, currents are considered steady (direct current, DC). Hence, in this case of charges moving with a constant velocity, a static magnetic (or magnetostatic) field is produced.

From the mathematical point of view, Maxwell’s equations, which are partial differential equations with given boundary conditions, delineate physical phenomena of magnetic nature. In the absence of free current, the magnetostatic problem is governed by Maxwell’s
equations. The magnetic circuit law according to Ampère’s theorem states:

$$\text{curl } \mathbf{H} = 0, \text{ or } \nabla \times \mathbf{H} = 0$$  \hspace{1cm} (2.1)

where \( \mathbf{H} \) is the magnetic field intensity vector.

The magnetic flux law revealing the nonexistence of magnetic monopoles and the continuity of the magnetic flux is given by:

$$\text{div } \mathbf{B} = 0, \text{ or } \nabla \cdot \mathbf{B} = 0$$  \hspace{1cm} (2.2)

where \( \mathbf{B} \) is the magnetic flux density vector.

In addition to the previous equations, we present the constitutive relation inside ferromagnetic materials (including permanent magnets):

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$$  \hspace{1cm} (2.3)

Here, \( \mu_0 \) denotes the magnetic permeability of free space (which is equal to \( 4\pi \times 10^{-7} \)) and \( \mathbf{M} \), which depends on \( \mathbf{B} \), is the magnetization vector of the ferromagnetic material. In free space, \( \mathbf{M} = 0 \) and the relation simplify to:

$$\mathbf{B} = \mu_0 \mathbf{H}$$  \hspace{1cm} (2.4)

We introduce now the notion of magnetic vector potential, which is a vector field that cannot really be interpreted physically. Nonetheless, relation (2.2) could be satisfied if the magnetic flux density vector \( \mathbf{B} \) is expressed in terms of the auxiliary vector \( \mathbf{A} \), called the magnetic potential vector, such that:

$$\mathbf{B} = \nabla \times \mathbf{A}$$  \hspace{1cm} (2.5)

Hence, Ampère’s theorem (2.1) together with relation (2.3) yields:

$$\nabla \times (\mu_0^{-1} \nabla \times \mathbf{A}) = \nabla \times \mathbf{M}$$  \hspace{1cm} (2.6)
2.2 Finite Element Method Modeling for Magnetoostatics

Partial differential equations (PDEs) arise in the mathematical modeling of many engineering problems such as magnetostatics. Most of the time the considered equations are very complicated such that finding their solutions in closed form or by purely analytical means (e.g. by Laplace and Fourier transform methods, or in the form of a power series) is either impossible or unfeasible, and one has to seek for numerical approximations to the unknown analytical solution [10].

In particular, Maxwell equations stand for the set of PDEs that describe electric and magnetic phenomena. Their treatment contains numerous difficulties either from the mathematical or numerical point of view. The complexity of the governing differential equations could arise from the presence of a large number of unknown fields or from the boundary (at infinity) and initial conditions [11]. To deal with such equations, one has to resort to numerical methods. While an analytical solutions give the exact behavior of the system of interest continuously (i.e. at all it points), the computed solutions approximate the exact solutions at discrete points, called nodes. Thus, a numerical technique divide the system into a number of small elements and nodes [12]. Hence, a particular class of numerical techniques for solving PDEs is finite element methods (FEM).

2.2.1 Literature Survey on the Use of the Finite Element Method for the Magnetic Flux Leakage Technique

The finite element analysis (FEA) is a powerful computational technique that approximates solutions to a variety of real-world engineering problems having complex domains subjected to general boundary conditions. Its modern formulation was originally introduced by Turner et al. (1956), evolving out of discrete stiffness methods of structural analysis. Zienkiewicz and Cheung were the first ones to write a book that is entirely
devoted for FEM in 1967 [12].

The pioneering of the FEM in MFL modeling started in the 70s with Lord and his colleagues at Colorado State University, due to the advancements in computational resources. In one his publications in 1975, Lord and Hwang described operational aspects of the finite element technique and showed how such method can be applied to electromagnetic modeling of a defect in a ferromagnetic bar carrying an axial magnetization current, by predicting the magnetic field distribution to characterize its interaction with the defect [13]. In another paper in 1979, Lord and Palanisamy used FEM again for electromagnetic modeling of NDT phenomena. They suggested that the resulting magnetic potential values can be used to calculate measurable electromagnetic quantities, such as magnetic flux density and leakage field in the vicinity of defects [14].

Atherton and his colleagues at Queen’s University have also an important contribution in FEAs for pipe inspection by MFL techniques. In one work, Atherton and Daly (1987) presented two-dimensional (2-D) FE calculations for anomalous leakage fluxes in steel pipes, detected by a pipeline inspection tool based on permanent magnets, that is aiming to improve the MFL sensing system [15].

Later, Atherton and Czura (1987) investigated the effects of permeability variation of the anomalous ferromagnetic region on MFL signal measurements, based on results obtained from 2-D FE calculations [16].

Once again, Atherton used 2-D FEM to calculate the anomalous leakage fluxes generated by grooves in pipes inspected by MFL anomaly detectors (1988). He compared the obtained data with experimental measurements of 3-D synthetic corrosion pits, deducing that there exists a strong linear correlation between peak anomalous radial flux densities and the corresponding results [17].

Moreover, Atherton, with Laursen and Maki from Pipetronix Ltd. (a company established in Concord, Canada), employed FEM to design an in-line inspection tool for corrosion monitoring (1995). They used 2-D, axisymmetric and 3-D FE modeling in order to ensure optimum designs, all along with special scaling methods, powerful magnets and
other high performance materials, validating simulations with experimental measurements [18].

In 2009, a team from the University of Tulsa (Breidenthal et al.) exploited the FEA for flux leakage density calculation to characterize defects in steel coiled tubing (CT). They focused on identifying and estimating the size of surface defects based on some features of MFL signals using FEA. The objective was to accurately extract surface flaw dimensions from conventional MFL signals in order to predict the lifetime of the steel pipe [19].

Another team from China [20] modeled and ran some numerical simulations using the FEM package ANSYS for MFL inspection of pipelines. They analyzed defect quantification of MFL testing by setting up a signal database based on contrasting the amplitude of the magnetic flux density of the model with different depths, lengths and obliquities.

Dutta and Ghorbel [21, 9] used the FEM package COMSOL Multiphysics to model an internal and external magnetizing systems using the MFL technique for pipe wall thinning defect type measurement. Toward this end, Maxwell’s equations are derived for each system and solved by the FEM package. The axial component of the MFL signal is then plotted against the pipe reduction depth in order to graphically determine the wall thickness.

Recently, a group from Schlumberger [22] developed a 3-D FE model to compute MFL for mechanical defects on steel CT. They used the outcoming results to identify defect’s geometry features based on MFL signals. They also presented a novel approach to reproduce the MFL signal in space based on a single MFL component measurement.

2.2.2 Continuous Formulation of the Magnetostatic Problem in the Three-dimensional Space

The objective of analyzing magnetic fields problems is to determine the value of certain unknown functions for the field considered, such as magnetic field intensity, magnetic flux density, magnetic scalar potential and magnetic vector potential.
In order to solve equation (2.6) numerically, we introduce a bounded domain \( \Omega \subset \mathbb{R}^3 \) as well as an artificial boundary \( \Gamma := \partial \Omega \) sufficiently removed from the region of interest. Hence, the elliptic boundary value problem for the magnetic vector potential \( \mathbf{A} \) can be formulated as [23]:

\[
\nabla \times (\mu_0^{-1} \nabla \times \mathbf{A}) = \nabla \times \mathbf{M} \quad \text{in} \ \Omega \\
\mathbf{A} \times \mathbf{n} = 0 \quad \text{on} \ \Gamma
\]

(2.7)

where \( \mathbf{n} \) represents the outward unit vector of \( \Gamma \).

2.2.3 Finite Element Method with ANSYS

The finite element method is a numerical procedure that can be applied to solve magnetostatics problems. Its purpose is to find the solution of a complicated problem by replacing it with a simpler one, which gives an approximate solution rather than the exact one.

There exists many commercial FEA software for solving engineering problems. For instance, ANSYS, a commercial computer program package, is a comprehensive general-purpose FEA software, capable of performing electromagnetism analyses. ANSYS has been leading the FEA programs for more than 40 years (released for the first time in 1971). It is a powerful and advanced package that can be used to solve a variety of complex problems, offering enhanced tools and capabilities to perform simulations in an efficient manner. In fact, it includes modules to create the system’s geometry, divide the domain into finite elements, solve the problem and do postprocessing tasks. These steps could be accomplished in a single graphical user interface (GUI), or via command lines which is useful to build parametric codes or run simulations in batch mode when working with clusters.

2.2.3.1 Concepts of Finite Element Method

In the FEM, the continuum of matter is represented as an assemblage of subdivisions called finite elements. The element distribution is termed as the mesh. The adjacent
elements are interconnected with each other at specified joints called nodal points, or simply nodes, lying on element boundaries. For these elements, the approximate solutions are computed by applying the variational approach, in particular. Thus, the FEA consider the problem as a finite number of unknowns by expressing the unknown field variable (like the magnetic flux density $B$) in terms of the approximating functions within each element. These functions, called also interpolation functions, are defined in terms of the field variables at nodes [24].

2.2.3.2 General Steps of the Finite Element Analysis

The FEA is achieved following the major steps below:

- Discretize the domain into a finite number of elements.
- Select the interpolation functions.
- Derive the individual element matrices.
- Construct the global matrix, corresponding to the entire model, by assembling individual element matrices.
- Define the boundary constraints.
- Solve the global system of equations.
- Do the additional computations if needed.

The global system of equations can written in matrix form as

$$Ku = F,$$

where $K$ represents the stiffness matrix of the system, $u$ denotes the vector of unknowns, and $F$ is the force vector.

2.2.3.3 Nodes and elements

After meshing the domain of interest, nodes are created to define the coordinate locations in plane or 3-D space, in which exists the degrees of freedom (DOF) and actions
of the physical problem. The DOFs of an element represent the primary nodal unknowns assigned to this element and to be determined by the analysis. The continuity of the nodal variables, or DOFs of elements, is ensured by common nodes between elements. Figure 2.1 represents a mesh of a small domain, depicting the element distribution and the common nodes at their vertices.

![Figure 2.1: Plane Mesh and Common Nodes between Adjacent Elements](image)

In magnetostatic discipline, the DOF of elements could be the magnetic potential (scalar or vector potentials). The corresponding force vector is the magnetic field intensity. The discretization of the domain of interest could be conducted using areas or volumes depending on the geometry of the problem’s domain. In fact, ANSYS models may be either 2-D or 3-D depending on the chosen element type. Figure 2.2 shows some of the common elements shapes used in FEA [24].

According to this figure, an element could be area, i.e., 2-D plane element that has a triangular or quadrilateral shape. It could also be a volume, i.e., 3-D solid element that has a tetrahedral or brick shape.

### 2.2.3.4 Magnetostatic Analysis Approach with ANSYS

In general, a magnetic analysis with ANSYS aims to calculate some quantities related to the magnetic field produced by permanent magnets, in particular, in parts or components of the problem’s domain. Typically, we can measure the flux leakage in air (non-permeable), the magnetic flux density and field intensity in soft magnetic material (like the steel). Obviously, static magnetic analyses do not take into account time-dependent
Figure 2.2: Common Elements Shapes used in FEA

effects such as eddy currents. We can model both saturable and nonsaturable material with ANSYS, as well as hard magnetic materials (like permanent magnets responsible for the magnetization).

The ANSYS program utilizes Maxwell’s equations to perform magnetic analyses, in order to primarily solve for the magnetic potential (DOF). The other quantities related to the magnetic field such as the magnetic flux density $B$ and the magnetic field intensity $H$ are derived consequently. The choice of element type and features (DOFs) is of high importance in the simulation. Plane or Solid are examples of element types used in our simulations. Selecting an element type for the analysis with the necessary DOFs characterize the response of the problem.

For magnetostatics analyses, the program offers three types of formulations depending on the material properties of the physical domain (non-, soft, or hard magnetic materials, typical conductors like the copper and aluminum, coils, ...), as well as the overall physics of the problem and analysis type (static, which is our case, harmonic and transient). These formulations are listed in the following:
- The magnetic scalar potential formulation, applicable only for 3-D geometry and restricted to static field analysis with partial orthotropic nonlinear permeability. It uses SOLID98 as an element type option.

- The nodal magnetic vector potential formulation, which is a nodal-based formulation applicable to both static and dynamic fields with partial orthotropic nonlinear permeability. It can be employed in 2-D and 3-D geometries. It is implemented in PLANE53 for 2-D problems (\( A_z \) DOF), and SOLID97 for 3-D (\( A_x, A_y, A_z \) DOFs), as examples.

- Edge-based magnetic vector potential, offers 3-D static and dynamic analysis capabilities for magnetic problem. It associates the DOFs with element edge nodes rather than corner nodes. It is implemented in SOLID236, for instance, where the DOF in magnetostatics is the magnetic edge-flux \( A_z \) at each midside node.

The low-frequency electromagnetic guide of ANSYS recommends the use of the edge formulation method for most 3-D magnetic analyses. It claims that the edge formulation is more accurate and efficient than the nodal-based formulations, for the same model, in terms of the active DOFs. For that reason, we opt for the edge formulation to conduct our magnetostatic simulations. The procedure for doing such simulations in ANSYS, consists of five main steps that can be categorized under three phases within ANSYS.

(a) **Preprocessing Phase**

1. Create the environment of the physical problem. This includes:
   - Specifying the elements types and options, as well as their coordinate system.
   - Defining material properties of the media constructing the model.

2. Build the model and assign physics attributes to each region, and then mesh this model.

3. Apply boundary conditions.
(b) Solution Phase

4. Obtain the solution by:
   - Defining the analysis type (static in our case).
   - Choosing the solver to use (the sparse solver is recommended)
   - Specifying the number of solution sequences and initiate the solution.

(c) Postprocessing Phase

5. Review the results and obtain all important information:
   - Primary data: nodal DOFs \(A_z\)
   - Derived data: nodal magnetic flux density \(B_x, B_y, B_z, B_{sum}\), nodal magnetic field intensity \(H_x, H_y, H_z, H_{sum}\), etc.

2.3 Conclusion

This chapter addresses the FEM and its application in magnetostatics. It presents its formulation limited to the case where permanent magnets are used to create the magnetic field, i.e., no electric currents are involved. It also describes the application of the FEM in the ANSYS Program. Different features of the package and analysis steps are mentioned as well.

The following chapter presents the results obtained using the FEM within ANSYS to determine steel pipe wall thinning defects for diagnostic purposes.
Chapter 3

Pipe Wall Thickness Measurement using the Magnetic Flux Leakage Technique

3.1 Introduction

Oil and gas pipelines may experience radial wall thinning while in-service due to corrosion, pitting or cavitations. This type of defect is one of the major degradation mechanisms that affects the piping systems. It causes serious problems for the maintenance since it attacks large surface of the pipe which may induce irreparable damage to the specimen. For this reason, it is important to develop methods to measure the reduction of pipe thicknesses and implement them in tools and machines used for pipe inspections (Pigs, robotic clamps).

The current chapter describes an approach for estimating, with a good precision, the amount of reduction or metal loss in the pipe’s wall based on the nondestructive testing technique, which is the magnetic flux leakage. The method is adopted from Dutta & Ghorbel [9] and implemented on an external pipe inspection system consisting of an MFL sensing device.

Wall thinning are large defects, i.e., not local. The applied magnetic field is then not constant. Therefore, in order to measure the flux leakage, we may refer to the finite element method to solve Maxwell’s equations of magnetostatics and deriving the magnetic flux density $\mathbf{B}$ components. Toward that end, we use the FEM package, ANSYS, to measure the MFL signal close to the pipe’s wall.
3.2 Presentation of the Wall Thinning Measurement Method

A flowchart of the method that allows to predict the wall radial thickness of pipeline is represented by Figure 3.1. When we face the problem of measuring the wall thickness of a pipe, we first investigate the characteristics of the tubular conduit and collect the information about its inner and outer diameters as well as its material property. These data are used to simulate the system that includes the ferromagnetic pipe and the designed magnetizing device in order to determine the axial magnetic flux leaking from the pipe’s wall, at a specific point where the magnetic sensor is located. These simulations are performed numerically in the lab for wall reductions ranging from 0% to 100%, which leads to plot the MFL signal against the actual thickness of the wall. Such plot is the result of the calibration process and represents the wall thickness reference curve. This procedure of calibration corresponds to the blue part of the flowchart of Figure 3.1. It is developed in the current chapter and it is conducted one time for the a pipe with specific and defined characteristics (inner and outer diameters and material property).

On the other hand, pipeline inspections are performed in the field regularly using the robotic MFL sensing tool described in Chapter 4, which scans the pipe’s length at a constant speed and takes readings of the axial magnetic flux density at a fixed rate. These readings are compared with the wall thickness reference curve generated from the numerical simulations in order to determine the actual wall thickness of the pipe at each measuring point. Hence, plotting the magnetic flux density versus the position of the sensor along the horizontal length of the pipe results in the wall thickness profile of the scanned section. This profile will help us evaluate the “health” of the energy pipeline.
Define the material property and the dimensions of the pipeline

Run FE simulations with the new parameters for wall thinning defects ranging from 0% to 100%

Determine the axial MFL signal magnitude at the point where the Hall effect sensor is located

Generate the wall thickness reference curve

One time procedure, performed in the lab, for the specific pipe type and diagnostic system

Scan the portion of the pipeline in question at a constant speed measuring the magnitude of the axial magnetic flux density

Collect the data measurements to plot the axial MFL signal of the scanned length of the pipe

Plot the wall thinning profile of the pipeline

Inspection in the Field

Figure 3.1: Flowchart of the Pipe Wall Thickness Method
3.3 Description of the Proposed Magnetic Flux Leakage Sensing System

The magnetic field can be produced by an electric current circulating in a coil of wire (solenoid), or, in a persistent way, by permanent magnets. The mobile robotic platform will be operating in a real-world field for the external inspection of oil and gas pipelines. Hence, the power supply represents one issue that has to be adequately resolved by providing a sustainable energy source. For this reason, we opt for permanent magnets, made of a powerful rare earth material, to generate the necessary magnetic field strength that induces the flux leakage phenomenon.

The permanent magnets are the Neodymium (NdFeB) type, made from an alloy that consists of primarily Neodymium, Iron and Boron. These magnets are considered as the strongest commercialized magnets available for industrial applications, existing in a variety of grades. These grades represent a good measure of the magnet strength and directly refer to the maximum energy product of the magnet material \( (BH_{\text{max}}) \), which quantifies the stored energy in a magnet and relates to the magnetic flux output per unit volume. We opt for the grade N50 which is a quite strong grade, producing a maximum energy product of 50 MGOe (megagauss-oersteds), saturating the ferromagnetic pipe at the center of the magnetizing device, which causes the magnetic flux to leak out in case of wall thinning defects.

In the finite element modeling, the magnetizing entity consists of two annular cylindrical permanent magnets (or rings). The two magnets are magnetized, i.e., magnetically polarized, in the radial direction of a cylindrical coordinate system associated with the magnet rings. The two magnets are magnetized in opposite sense, the right magnet in the radially inward direction and the left magnet in the radial outward direction. Figure 3.2 shows a schematic representation of the two magnets depicting the opposite poles (north pole in red and south pole in blue), the radial magnetic field and the direction of magnetization of each ring. In Figure 3.2, we represents a 2-D axisymmetric cut of the two
magnets placed next to ferromagnetic material entities, showing the flow of the magnetic flux lines into the different media to constitute the closed magnetic circuit.

In the real application, the magnets are held and carried by a robotic gripper in order
to perform the inspection of the steel pipe. We assume that the gripper has an annular cylindrical shape like the magnets. The robot end-effector consist of 1018 mild (low-carbon alloy) steel, which offers a good balance in term of toughness, strength and ductility, as well as a comparative ease of machining. The ferromagnetic end-effector circulates the magnetic field lines, and hence closing the magnetic circuit.

A representation of the MFL tool while inserted in a steel pipe is given in Figure 3.4. A detailed CAD representation with dimensions of the system is given in Appendix A.

![Figure 3.4: MFL Tool and Pipe with Wall Thinning Defect](image)

The following sections represents the designed MFL sensing tool, describing its components and the way MFL signals are captured. This tool is then modeled and implemented within its environment in ANSYS to analyze the whole system and detect MFL signals.

### 3.4 Magnetostatic Modeling and Simulations with ANSYS

In the previous chapter, the FEM package ANSYS was introduced presenting the methodology to conduct a magnetostatic analysis. In this section, we will present the procedure and results of such analysis applied to the system described above. The problem can
be dealt with in two different ways of modeling: axisymmetrically and three-dimensionally.

### 3.4.1 Axisymmetric Magnetostatic Analyses

The geometry of the different entities constituting the system as well as the boundary conditions have a cylindrical symmetry with respect to an axis of rotation. Because of this property, the system is considered axisymmetric and we can model the system on a two-dimensional (2D) environment represented by the plane defined by the radial and axial directions of the associated cylindrical coordinate system.

#### 3.4.1.1 Modeling and Simulations

Following the steps described in section 2.2.3.4 to do a static magnetic analysis, we create in ANSYS the physics environment, build the model and assign the physics attributes to each region within it, and then perform the meshing. In the following, we define the material properties of the different components constituting the model. We specifically need to define magnetization vectors of the pipe, permanent magnets and the gripper.

The portion of steel pipeline, made of ferromagnetic material, is 90 grade coiled tubing (HS-90). It is assumed to be homogeneous isotropic. Its magnetization curve, also called B-H or hysteresis curve, at 20 °C (room temperature) is given by Figure 3.5 [9]. The B-H curve shows the relationship between the magnetic flux density B and the magnetic field intensity H for a particular material. It is given as a data table to ANSYS to define the material property of the geometric entity.

The permanent magnets are made from neodymium magnet (NdFeB), N50 grade. The demagnetization curve at room temperature of this type of rare-earth magnets is plotted in Figure 3.6 [25]. It corresponds to the curve of the second quadrant of a normal hysteresis loop.

The robot’s end-effector made of 1018 mild steel. It serves as a holder for the MFL sensor tool. This part is assumed to be homogeneous and isotropic as well. Figure 3.7
The axisymmetric model is surrounded by an area of air (which has a relative magnetic permeability $\mu_r = 1$) sufficiently large to ensure that the magnetic field theoretically vanishes at the boundaries. Once the material properties are defined, we create the geometric regions of the system, assign the material characteristics to each area within the model, and then generate the mesh over the whole model. A controlled mesh is adopted here in order to optimize the resolution process; i.e., obtain the most accurate solution in the shortest amount of time possible. In other words, we aim to make a compromise between condensing a high number of elements by decreasing the element sizes especially in the regions of interest (sensor and defect locations) and minimizing the resolution time.

The model created in ANSYS is given by Figure 3.8. The different area colors shows
After meshing the model, we apply the boundary conditions by constraining the nodes DOF at the edges of the air to zero. This corresponds to the fact of cancelling the z-component of the magnetic vector potential \((A_z)\) at the nodes lying at the boundary of the model. There are no field lines that go through the symmetry axis. Thus, \(A_z\) is null by nature at this axis because, otherwise, \(\mathbf{B} = \nabla \times \mathbf{A}\) would be singular in this line domain. The boundary constraints are represented in ANSYS by the magenta colored cross, as shown in the mesh of Figure 3.9b.

The next step is to initiate the solution process of the FEA using the appropriate solver implemented in ANSYS. We opt for the Jacobi Conjugate Gradient (JCG) solver, which is useful for large models. For our nonlinear problem, we use a two-step solution
sequence: ramp the loads over five substeps, each with one equilibrium iteration, and then calculate the final solution over one substep, with ten equilibrium iterations. When the simulation is completed and actually converges, we proceed to extract the relevant results to our analysis.

3.4.1.2 Results and Interpretations

It is known that the MFL field is composed of three spatial signals: axial, radial and tangential. Figure 3.10 depicts the direction of each component in 3-D with respect to the cylindrical pipe. Dutta [21] discussed the importance and contribution of each component in the detection and characterization of anomalies in steel pipelines using the MFL method. When dealing with typical axisymmetric wall thinning defects characterized...
Figure 3.8: The Implemented Model in ANSYS

by a large length along the circumference of the pipe, the axial magnetic flux is the only useful component. In fact, this can be proved by performing a line scan above the defect and reproduce the axial and radial components of the MFL field. Due to the axisymmetric property of the model, the tangential will be zero at any point within it. Figure 3.11 plots the axial MFL signal while Figure 3.12 depicts the radial signal. Hence, it can be noted that the magnitude of the axial component varies considerably and maintains a constant value inside the defect. However, the radial signal varies only at the defect edges when there is a change in the wall surface and it is almost zero at the center of the defect.

In order to observe the phenomenon of the MFL, we represent the dispersal of the magnetic field contour lines all over the model. Focusing at the center of the MFL tool, we can see in Figure 3.13 the leaking magnetic flux from the interior and exterior wall of the pipe due to its saturation at this region.

We can also view the flow of the magnetic flux density $\mathbf{B}$ in the vicinity of the magnetizing device as shown in Figure 3.14. The flux vectors start from the north pole of the right magnet pointing in the radially inward direction, propagate in the surrounding air
Figure 3.9: The Discretization of Model in ANSYS

and flow through the pipe wall to the left, and then enter the south pole of left magnet with respect to the radially inward direction. After that, the flux lines travels inside the ferromagnetic robot’s gripper from left to right and finally enter the south pole of the right magnet, completing thus the magnetic circuit.
The pipe is saturated at the closest region to the center of the magnetizing tool as indicated by the red color in Figure 3.14, as well as Figure 3.15 which depicts the distribution of the axial component magnitude of the magnetic flux density in the vicinity of the defect. Based on the last Figure 3.15, we take the value of the axial magnetic flux density magnitude at the point where the Hall effect sensor is located.

The same simulations are repeated for an interval of wall thinning defects ranging from 0% (no defect) to 99% of the original pipe’s wall thickness. In each wall thinning, we record the axial flux density at the same Hall effect sensor position. Hence, we obtain a plot of the axial MFL signal against the actual wall thickness of the pipe. Such plot is called the wall thinning reference curve [9] represented by Figure 3.16. It is a calibrated curve used in practice to evaluate real axisymmetric wall thinning defects by simply measuring the magnetic flux density in the axial direction by a Hall effect sensor.

Axisymmetric analyses are conducted in a 2-D environment and hence much easier and faster than 3-D analyses. Nonetheless, working in 3-D has many advantages. The next section presents the 3-D simulations and results of the system.
3.5 Three-dimensional Magnetostatic Analyses

The 3-D model represents the geometry of the structure being analyzed in a more comprehensive way. Although there is no point of modeling a system in which all its components have an axisymmetry property about the same axis of rotation, modeling our system in 3-D open the space to account for nonaxisymmetric defects or magnetization that are not truly in the radial direction, which is the case of our experimental validation conducted in Chapter 4.

The 3-D model of the system is given by Figure 3.17 depicting the different entities without the surrounding air (to actually see the different parts). The definition of the
physics environment for the analysis is similar to a 2-D or an axisymmetric static analysis. The 3-D magnetic vector potential element SOLID97 is used here to model the system and perform a static 3-D nodal-based analysis.

After running the simulation and obtaining the solution, and similarly to the axisymmetric case, we represent the inside the pipe, as shown in Figure 3.18, and measure the magnitude of the axial magnetic flux density at the point where the Hall effect sensor is located. By performing the simulations for different wall thinning defects of depth varying from 0% (no defect) to 90%, we obtain a reference curve that coincides with the one of the axisymmetric model. Figure 3.19 superimposes the wall thinning reference curves of both
Figure 3.13: Magnetic Field Contour Lines in the Vicinity of the MFL Tool

Figure 3.14: Magnetic Flux Density Flow in the Model
Figure 3.15: Axial Magnitude of the Magnetic Flux Density Flow in the Model

It can be clearly seen from Figure 3.19 that the two wall thinning reference curves obtained from the types of analyses (axisymmetric and 3-D) match each other. Hence, the 3-D model can be used to conduct analyses that have more complex, nonaxisymmetric geometries. Consequently, by characterizing and modeling the magnetizing device with the pipe under inspection, and therefore deriving the wall thickness reference curve from simulations, there will be no need to do further experimental calibrations. Based on the curve of Figure 3.19, the wall thickness of the pipeline can be determined in a straightforward manner.

3.6 Conclusion

This chapter described the method used to detect and evaluate the wall thinning defects in steel pipelines based on the MFL technique and on a numerical approach using the FEM with ANSYS. This method results in a calibration tool of reference that allows
Figure 3.16: Wall Thinning Reference Curve for the Particular Steel Pipe Sample Characteristics

to determinate the wall thicknesses by just measuring the magnetic flux density in one direction which is the axial using a Hall effect sensor. To implement this method, we designed and modeled by FEM a magnetizing device based on permanent magnets and a robotic gripper, along with a steel pipe with radial reduction in its wall. Running simulations with variable wall reductions leads to a wall thinning reference curve which represents the calibrated curve that gives a good estimation of the pipe’s wall thickness based on measured axial magnetic flux density.

Having a well characterized magnetizing device, make the method of predicting wall thickness generic and applicable for any steel pipe with specific properties. In order to validate this method, it is necessary to build an experimental prototype and run some tests.
Figure 3.17: Three-dimensional Model of the System

Figure 3.18: Axial Magnetization of the Pipe

to come up with such wall thickness reference curve for the particular pipeline specimen.
Figure 3.19: Wall Thinning Reference Curve from both Axisymmetric and 3-D Simulations
Chapter 4

Experimental Prototype for the External Magnetizing Device

In the previous chapter, we presented the method that allows to detect and measure the wall thinnings in steel pipelines based on calibrated curves of reference generated from numerical modeling with FEM. This chapter addresses the experimental implementation of this method in the real context by constructing a prototype of an MFL sensing tool which is going to be associated with the end-effector of the robotic platform devoted for external inspection of energy pipelines.

The current chapter describes the steps of building the MFL tool presenting the different mechanical and electronic parts involved. Then some demonstrations are conducted with pipe samples that have reductions in the its wall of different depth. Experimental measurements are recorded and compared with the numerical results for validation.

4.1 Description of the Experimental Magnetic Flux Leakage Tool

The MFL tool is based on two rings of magnets that have an annular cylindrical shape. Since the gripper clamshell is related to the robotic platform which is not part of the current study, we were supposed to build a system that hold these magnets as well as a Hall effect sensor and allow the crawling of the tool on the surface of the pipe in a smooth way even in the presence of wall reductions.
4.1.1 Mechanical Parts

The permanent magnets are the source of the magnetic field that magnetize the steel pipe. Hence, any additional parts should not intervene with this magnetic field. For this reason, non-magnetic metals are used such as the aluminum or non-ferrous alloys (stainless steel). In order to hold the magnets and keep them at a fixed distance from each other, we design some sort of a housing case made of aluminum. Figure 4.1 gives a CAD representation of the aluminum holder on top of which the permanent magnets are inserted one from the right and the other from the left.

![Figure 4.1: CAD Representation of the Magnet Holder](image)

The movement of the MFL tool on the surface of pipe is ensured by a wheeling system integrated with the holder. In fact, on the edge of each side of the holder, three wheels are installed equidistantly, with aluminum supports and stainless steel springs. Figure 4.2 illustrates the wheel/support with a CAD representation. The damping systems make the housing case more flexible when encountering obstacles (defects) in the pipe surface. Another advantage is that with springs the MFL tool can work with pipe of different diameters between 2 in and 2.875 in.

The magnet rings are manufactured from arc pieces of 60° and glued together to form
Figure 4.2: CAD Representation of the Wheel/Support Assembly

the annular cylindrical shape. The formed ring is then fixed to a thin baking stainless steel plate in order to strengthen its durability. The magnet polarization is not truly radial, i.e., the vector field $\mathbf{M}$ at every point of the magnet volume is not always pointing toward the rotational axis of symmetry. This is only true at the center line of the magnet arc. Figure 4.3 illustrates that by showing the actual direction of magnetization in a side view of the magnet arc.

Figure 4.3: Side View of the Magnet Arc
The complete assembly of the housing case with the MFL tool while inserted in a pipe specimen with a wall reduction is shown in Figure 4.4. The Hall effect sensor is placed on an acrylic piece inserted and fitted to the holder window, such that the sensor will be located exactly at the center of tool (between the two magnets) at a fixed lift-off with respect to the original surface of the pipe, in such a way that the Hall element is oriented to capture the magnetic flux in the axial direction.

![Figure 4.4: MFL Tool Inserted in a Pipeline](image)

Next, we present some photographs of the actual MFL prototype. Figure 4.5a shows the constructed MFL tool. Figure 4.5b depicts the tool while scanning a steel pipe sample of 2 in outer diameter and 0.204 in radial with a wall thinning defect of 50%.

### 4.1.2 Electronic Circuit and Data Acquisition Systems

The axial magnetic flux density \( B_{ax} \) by the A1301 Hall effect sensor from Allegro family. It is a continuous-time, ratiometric (the output is directly proportional to the input) and linear sensor with a typical magnetic sensitivity of 2.5 mV/G (or 25 V/T). Hence, powered with a DC voltage \( V_{CC} = 5V \), the sensor allow measurements up to 100 mT, typically. The output pin of the A1301 Hall effect sensor which shown in Figure 4.6 vary its voltage in response to a magnetic field perpendicular to the Hall element. In fact, the presence
of a south-polarity (+B) magnetic field perpendicular to the upper face (that has the brand sign) of the device package, increases the output voltage $V_{OUT}$ in proportion to the magnetic field applied.

The output voltages are read and acquired through a microcontroller based board which is the Arduino Uno R3 (Revision 3) depicted in Figure 4.7. Arduino is an open-
source electronics platform with computer hardware and software, based on the Atmel 8-bit AVR microcontroller along with complementary components to allow the incorporation into other circuits. The Arduino board is programmed using the Arduino development environment with the specific programming language in order to process the data using a centralized computing system.

4.2 Experimental and Numerical Results

We use the MFL inspection system that we built in order to run some tests on some coiled tubing (HS-90) specimens, that have originally 2 in outer diameter and 0.204 in
radial wall thickness. For these specimens, we machine a couple of axisymmetric wall thinning defects, up to 60% of depth, just as a precaution in order not to break the pipe for more deeper defects, and we pick up the axial magnetic flux density magnitude for each defect.

We reproduce the actual setup in 3-D numerical simulations with ANSYS taking into account the new properties of the system (pipe dimensions, no gripper, magnets with arc pieces, and magnetization not perfectly radial). We plot in Figure 4.8 the wall thinning reference curve (blue curve).

![Wall thinning reference curve with experimental data](attachment:figure48.png)

**Figure 4.8: Wall Thinning Reference Curve with the Actual Experimental Data**

### 4.3 Discussion

We may notice the existence of a relative error of 3% maximum between the modeled wall thickness reference curve and the experimental wall thickness corresponding to the actual MFL readings. This is due to the fact that the permanent magnets that we have are not well characteristic, i.e., the B-H demagnetization curve is not accurately given by the manufacturer. Although the 50 grade NdFeB magnets have a demagnetization curve
of reference that can be found in material handbooks, this curve can slightly change due to the magnet manufacturing process and the magnetization techniques used. In fact, using a different B-H demagnetization curve provided by another magnet manufacturer, we obtain a close matching between the wall thickness reference curve generated by simulation and the experimental data.

An important point in the MFL signal measurements is the position of the Hall effect sensor with respect to the actual surface of the pipe’s wall, which is called the lift-off. At this stage, the designed prototype doesn’t guarantee a constant lift-off. Since we perform external inspection of pipelines with wall reductions and a fixed sensor position, then the lift-off will vary. Additionally, for our prototype, the lift-off is almost 10 mm which quite high. Consequently, we are picking small MFL signals and the difference of magnitude between two different wall thickness is low. These issues can be overcame in future work.
Chapter 5

General Conclusion

Industrial pipelines are conduits made from steel pipes that transport valuable energy resources such as oil and natural gas over thousands of miles, to continuously feed electric generators and then keep substantial utilities in continuous service. Hence, an uninterrupted supply in these resources is very necessary, while ensuring the integrity of the piping system with respect to the process, the business, the safety and the environment. Unfortunately, steel pipes are prone by time to different types of defects as much as the duration of being in service increases, such as corrosion, cracks and dents that attack the pipe’s wall surface and may have brutal impacts on both economic and environmental aspects. Hence, pipeline inspection play an important role in keeping the process working and in preventing catastrophic failures from happening. This can be achieved by regularly monitor and diagnose the health of the pipeline and intervene preventively in case of problems.

The diagnosis of pipelines can be performed using nondestructive testing (NDT) techniques, which represent a group of advanced methods that evaluate the properties and status of the material of an entity without causing any damage. The Magnetic flux leakage (MFL) is one of the most promising NDT technique for robotic inspection of ferromagnetic pipes. It is a noncontact method that uses powerful magnetic field which can be generated by portable permanent magnets to locally magnetize and saturate a portion of the pipe under examination. Thus, when there exist a defect in the pipe, a specific amount of flux leaks out from the wall surface. The idea is to detect and evaluate this leaking flux at the site of the anomaly to assess the severity of the problem.
Large wall thinning is a type of defect that assails steel pipes and represents a serious problem threatening aging pipelines. This work follow and develop a numerical approach to measure the wall thickness of a given ferromagnetic pipe specimen. The method consist in modeling and simulating the specimen with a designed diagnosing tool using the Finite Element Method (FEM) implemented in the powerful FEM package ANSYS. This technique results in a calibrated curve serving as a reference to estimate with a good precision the radial pipe’s wall thickness in the real applications. The proposed technique is generic and can be applied systematically for any ferromagnetic pipeline with specific size and material properties. It represents an enhancement over the current practices by avoiding the long procedure of conducting multiple physical laboratory experiments to come up with such calibration curve.

The MFL tool is designed for scanning external pipes crawling smoothly on top of its outer surface. It is made to be carried by a robotic platform, as its end effector, which dedicated for external inspection. It is basically constructed of two rings of permanent magnets, made of Neodymium (NdFeB), that have an annular cylindrical shape, radially magnetized with the respect to a cylindrical coordinate system associated with the magnet rings. The right magnet is magnetized in the radially inward direction and the left magnet is magnetized in the radial outward direction. The magnets are hold by a robotic gripper, also designed with an annular cylindrical shape. It consists of low-carbon alloy steel, circulating the magnetic field lines and hence closing the magnetic circuit.

An experimental laboratory prototype for pipeline inspection is constructed in order to validate the proposed method of measuring the wall thickness of ferromagnetic pipes and prove the accuracy of the numerical simulations. A couples of wall thinning defects are also machined in a steel pipe specimen to test the prototype. The magnetic flux is measured by a Hall effect sensor which is a transducer that varies its output voltage in response to a magnetic field. The sensor is positioned at the center of the MFL tool at a certain lift-off with respect the surface of the pipe. To collect the magnetic flux measurements from the Hall effect sensor, an electronic circuit based on an Arduino board is set up, collecting
and allowing the data to be viewed by a monitoring system which is a computer in our application. Hence, at the areas where there is some metal loss, the magnetic flux flowing in the pipe leaks out from the wall surface. The leaking flux is then captured by the sensor and the wall thickness of the pipe is measured referring to the calibrated curve.

We have been limited in this research work to axisymmetric wall thinning defects which represent an ideal case of pipe’s anomalies. A further step in the project is to consider more realistic defects which could have different 3-D shapes or radial depths in the wall. Hence, it is necessary to model and simulate these irregular geometries using the tools that we introduced in Chapter 3 in order to prove whether the method implemented here is applicable or not.

The next step in this project is to guarantee the perfect fit and integration of the MFL sensing tool with end-effector of the mobile robotic platform. The data acquisition system has to be also portable allowing the processing of the information in real time.
Appendix A

CAD Representations of the MFL System
Appendix B

ANSYS Code for the Axisymmetric Wall Thickness Measurement with the External MFL Device

/TITLE, Axisymmetric Wall Thickness Measurement with the External Magnetizing Device
/PREP7 ! Initiate ANSYS preprocessor level

! *** MODEL DIMENSIONS

EMUNIT,MKS ! MKS UNITS
P=.5 ! Percentage of wall thinning defect
R=32.501E-3 ! Pipe inner radius
T=3.9624E-3 ! Original pipe wall thickness
B=R+T ! Pipe outer radius
D=P*T ! Defect depth
C=B-D ! Defected pipe radius
E=5E-3 ! Distance between the pipe and the magnets
G=B+E
LO1=2.5E-3 ! Lift-off
LO2=B+LO1
M=3.175E-3 ! Magnets height
H=G+M
F=5E-3 ! End effector height
I=H+F
L=34.925E-3 ! Magnetic pole width
S=19.05E-3 ! Width of the sensor area
W=177.8E-3 ! Width of the defect
U=25.4E-3 ! Taper
WU=SQRT(U*U-D*D)
W1=3*W ! Length of the pipe
W2=2*L+S

NW=4*W
NH=2.5*I

QH=8*I
QW=4.5*W

! *** MODEL CREATION

LOCAL,22,0,0,QW/2,0,-90,0,0
WPCSYS,1,22

!BLC5,0,R+T/2,W1,T ! Pipe

! Defect & area between pipe and magnets
K,201,-W1/2,R
K,202,-W/2,R
K,203,W/2,R
K,204,W1/2,R
K,205,W1/2,B
K,206,W/2,B
K,207,W/2-WU,C
K,208,-W/2+WU,C
K,209,-W/2,B
K,210,-W1/2,B
A,201,202,203,204,205,206,207,208,209,210

!ASBA,1,2,,DELETE,DELETE

/PNUM,AREA,1
APLOT
/REPLOT

BLC5,0,G+M/2,W1,M ! Magnets & sensor area

BLC5,0,G+M/2,S,M ! Sensor area

ASBA,2,3,,DELETE,DELETE

NUMCMP,AREA
/REPLET

BLC5,0,H+F/2,W2,F ! End effector

BLC5,0,QH/2,QW,QH ! Far Outside

! ASBA,5,ALL,,DELETE,KEEP
! NUMCMP,AREA
!/REPLET

ALLSEL
! NUMMRG,ALL
! AGLUE,ALL
AOVLAP,ALL
NUMCMP,AREA
/REPLET

! *** MATERIAL PROPERTIES DEFINITION AND ATTRAIBUTION

MP,MURX,1,1 ! Assign relative permeability of 1 to air

! * Demagnetization curve of N50 grade NdFeB at 20C
HC=867710 ! Magnetic Coercive force
! Left magnet
MP,MGXX,2,HC ! Coercive force in terms of X vector component
MP,MGYY,2,0 ! Coercive force in terms of Y vector component
TB,BH,2,,89
TBPT,DEFI,0,
,0,0.352
,2709.99999999998, 0.0777
,5709.99999999998, 0.1241
,7709.99999999998, 0.158
,12709.9999999999, 0.202
,23709.99999999999, 0.259
,33709.99999999999, 0.2952
,43709.99999999999, 0.3227
,53709.99999999999, 0.3457
,64709.99999999999, 0.366
,74709.99999999999, 0.3846
,84709.99999999999, 0.4021
,95709.99999999999, 0.4188
,105710.0000000000, 0.4349
,115710.0000000000, 0.4505
,126710.0000000000, 0.4659
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! Right magnet
MP, MGXX, 3, -HC
MP, MGYY, 3, 0
TBCOPY, BH, 2, 3

! * Data table for the pipe (CT90)
TB, BH, 4, , 60
TBPT, , 0, 0
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, 7.39979E+3, 1.47599
, 8.01644E+3, 1.52542
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, 9.24974E+3, 1.61017
, 9.86639E+3, 1.65607
, 1.04830E+4, 1.69492
, 1.14080E+4, 1.73376
, 1.26413E+4, 1.79666
, 1.38746E+4, 1.80085
, 1.47996E+4, 1.82910
, 1.63412E+4, 1.876088
, 1.81912E+4, 1.89972
, 2.03494E+4, 1.93150
, 2.25077E+4, 1.96681
, 2.49743E+4, 2.00212
, 2.80576E+4, 2.03743
, 3.11408E+4, 2.06921
, 3.45324E+4, 2.09746
, 3.76156E+4, 2.12218
, 4.06991E+4, 2.14336
, 4.43988E+4, 2.16455
, 4.87153E+4, 2.18573
, 5.30319E+4, 2.20692
, 5.88900E+4, 2.23164
, 6.41316E+4, 2.24929
, 7.09147E+4, 2.27401
, 7.67729E+4, 2.28814
, 8.32477E+4, 2.30579
, 9.03392E+4, 2.31992
, 9.77390E+4, 2.33051
, 1.12847E+5, 2.35169
, 1.26721E+5, 2.36935
, 1.44296E+5, 2.39054
, 1.60946E+5, 2.41172
, 1.77903E+5, 2.43291
, 1.99794E+5, 2.46116
, 2.22610E+5, 2.48941
, 2.50051E+5, 2.52472
, 2.75026E+5, 2.55650
, 2.99692E+5, 2.58828
! TB PLOT, BH, 4

! * B-H curve of Steel 1018 (Low carbo steel)
TB, BH, 5
TBPT,, 0.0
TBPT,, 238.73, 0.250
ET,1,PLANE53,0,0,1,0 ! Define PLANE53 as element type

MSHKEY,0 ! Free area mesh
MSHAPE,1,2D ! Using tetrahedral-shaped elements
MSHMID,0 ! Midside nodes on boundaries follow its curvature

!ESIZE,30E-3
SMRTSIZE,OFF

ALLSEL
ACLEAR,ALL

!/PNUM,AREA,0
!/PNUM,LINe,1
!/LPLOT
!/REPlot

ASEL,U,AREA,,5
LSLA
LSEL,U,LINe,,3,5
LSEL,U,LINe,,9,10
LSEL,U,LINe,,1
ASEL,U,AREA,,1

LE1=4E-3
AESIZE,ALL,LE1
LESIZE,ALL,LE1,,1

ALLSEL
LSEL,S,LINe,,3,5
LSEL,A,LINe,,9,10
LSEL,A,LINe,,1

LE2=8E-3
LESIZE,ALL,LE2,,1

ALLSEL
LSEL,S,LINE,,23
LE3=16E-3
LESIZE,ALL,LE3,,,,,,1

ALLSEL
LSEL,S,EXT
LSEL,U,LINE,,23
LE4=32E-3
LESIZE,ALL,LE4,,,,,,1

ALLSEL
AMESH,ALL
!ELIST

ALLSEL
EREFINE,ALL,,,2,0,CLEAN,OFF
!ELIST

!/PSYMB,ESYS,1

! *** BOUNDARY CONDITIONS
ALLSEL
LSEL,S,EXT
LSEL,U,LINE,,23
NSLL,S,1
!NPLT,0
D,ALL,AZ,0

FINISH

! *** SOLUTION

/SOLU

ALLSEL

ANTYPE,STATIC,NEW
OUTRES,ALL,ALL ! Compute results for all entities

EQSLV,SPARSE

MAGSOLV,0,5,,,1
MAGSOLV,0,1,,,10

FINISH
! *** POST-PROCESSING

/POST1

ALLSEL

!/PSYMB,CS,0
!PLNSOL,B,Y
!PLVECT,B,,B,VECT,ELEM,ON,0
!PLF2D,90,0,10,1                   ! Plot magnetic field line
!/IMAGE,SAVE,D2_MFDD,PNG           ! Save as png

ALLSEL

!PADELE,ALL

/OUTPUT,Path01,txt

PATH,SENS,2,5,10
PPATH,1,,LO2,QW/2+S/2
PPATH,2,,LO2,QW/2-S/2
PDEF,ZFLUX,B,Y,AVG
/PBC,PATH,,1
NSLL,S,1
NPLOT,0

PRANGE,,,ZFLUX
PRPATH,ZFLUX

PASAVE,S,Path02,txt

ALLSEL

!/PSYMB,CS,0
PLNSOL,B,Y
!PLVECT,B,,B,VECT,ELEM,ON,0
!PLF2D,90,0,10,1                   ! Plot magnetic field line

!/IMAGE,SAVE,D2_MFDD,PNG           ! Save as png

!FINISH

!/EXIT
Appendix C

ANSYS Code for the Axisymmetric Wall Thickness Measurement with the External MFL Device

/TITLE, 3D Wall Thickness Measurement with External Magnetizing Device
/PREP7 ! Initiate ANSYS preprocessor level

! *** MODEL DIMENSIONS

EMUNIT,MKS ! MKS UNITS
!*AFUN,DEG ! Set angular function unit to degrees

P=.5 ! Percentage of wall thinning defect
DA=360 ! Defect arc

R=32.5501E-3 ! Pipe inner radius
T=3.9624E-3 ! Original pipe wall thickness
B=R+T ! Pipe outer radius

D=P*T ! Defect depth
C=B-D ! Defected pipe radius

E=5E-3 ! Distance between the pipe and the magnets
G=B+E

L01=2.5E-3 ! Lift-off
L02=B+L01

M=3.175E-3 ! Magnets height
H=G+M

F=5E-3 ! End effector height
I=H+F

L=34.925E-3 ! Magnetic pole width
S=19.05E-3 ! Width of the sensor area

W=177.8E-3 ! Width of the defect
U=25.4E-3 ! Taper
WU=SQRT(U*U-D*D)

W1=3*W ! Length of the pipe
W2=2*L+S

NW=4*W
NH=2.5*I

QH=8*I
QW=4.5*W

! *** MODEL CONSTRUCTION

CSYS,1

! Pipe & Defect

K,401,R,90,-W1/2
K,402,R,90,-W/2
K,403,R,90,W/2
K,404,R,90,W1/2
K,405,B,90,W1/2
K,406,B,90,W/2
K,407,C,90,W/2-WU
K,408,C,90,-W/2+WU
K,409,B,90,-W/2
K,410,B,90,-W1/2
K,411,0,0,QW/2
K,412,0,0,-QW/2

KSEL,S,KP,,401,412
/PNUM,KP,1
/REPLOT
KPLOT

A,401,402,403,404,405,406,407,408,409,410

LSLK
ASLL,S,1
/PNUM,KP,0
/PNUM,AREA,1
/REPLOT
APLOT
VROTAT, ALL,, , , 411, 412, -DA, 2

! ASEL, U, VOLU,, 10

/PNUM, AREA, 0
/PNUM, VOLU, 1
VPLOT
/VIEW, 1,.5,.5,.5
/REPLOT

! Magnets

CYLIND, G, H, S/2, S/2 + L, 0, 360  ! Left Magnet
CYLIND, G, H, -S/2, -S/2 - L, 0, 360  ! Right Magnet

CYLIND, H, I, -W2/2, W2/2, 0, 360  ! End effector

CYLIND, 0, QH, -QW/2, QW/2, 0, 360  ! Outside volume

! ALLSEL
! VSBV, 6, ALL,, DELETE, KEEP
! NUMCMP, VOLU
!/REPLOT

! **TEST
! CYLIND, 0, Q, -QW/2, QW/2, 0, 180
! VSBV, 4, 12,, DELETE, KEEP
! VSEL, S, VOLU,, 13

ALLSEL
! NUMMRG, ALL
! VGLUE, ALL
VOVLAP, ALL
NUMCMP, VOLU
!/REPLOT

! ALLSEL
! VSEL, U, VOLU,, 6
!/REPLOT

! *** MATERIAL PROPERTIES DEFINITION AND ATTRIBUTION

MP, MURX, 1, 1  ! Assign relative permeability of 1 to air

! * Demagnetization curve of N50 grade NdFeB at 20C
HC=867710  ! Magnetic Coercive force
! Left magnet
MP, MGXX, 2, HC  ! Coercive force in terms of X vector component
MP, MGYY, 2, 0  ! Coercive force in terms of Y vector component
MP, MGZZ, 2, 0  ! Coercive force in terms of Z vector component
TB, BH, 2, , 89
TBPT, DEFI, 0, 0.0352
, 709.9999999999984, 0.0777
, 5709.999999999998, 0.1241
, 12709.99999999999, 0.202
, 23709.99999999999, 0.259
, 33709.99999999999, 0.2952
, 43709.99999999999, 0.3227
, 53709.99999999999, 0.3457
, 64709.99999999999, 0.366
, 74709.99999999999, 0.3846
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, 332710.000000000, 0.7478
, 342710.000000000, 0.7615
, 352710.000000000, 0.7752
, 362710.000000000, 0.7888
, 373710.000000000, 0.8024
, 383710.000000000, 0.816
! Right magnet
MP,MGXX,3,-HC
MP,MGYY,3,0
MP,MGZZ,3,0
TBCOPY,BH,2,3

! * Data table for the pipe (CT90)
TB,BH,4,,60
TBPT,,0,0
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,,6.16650E+2,0.19421
,,9.24974E+2,0.27542
,1.23330E+3,0.35311
,1.54162E+3,0.42373
,1.84995E+3,0.48376
,2.15827E+3,0.55791
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,2.77492E+3,0.68150
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,3.39157E+3,0.83333
,3.69990E+3,0.91102
,4.01655E+3,0.99223
,4.62487E+3,1.06992
,4.93320E+3,1.14407
,5.54985E+3,1.20763
,6.16650E+3,1.30650
,6.47482E+3,1.35593
,7.09147E+3,1.41243
,7.39979E+3,1.47599
,8.01644E+3,1.52542
,8.63309E+3,1.56073
,9.24974E+3,1.61017
,9.86639E+3,1.65607
,1.04830E+4,1.69492
,1.14080E+4,1.73376
,1.26413E+4,1.77966
,1.38746E+4,1.80085
,1.47996E+4,1.82910
,1.63412E+4,1.86088
,1.81912E+4,1.89972
,2.03494E+4,1.93150
,2.25077E+4,1.96681
,2.49743E+4,2.00212
,2.80576E+4,2.03743
,3.11408E+4,2.06921
,3.45324E+4,2.09746
,3.76156E+4,2.12218
! B-H curve of Steel 1018 (Low carbo steel)
TB,BH,5
TBPT,,0,0
TBPT,,238.73,0.250
TBPT,,795.78,0.925
TBPT,,1591.55,1.250
TBPT,,2387.33,1.390
TBPT,,3978.88,1.525
TBPT,,7957.75,1.710
TBPT,,15915.5,1.870
TBPT,,23873.25,1.955
TBPT,,39788.75,2.020
TBPT,,79577.5,2.110
TBPT,,159155,2.225
TBPT,,318310,2.430
!TBPLDT,BH,5

ALLSEL
VSEL,S,VOLU,,6
VATT,1

VSEL,S,VOLU,,3
VATT,2

VSEL,S,VOLU,,4
VATT,3
VSEL,S,VOLU,,1,2
VATT,4
VSEL,S,VOLU,,5
VATT,5

ALLSEL
/PNUM,MAT,1
/NUMBER,1

!VSEL,U,MAT,,1
!VSEL,U,MAT,,5
!VPLOT
!/REPLOT

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!/PLOPTS,LEG1,OFF
!/PLOPTS,LEG2,OFF
!/PLOPTS,TITLE,OFF
!/PLOPTS,FRAME,OFF
!/PLOPTS,MINM,OFF
!/PLOPTS,INFO,3

!/ZOOM,1,OFF
!/VUP,1,Y
!/VIEW,1,1,1,1

/RGB,INDEX,100,100,100,0
/RGB,INDEX,80,80,80,13
/RGB,INDEX,60,60,60,14
/RGB,INDEX,0,0,0,15

/PSYMB,CS,0
!/REPLOT,FAST
!/IMAGE,SAVE,MOD.png

!/CMAP
!/PNUM,MAT,0
!/NUMBER,0

! *** MESHING THE MODEL

ET,1,SOLID97,0,0,,0           ! Define SOLID97 as element type

MSHKEY,0                     ! Free area mesh
MSHAPE,1,3D ! Using tetrahedral-shaped elements
MSHMID,0 ! Midside nodes on boundaries follow the curvature (default)

!ESIZE,40E-3
SMRTSIZE,OFF

LOCAL,44,1,0,0,0,0,0,0
ESYS,44

ALLSEL
!VCLEAR,ALL

ALLSEL
VSEL,U,VOLU,,6
ASLV
LSLA

LE1=3E-3
AESIZE,ALL,LE1
LESIZE,ALL,LE1,,,,,1

ALLSEL
ASEL,S,EXT
LSLA
LE2=40E-3
AESIZE,ALL,LE2
LESIZE,ALL,LE2,,,,,1

ALLSEL
VSEL,S,VOLU,,1,5
VMESH,ALL

!ALLSEL
EREFINE,ALL,,,1,0,OFF,OFF
!ELIST

! *** BOUNDARY CONDITIONS
ALLSEL
ASEL,S,EXT

NSLA,S,1
!NPLT,0
D,ALL,AX,0,0,,AY,AZ

FINISH

! *** SOLUTION
/SOLU

ALLSEL

ANTYPE,STATIC,NEW
OUTRES,ALL,ALL ! Compute results for all entities

EQSLV,JCG

MAGSOLV,0,3,,,1
MAGSOLV,0,1,,,5

FINISH

! *** POST-PROCESSING

/POST1

ALLSEL
CSYS,1
!PADELE,ALL

/OUTPUT,Path01.txt

PATH,SENS,2,10,20
PPATH,1,,0,L02,-S/2
PPATH,2,,0,L02,S/2
PDEF,ZFLUX,B,Z,AVG
!/PBC,PATH,,1
!NSLL,S,1
!NPLOT,0

PRANGE,,,ZFLUX
PRPATH,ZFLUX

PASAVE,S,Path02.txt

!FINISH
!/EXIT
Appendix D

Arduino Code for the Axial Magnetic Flux Density Measurements

```c
#define NOFIELD 512L // Analog output with no applied field
#define TOGAUSS 5/(2.5*1024)*1000L

void setup()
{
    Serial.begin(9600);
}

void DoMeasurement()
{
    // measure magnetic field
    int raw = analogRead(0);  // Range : 0..1024
    long compensated = raw - NOFIELD; // adjust relative to no applied field
    long gauss = compensated * TOGAUSS; // adjust scale to Gauss

    Serial.print(gauss);
    Serial.print(" Gauss ");

    if (gauss > 0) Serial.println("(South pole)");
    else if(gauss < 0) Serial.println("(North pole)");
    else Serial.println();
}

void loop()
{
    delay(750);
    DoMeasurement();
}
```
Bibliography


