RICE UNIVERSITY

Hall Effect and Magneto Optical MFL Sensing

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

Master of Science

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DECEMBER, 2013
Abstract

In the field of nondestructive testing (NDT), various technologies have been developed to establish a better NDT sensing device. In this study, we deal with two NDT technologies based on the Magnetic Flux Leakage (MFL) technique. The first is the Hall Effect sensor. This device has been extensively developed during the last century, especially after the rise of integrated circuit technology. The second technology is Magneto Optical Imaging (MOI). This technique has gained prominence recently, and scientists hold high expectations about its performance. In this work we: (1) review the physics behind the Hall Effect and Magneto Optical MFL sensing, (2) run simulations of a given defected pipeline using the Magnetic Dipole Models to extract the theoretical MFL signals, (3) make an area measurement of the MFL signals using the Hall Effect sensor, (4) build an experimental setup of the Magneto Optical sensor to obtain the MFL signals, and (5) validate the Hall Effect and the Magneto Optical Imaging experimental results using the Magnetic Dipole Model simulations.
Acknowledgments

First of all, I thank ALLAH for giving me the strength to achieve this task.

I express my sincere gratitude and appreciation to my adviser Dr. Fathi H. Ghorbel, who has supported me throughout my stay at Rice and guided me on my work and research. He has been extremely helpful throughout this adventure, and he has made my goals so much clearer. He supervised my project from its inception. He offered precious feedback and useful criticism throughout. He helped me develop as a person, and I will miss working under his supervision.

I would also like to thank my thesis committee members, Dr. Marcia O’Malley, Dr. John W. Clark and Dr. Adnan Sarmad. All of them have been constant pillars of support and valuable advice. The personal interest they took in my work helped it grow and progress more rapidly than I could ever expect in my research. Special thanks goes to Mrs. Hanen Dammak Choura for her help and patience.

I am grateful to the various people at RiSYS lab, especially David Garcia and Islem Megdiche. Their presence helped make the lab feel like home and thus enabled me to spend the many, long hours needed to complete my research. My endless conversations with them helped me grow as a person and furthered my research project. I am also appreciative of all of the undergraduates I had the chance to mentor as a teaching assistant. Working with such a talented and enthusiastic group encouraged my own work and inspired me to excel in my research.
I dedicate this work to my grandparents Ummah Mahbouba and Baba Wahab; to my parents Mohammed and Awatef; and the rest of my family including: Tawfik, Abd Almajid, Mohamed, Salah, Anouar, Mohyieddin, Moktar, Yassine and Bachar. I also dedicate this work to my aunties, Om Wissem, Om Abd Alrazzak, Om Yahya and my beautiful rose Nihed. My studies and research have been possible only through the rock solid support and nurturing they have offered me since I was a young child.

Special thanks also go to my two brothers Aymen and Ibrahim. Thank you for your patience and all the sacrifices that you made for me. I am also indebted to the various people who have made Houston such a special place to me and who have offered me moral support throughout my work. They stood by my side and encouraged me even at moments when I lost hope. These dear friends include Fakhri Andolsi, Majdi Chaari, Amine Mziew, Lasad Adalet and Hamdi Ben Slimen. I will always remember their companionship and hope we continue our friendship for years to come.

Finally, I dedicate this work to my beloved fiancee Dr. Darine Hajji. Words can not express my deep gratitude for supporting me all the time. I ask ALLAH to bless and join us for the rest of this life and in the next one.
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Chapter 1

Introduction

Nondestructive evaluation (NDE), also known as nondestructive testing (NDT), is a well known and very effective inspection technique for the evaluation of the sample under investigation without alerting it. There exist several ways for the evaluation of the defected samples, based on various physical properties. One of the most important techniques is Magnetic Flux Leakage sensing (MFL). This technique received the attention of scientists and engineers thanks to its advanced properties. It also resulted in countless applications because it is such a powerful method for detecting and characterizing defects in the affected samples. The main idea behind the MFL technique is to expose the sample to an external magnetic field $B$ causing it to saturate. In the presence of the defect, a leakage flux will result. The MFL method is based on capturing the information coming from the leaked flux to detect and characterize, if possible, the defect. Since sensing the leaked flux is the most important step to provide maximum information, engineers have developed a reliable technique serving that purpose[1].

This study will focus on two methods for MFL sensing: (1) the well-known technique using the Hall Effect sensor, and (2) the newly developed method using Magneto Optical sensing technique.
The following section introduces the fundamentals of the MFL sensing.

1.1 Magnetic Flux Leakage Sensing

The main objective of any MFL inspection procedure is to extract the maximum information from the leaked flux. This ensures our ability to detect and characterize the defect in the specimen.

![MFL Inspection Principle](image)

Figure 1.1: MFL Inspection Principle.

Suppose a specimen is exposed to a uniformly high magnetic field $\mathbf{B}$, as in Figure 1.1. This magnetic field is needed to saturate the specimen locally where the sensing device will be placed. Saturation is one of the properties characterizing the specimen under inspection. For ferromagnetic materials, saturation is defined as the region where the change of the magnetic field tends to be negligible. The following statement defines the general properties of the magneto-static problem:

The magnetic flux density $\mathbf{B}$ is a function of the magnetic field intensity $\mathbf{H}$. In free space this relationship is given by

$$\mathbf{B} = \mu_0 \mathbf{H},$$  \hspace{1cm} (1.1)
where $\mu_0$ is the magnetic permeability of free space. For any material, the magnetic permeability can be defined as the tendency of magnetic flux to flow inside that material. Ferromagnetic specimen, by definition, has higher permeability than free space. It is not constant for a ferromagnet, and it is governed by the magnetic behavior of the material [2].

Figure 1.2: Magnetic Characteristics of a Typical Soft Ferromagnetic Material.

After being magnetized, the relationship between the magnetic flux density and the magnetic field intensity inside the ferromagnetic material is given by

$$B = \mu_0(H + M),$$  \hspace{1cm} (1.2)

$M$ is called the magnetization. Saturation can then be defined rigorously due to the magnetization curve. In ferromagnetic material, saturation is the region where an increase in the applied magnetic field $H$ causes no change in its magnetization $M$. The material is said to be saturated.
To have a fair comparison, we need to make sure that the region under inspection reaches the saturation level. Far from the saturation region, any slight change to the magnetic field will result in a significant difference in the MFL signal. A higher magnetic field will allow us to get a better signal. In the presence of defects, the magnetic field tends to leak due to material loss, or due to inhomogeneous characteristics in case of corrosion. The leaked field contains the information needed to describe the defect. The 3D representation of the MFL signal model obtains information from three Cartesian components: $B_x$, $B_y$ and $B_z$ as shown in Figure 1.4.
1.2 Case Study

Our study focused on investigating the MFL technique on a cylindrical pipe where we have included different sizes and shapes of defects.
The defect is modeled to be a cylindrical shaped hole with a diameter of \( d = 1 \text{ (mm)} \) and with a height of \( b = 5 \text{ (mm)} \), Figure 1.6. Taking into consideration the fact that the Magneto optical sensor is based on a MO film that comes with the dimensions of \( 4 \times 7 \text{ (mm)} \), we need to make sure that the MO film covers all of the MFL signal.

![Defect Modeling](image)

Figure 1.6: Defect Modeling.

The next step is to have a sensing device that can read the MFL signal. Finding the best sensor generally depends on many parameters. The following properties will define whether a sensor is good for such an application:

- Environmental conditions (pressure, temperature and humidity)
- Sensitivity
- Noise resistance
- Linearity
- Range of sensing
- Output signal
- Response time
- Sensor size
1.3 Contribution

Our aim in this work is to investigate a new technique for MFL inspection known as Magneto Optical Imaging (MOI) and link it with the known MFL Hall Effect sensing technology.

Our study will therefore focus on understanding both the Hall Effect sensing and the Magneto Optical MFL sensing. Our contribution mainly consists on designing an MFL Magneto Optical sensing system. The output result of the MOI experiment will yield a 2D image characterizing the MFL signal. This 2D image will give us the chance to run several line scans using the Hall Effect sensor in order to provide a 2D image equivalent to the MOI output signal. That allows us to figure out the similarities and the differences between both results.

Finally, an essential section of this work was to validate Hall Effect sensing and Magneto Optical sensing using mathematical models. Known as Magnetic Dipole Models, these mathematical models have been previously developed at Rice University’s RiSYS Lab.

1.4 Thesis Outline

Chapter 2 of this thesis covers the physics behind the Hall Effect sensor and the theoretical properties of an effective Hall Effect sensor. The chapter also introduces the magnetic dipole models as mathematical models capable of deriving MFL signals. Chapter 3 looks at Magneto Optical Imaging and how it can be used as an MFL sensing device. This section especially focuses on the specific physics concepts behind Magneto Optical Imaging. Chapter 4 goes through our simulations and experiments, explaining the design and the process. This section also displays the results and implications of each experiment. Chapter 5 is the conclusion of the thesis, summarizing and explaining the significance of this study.
Chapter 2

Hall Effect Sensor

Before discussing the MFL sensing technologies, the Hall Effect, or the Magneto Optical sensors, it is important to understand the theoretical distribution of the MFL signals for a given defect. This knowledge helps in selecting the needed sensing tool with regards to capability and performance.

In this thesis, we proceeded by modeling the defect and running a simulation based on the Magnetic Dipole Models. This mode can give the distribution of the MFL signals for a given defect geometry. The following section introduces the Magnetic Dipole Models and resulting simulation in our case of study.

2.1 Magnetic Dipole Models

In the work of S. M. Dutta [2], a mathematical model has been established to yield the 3D MFL signals based on magnetic dipole models. These models were derived from Maxwell’s equations. It apply the approach of dipole magnetic charge induction to yield the three dimensional MFL signal in terms of surface integration. By using these models, we can derive directly the three components of the MFL signal.
The radial, axial and the tangential components characterize the magnetic field by describing its distribution. This model introduces the effect of the lift-off $h$, the distance separating the sensor from the surface of the defect. This distance have a direct effect on the MFL signal as it is very sensitive to lift-off.

For a cylindrical defect, Figure 2.2 case of our study, for a point $P$ the MFL field is
given by the equation:

\[ H_{MFL}(r) = \frac{MR}{4\pi} \int_S \frac{r - s}{|r - s|^3} \sin \beta \, dS(s), \]  

(2.1)

where \( dS \) is the elementary surface with a magnetization charge \( M \). Let \( t \) be equal to:

\[
\begin{align*}
t &= r - s \\
&= (x - R \cos \beta)x + (y + R \sin \beta)y + (h - z)k \\
&= t_x x + t_y y + t_z k.
\end{align*}
\]

(2.2)

(2.3)

(2.4)

The equations modeling the magnetic dipole model will be as a result:

\[
\begin{align*}
B_x(r) &= \frac{\mu_0 MR}{4\pi} \int_0^{2\pi} \int_{-b}^{b} \frac{t_x}{t^3} \sin \beta \, dz \, d\beta \\
B_y(r) &= \frac{\mu_0 MR}{4\pi} \int_0^{2\pi} \int_{-b}^{b} \frac{t_y}{t^3} \sin \beta \, dz \, d\beta \\
B_z(r) &= \frac{\mu_0 MR}{4\pi} \int_0^{2\pi} \int_{-b}^{b} \frac{t_z}{t^3} \sin \beta \, dz \, d\beta \\
B_{MFL}(r) &= B_x i + B_y j + B_z k.
\end{align*}
\]

(2.5)

(2.6)

(2.7)

(2.8)

The above equations explicitly clarify the three components of the magnetic field and give the mathematical expression of the radial, axial, and tangential MFL signals.

The next simulations were done with a lift-off distance \( h = 1(mm) \).
Figure 2.3: Top View: Radial Theoretical Normalized MFL Signal, $h = 1\, mm$. 
Figure 2.4: Radial Theoretical Normalized MFL Signal, $h = 1\text{mm}$. 
Figure 2.5: Top View: Axial Theoretical Normalized MFL Signal, $h = 1\text{mm}$. 
Figure 2.6: Axial Theoretical Normalized MFL Signal, $h = 1mm$. 
Figure 2.7: Top View: Tangential Theoretical Normalized MFL Signal, $h = 1mm$. 
This study aims to measure the leaked magnetic field. The accuracy of measurement will lead to better analyses of the MFL signals. One of the commonly used sensors in MFL inspections is the Hall Effect sensor. The following section, explains the physics behind this device, and discusses its features.
2.2 Physics

The physics of the Hall Effect sensor have been well explored in the literature. This section is mainly a review on the properties of the Hall Effect sensor and how it works. This chapter is based on the work of Edward Ramsden “Hall-Effect, Theory and Applications Sensors (Second Edition 2006)” [3].

The Hall Effect is based on the Lorentz force

\[ \mathbf{F} = q_0 \mathbf{E} + q_0 \mathbf{v} \times \mathbf{B}, \]  

where a particle with charge \( q_0 \) and velocity \( \mathbf{v} \), in the presence of an external magnetic field \( \mathbf{B} \), will experience a force perpendicular to the plane formed by the magnetic and the velocity vectors. This force is perpendicular to the direction of the current flow \( i \), if we are in a planar conductive sheet. Due to this force, the electron will be concentrated on one of the edges of the conductor. As a result, positive charges will appear on the other edge. This distribution will give rise to an electrical field \( \mathbf{E} \) opposite to the Lorentz force. Reaching the equilibrium state, the difference in potential between the edge will give a voltage known by \( V_H \), proportional to the external magnetic field \( \mathbf{B} \). This equation presents two effects: the response of a charge, \( q_0 \), to an electric field \( \mathbf{E} \), and its response to a magnetic field \( \mathbf{B} \).
In the case of the electric field, the resulting force is in the same direction as the electric field, proportional to it and to the magnitude of the charge. This is the origin behind the flow of an electric current, where the electron travels along the electrical field as a result of the differences in potential. In the case of a magnetic field at a static state, there is no resulting force because the velocity of the particle is zero. The particle is subject to the force only if it is moving. In this case, the resulting force will be a function of the particle velocity, the charge magnitude, the external magnetic field $\mathbf{B}$, and the angle between the displacement direction and $\mathbf{B}$. 

Figure 2.9: Hall Effect Sensor.
Figure 2.10: Hall Effect Sensor: Geometry.

The above figure demonstrates how the charge carriers move inside the Hall Effect sensor. The external magnetic field is perpendicular to the sensor plane, \( \mathbf{B} = B_z \), and the charge carrier has a planar displacement with initial velocity \( \mathbf{v} = v_x \). The resulting force in Equation (2.9) will be:

\[
\mathbf{F} = F_y = q_0 v_x B_z.
\]  
\hspace{1cm} (2.10)

For a constant charge \( q_0 = cte \) and velocity \( v_x = cte \) the resulting force \( \mathbf{F} \) is a function only of the perpendicular component of the external magnetic field \( B_z \). This implies that we need to place the Hall Effect sensor perpendicular to the direction that we want to measure. Ideally, three Hall Effect sensors placed respectively on the three axes will give the magnitude of the real external magnetic field.

\[
\mathbf{B} = \begin{pmatrix}
B_x \\
B_y \\
B_z 
\end{pmatrix}.
\]

The Lorenz resulting force, \( F_y \) in this case, will concentrate the charges on the side of the Hall Effect sensor. But this effect is limited due to the fact that in this distribution
of charges, one side is positive and the other is negative, thereby creating an electric field across the sensor. The effect of this field is an attempt to redistribute the charges more uniformly. At the equilibrium status, $F = 0$ we obtain the following relation:

$$q_0 E_H + q_0 v_x B_z = 0. \quad (2.11)$$

$E_H$ the electric field solution for this equation at the equilibrium will be equal to:

$$E_H = -v_x B_z. \quad (2.12)$$

![Figure 2.11: $E_H$ Electric Field.](image)

The difference in potential between the two sides of the Hall Effect sensor produces a voltage $V_H$ used to measure the magnetic field by integrating the electric field all the way along the sensor width $w$.

$$V_H = -w v_x B_z. \quad (2.13)$$

The above equation can be developed further by explicitly expressing the parameters chosen by the Hall Effect sensor’s designer, and those fixed by the transducer itself. For a metallic transducer, the electric current $I$ is given by:

$$I = v q_0 N S. \quad (2.14)$$
Where:

- $q_0$ is the charge of the particle.
- $v$ is the velocity of the charge carrier.
- $N$ is the density of the carriers.
- $S$ is the cross section of the transducer.

![Diagram of a metallic transducer with charge carriers and velocity vector](image)

Figure 2.12: Current Across a Metallic Transducer.

So the design of the sensor, by fixing the external current $I$, determines the velocity of the charge carrier $v$ for a given transducer.

$$v = \frac{I}{q_0NS}.$$ \hspace{1cm} (2.15)

Using this relation in Equation (2.13) leads to write the output voltage as follows:

$$V_H = \frac{Iw}{q_0NS} B \hspace{1cm} (2.16)$$

$$= \frac{I}{q_0Nd} B. \hspace{1cm} (2.17)$$

This equation shows the linearity between the output voltage $V_H$ and the external magnetic field $B$ for fixed parameters ($I, q_0, N$ and $d$).
2.3 Properties

Design of an efficient Hall effect sensor depends on finding the best combination of parameters to perform characteristics like linearity, heat resistance, and sensitivity. For this reason, we need to analyze the parameters and how they affect the response of the Hall Effect sensor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>I, d</td>
<td></td>
<td>N</td>
</tr>
</tbody>
</table>

Table 2.1: Hall Effect Sensor Parameters.

From Equation (2.17) we can distinguish two sets of parameters: those fixed by the type of material conducting the electric charges (in this case the charge density N), and those fixed by the designer (like the geometry of the Hall Effect sensor and the external bias current, d and I). The following section will discuss several properties of the Hall effect sensor when it has a given current and a fixed geometry.

2.3.1 Semiconductor Based Hall Effect Sensor:

The effect of the charge carrier’s density $N$ is the first parameter we investigate. If we assume that the other parameters are all constants, then the relation between the output voltage $V_H$ and the charge carrier’s density $N$ is an inversely proportional relation.

$$V_H = \frac{cte}{N}.$$  

(2.18)

So the need for a higher output signal will require a lower density material that does not contain many carriers per unit volume. For metals, copper for example, $N = 8.42 \times$
$10^{22}\text{cm}^{-3}$. Meanwhile, for semiconductors, Silicon for example, $N = 1.4 \times 10^{10}\text{cm}^{-3}$. This huge difference will directly be reflected on the output signal $V_H$ where

$$V_{H_{Silicon}} = V_{H_{Copper}} \times 10^{12}. \quad (2.19)$$

This difference justifies the extensive use and development of semiconductor materials in making the Hall Effect sensors. Another benefit of using the semiconductor materials is that they provide flexibility of choice in the number of charge carriers per unit volume $N$. This flexibility is due to doping with substances from column $V$ of the periodic table, such as Phosphorous. This act not only allows the possibility of choosing the charge density of the transducer, but also overcomes certain intrinsic properties of the semiconductor materials, like their sensitivity to the external temperature.

### 2.3.2 Linearity

From Equation (2.17) we can write the output voltage $V_H$ as a linear function of the external magnetic field $B$:

$$V_H = C_1B, \quad (2.20)$$

where $C_1 = \frac{I}{q_0Nd}$ is a constant in ideal circumstances assuming that the external current $I$ and the charge density $N$ are constants.

This property is highly preferred for instrumentalists for it facilitates the conversion from the measured signal, $V_H$, to the real signal, $B$. 
2.3.3 Sensitivity

Sensitivity is the minimum detectable variation of the magnetic field $B$ (input signal) required to excite a variation in the voltage $V_H$, output signal. In ideal environments where $C_1$ is constant, the sensitivity is constant for the presented Hall Effect sensor SS49E, which is a very important criterion to choose any sensor. The higher it is, the easier it is to detect the variation of the magnetic field. Sensitivity, as discussed in the previous section, is very dependent on environment conditions and external noise.

In general, there is a compromise between sensors sensitivity and the dynamic range. To have great sensitivity, the hall effect dynamic range is reduced. This will affect the maximum value that we can read. However, a small sensitivity gives a bigger dynamic range. Consequently, this allows to measure a greater magnitude of the magnetic field,
but we still can not observe small variations. So a good selection must be considered and for that we must know:

- The maximum magnitude that can reach the measured magnetic field.
- The desired precision as a minimum variation.
- Noise dependence.

For the SS49E Hall Effect sensor, the dynamic range can reach 1000 G with a sensitivity equal to 1.4 mV/G.

\section*{2.4 Conclusion}

In this chapter, we presented magnetic dipole models; mathematical models capable of yielding MFL signals. We also presented the simulations resulting from these models. Then, we described the main properties of the Hall Effect sensor. This sensor is important because it reveals the real MFL signals simulated by the magnetic dipole models. Finally, we discussed the physics behind the sensor in order to achieve a better understanding of how it detects the magnetic field.
Chapter 3

Magneto Optical Imaging

As explained in the previous chapters, NDT techniques allow us to evaluate the specimen without altering it. But the challenging part of NDT techniques is the sensing technology. Inspectors need maximum information to extract the properties of the sample under investigation. Magneto Optical Imaging (MOI) comes to fulfill these requirements. It has been used to observe the magnetic field strength and its distribution. This technique was the focus of many studies trying to demonstrate its features and attempting to understand the physics behind it. The MOI is based essentially on the Faraday Effect, discovered by Michael Faraday in 1845. Next section investigates the physics behind the MOI.

3.1 Physics

3.1.1 Faraday Effect

Magneto-optical sensors are based on the Faraday effect. Faraday recognized that light passing through a transparent medium with an external applied magnet field alters the light wave depending on the magnetic field. This discovery was the first indication of the interaction between light and magnetism, and it later led to the establishment of Maxwells equations. These equations, among other things, describe light as electromagnetic waves.
The fundamentals of electromagnetic interactions in classical physics were created through these discoveries. The Faraday-effect describes the rotation of a polarization plane (plane of vibration) of linear polarized light passing through a magneto-optical medium. This light passes under the influence of an external magnetic field parallel to the propagation direction of the light wave.

![Figure 3.1: Faraday Effect.](image)

The rotation angle of the polarization plane is defined by the empirical equation

\[ \theta = \int dB \, dl, \]  
\[(3.1)\]

where \( \theta \) is the rotation angle and \( V \) is the Verdet constant of the magneto-optic sensing medium.

For small thickness, we can write Equation (3.1) as follow:

\[ \theta = VB_{eff}d, \]  
\[(3.2)\]

where \( d \) is the total geometrical path length along the direction of the applied magnetic
field and $B_{eff}$ is the effective magnetic field[5].

The change of the plan of polarization in the Faraday Effect is related to the difference in the refractive indices of the light if we consider it as an electromagnetic wave[6]. This difference in the refractive indices lead to a difference of dispersion between two components of the linear polarized light: the right circularly polarized (RCP) light and the left circularly polarized (LCP) light. The RCP light shifts relative to the LCP, so the resulting plane of polarization rotates with respect to its first orientation with an angle $\theta$ [7].

$$n_+ - n_- = \frac{\rho e^3}{nm_0^2\epsilon_0} \frac{B\omega}{(\omega_0^2 - \omega^2)^2},$$

(3.3)

where $\rho$ is the oscillator density, $\omega_0$ is the natural frequency, $e$ is the charge, $m$ is the mass
of an oscillator, \( B \) is the magnitude of the external magnetic field, \( \omega \) is the frequency of the optical field, \( \epsilon_0 \) is the vacuum permittivity, and

\[
n = \sqrt{1 + \frac{pe^2}{m\epsilon_0(\omega_0^2 - \omega^2)}};
\]

is the index of refraction of the medium of oscillators in the absence of the magnetic field [9]. The change in the plan polarization is then expressed:

\[
\theta = \frac{\omega}{c} \left( \frac{n_- - n_+}{2} \right)d = V Bd,
\]

with \( V \) is the Verdet constant:

\[
V = \frac{\omega}{2c} \left( \frac{n_- - n_+}{B} \right) = \frac{e}{2mc} \omega \frac{dn}{d\omega}.
\]

From Equation (3.1) we can conclude that:

- The magnitude of the Faraday rotation \( \theta \) depends linearly on \( \int B dz \).
- The direction of the rotation \( \theta \) depends on the direction of the applied magnetic field \( B \).

### 3.1.2 Magneto Optical Film

After knowing how light is affected by changing its polarization plan, now we develop the physics of the Magneto Optical film. It is essential to know the properties of the sensing film. The following subsections highlight the outlines of the general properties characterizing the Magneto Optical film based on garnets. Some of the main properties are: magnetization, magnetic domains, and total free energy.

**Magnetization:** One of the essential properties of the MO film is the Anisotropy property. This property describes the dependence of the energy of a ferromagnet on the direction of the magnetization relative to the structural axes of the material. The crystal structure of the MO film will yield preferred crystallography directions, also known as the *easy axes* for magnetization. The MO film presents two main magnetization directions.
The magnetization $M$ is related to the geometry of the MO film. The In-plane Magnetization is the case where $M$ is in the plane of the MO film. The other case is where $M$ is in the direction perpendicular to the MO film plane (up and down). The output result has a significant difference in each case, and so does the application of each of these films [10].

![Diagram of magnetization with linear and elliptical polarization](image)

**Figure 3.3:** Magneto Optical Effect for In-plane and Perpendicular Magnetization. In a) the plane of polarization shifts with an angle $\pm \theta$. In b) the output wave of the in-plane film has an elliptical polarization.

**Magnetic domains** Another important characteristic we need to highlight while working with the magneto optical material is the fact that these MO films exhibit a periodic alternation in their structure. This alternation is well known by the magnetic domain theory.
Figure 3.4: Domain Wall Distribution in Presence and Without an External Magnetic Field.

These domains appear to minimize the total energy of the system. The domains which are in the same direction as the applied magnetic field $\mathbf{B}$ tend to extend to where those anti-parallel to $\mathbf{B}$’s direction will shrink and minimize. This behavior reaches a saturation when the film hosts a unique configuration. This will lead to saturation in the Faraday angle $\theta$ because the film magnetization $\mathbf{M}$ will not affect the light after being totally oriented in the same direction as $\mathbf{B}[11]$. 
We can see, in a), that the domain’s distribution is random and also equal \((L_1 = L_2)\). In the presence of an external magnetic field, \(B \neq 0\), the magnetization vector \(M\) changes its orientation to align the magnetic field \(B\). This will enlarge the domain with a magnetization vector in the same direction as the applied field, \((L_1 > L_2)\).

**Total Free Energy:** For the Magneto optical film, the magnetic domains (positive and negatives) are distributed randomly in the absence of any external magnetic field. In other words, the distribution of these domains is equivalent to the distribution of electrical charges. So the total energy will appear and redistribute any inhomogenous charge to reach the minimum [12]. In the magneto optical material, the total free energy is the summation of two energies:

- The local magnetic energy, based on the energy densities given by the local values of the...
magnetization direction only. This is due to the inhomogeneity in the distribution of the directions of magnetic moment.

- The two non local energies, the stray field energy and the magnetostrictive self-energy. “The energy connected with elastic interactions between regions magnetized along different axis.” These energies create a torque on the magnetization vector, depending on any point of the magnetization direction at every other point[11].

The total energy is the summation of all of these energies: Zeeman-, anisotropy-, demagnetization-, and exchange energy.

### 3.1.3 Photo Response

The photo response (PR) is the ratio between the output and the input light intensity, respectively $I$ and $I_0$. The following expressions are based on the work of M. Shamonin [13].

$$PR = \frac{I}{I_0}.\quad (3.7)$$

In order to model the PR of the image characterizing the light distribution related to the magnetic field near the defect, we need first to understand how the magnetization vector inside the magneto optical film interacts with the external magnetic field. This approach considers that the magnetization vector $M$, oriented with an angle $\gamma$ with respect to the plane normal, will be reoriented in the presence of an external magnetic field to minimize the total free energy of the film.
Figure 3.6: Magnetization Vector Inside the Magneto Optical Medium.

The distribution and the orientation of the magnetization vector \( \mathbf{M} \) will result in a total energy inside the magneto optical film. The magnetization vector \( \mathbf{M} \) intervenes to minimize the total energy of the film in the presence of an external magnetic field. Therefore, the MO film rearranges its distribution in terms of domains in order to reach equilibrium. The total free energy of the magneto optical film is given by the following expression [13]:

\[
\frac{F}{\mu_0 M_S |H_A|} = -a \cos(\gamma) - b \sin(\gamma) \cos(\phi - \phi_H) - \frac{1}{2} \sin^2(\gamma),
\]

(3.8)

where \( \gamma \) and \( \phi \) denote respectively the angle between the film normal and the magnetization \( \mathbf{M} \), and the angle between the projection of the magnetization \( \mathbf{M} \) and the \( x \) axis [100].

\[
a = \frac{H_Z}{|H_A|},
\]

and

\[
b = \frac{(H_X^2 + H_Y^2)^{1/2}}{|H_A|},
\]

are normalized out of plane and in-plane magnetic field components, where

\[
H_A = \frac{2K_u - \mu_0 M_S^2}{\mu_0 M_S},
\]
is the characteristic field of uniaxial magnetic anisotropy, with $M_S$ denoting the saturation magnetization and $K_u$ the uniaxial anisotropy constant.

The angle $\gamma$ is computed after minimizing the total free energy, and the magnetization vector reaches the equilibrium state in the presence of an in-plane magnetization, $b \neq 0$:

$$\cos(\gamma) = a - b \cot(\gamma).$$

(3.9)

The MFL, Radial, Axial and Tangential signals are the externally needed components to compute the two parameters $a$ and $b$ in the above equation. $\gamma$ can be derived by numerical simulation for any normalized field $a$ and $b$.

Once $\gamma$ is computed, this can lead to figure out the photo response:

$$PR = \frac{I}{I_A} = 1 + \frac{\cos(2(\alpha - \theta_{max} \cos(\gamma))))}{2},$$

(3.10)

where $\alpha$ denotes the angle between the polarizer and the analyzer. $\theta_{max}$ is the maximum Faraday rotation in the film.

### 3.2 Conclusion

In this Chapter we highlighted the physics behind the Magneto Optical Imaging. The main characteristics of the sensing film, based on garnet, were defined. To understand the interaction between the external magnetic field and the resulting output image of the Magneto Optical sensor, we cited the equations linking the magnetic field $B$ to the photo response $PR$. All of these steps will attribute in the following chapter covering the simulations and the experiments.
Chapter 4

Simulations and Experiments

This chapter presents the simulation and the experimental analysis of the defect. First, we run a scan measurement using a Hall effect sensor. Once we get an idea about the amplitude and the shape of the MFL signal, we run a Magneto Optical Imaging simulation that takes as an input the MFL signal coming from the theoretical Magnetic Dipole Models and the Hall Effect sensor scan. We made a setup that allows us to extract the Magneto Optical Imaging response of the MO film to characterize the defect.

4.1 Hall Effect Sensor Experimental Scan

In this section we provided an area scan to extract the three experimental components of the MFL signal. We used the magnetic test bed composed of two motors, one motor for x displacement and the other for circumference rotation. The pipe is attached in such a way to satisfy the coaxiality property with the Helmholtz coil. This coil is able to afford a central magnetic field equal to $B_{\text{center}} = 250G$. This external magnetic field is able to saturate the pipe.
The Hall effect sensor that we used to get the scan values has the following transfer characteristics:

![SS49E Hall Effect Sensor: Transfer Characteristic](image)

Figure 4.2: SS49E Hall Effect Sensor: Transfer Characteristic [4].
This sensor presents a good linearity property with a typical sensitivity equal to 1.4mV/G at room temperature. The SS49E Hall Effect sensor was interfaced with the computer through an Arduino Uno card.

![Arduino Uno Interfacing Card](image)

Figure 4.3: Arduino Uno Interfacing Card [14].

The Hall Effect sensor was connected through the analog input with 10 bits resolution. The communication between the two stepper motors and the Arduino Uno was established through the PWM pins. The data are directly transmitted to the PC with USB cable, assuring real time processing. The following figure illustrates the Input/Output communication.
Comparing to the previous setup made of two electronic cards (Luminary + Arduino), the new setup uses only one Arduino card. This is sufficient to run the experiment.

After setting the hardware interface, we designed a graphical user interface, GUI, to run the test-bed. The previous interface was only able to run a line scan. The new version that we made allowed the possibility to run both the line scan and the area scan, which is the subject of this thesis.

Area measurement is obtained by assembling many scan lines side by side. First, one of the main advantages of this new interface is that it takes into consideration the different radius of pipes subject to scan. Second, we give access to the user to choose the elementary displacement $dy$ separating each line. Finally, all the data are assembled and saved in one file, a feat very difficult to get with the previous setup where it was not possible to start all the line scans from the same starting point, and we could not make the one line scan vectors have the same dimensions. So the new design solved all of these problems.
This new design comes with great features since it:

- Reduces the hardware cards from two (Luminary + Arduino) to one Arduino Uno data acquisition card.
- Gives the ability of area scan.
- Gives great flexibility in testing different pipes with different radiiuses.
- Saves all the scans in one file.
- Overcomes the weak point of the previous setup.

For our experiment, we made a $10 \times 16\text{mm}$ area scan with elementary displacement $dy = 1\text{mm}$. By changing the orientation of the Hall Effect sensor, we got the following
three components of the MFL signal.

Figure 4.6: Hall Effect Scan: Top View, Radial MFL Signal (Gauss), $h = 1\text{mm}$. 
Figure 4.7: Hall Effect Scan: Radial MFL Signal (Gauss), $h = 1\text{mm}$. 
Figure 4.8: Hall Effect Scan: Top View, Axial MFL Signal (Gauss), $h = 1\text{mm}$. 
Figure 4.9: Hall Effect Scan: Axial MFL Signal (Gauss), $h = 1\text{mm}$.
Figure 4.10: Hall Effect Scan: Top View, Tangential MFL Signal (Gauss), $h = 1\text{mm}$. 
Figure 4.11: Hall Effect Scan: Tangential MFL Signal (Gauss), $h = 1\text{mm}$.

We can see from the previous signals that the tangential component is very small. The axial component has a small variation and we can see the effect of the external magnetic field by shifting the axial signal to reach a minimum of $168G$. The radial signal presents some similarity to the theoretical signal given in the dipole model.
4.2 Magneto Optical Imaging

In this section we provided different simulations before making the experimental magneto optical image inspection. The first simulation was based on the mathematical dipole model results (Figures 2.4, 2.6 and 2.8). The theoretical dipole model was the input for the magneto optical photo response Equations (3.9) and (3.10).

4.2.1 Results Based on the Dipole Models Simulation

Figure 4.12: Magneto Optical Image Top View, Based on Dipole Models.
4.2.2 Results Based on the Hall Effect Sensor Scan

This section takes as input the MFL signal given by the experimental Hall Effect scan. The following figures represent the simulation of the photo response based on the experimental data.
Figure 4.14: Magneto Optical Image, Top View Based on the Hall Effect Scan.
Figure 4.15: Magneto Optical Image, Based on the Hall Effect Scan.

The magneto optical image based off the Hall Effect scan has great similarity with the original Hall Effect scan, and the Radial component is the main component appearing in this simulation.

4.2.3 Experimental Results of the Magneto Optical Imaging

The experiment is based on the Faraday effect. This effect is described by the change of the polarization plan of the light after passing through the magneto optical ma-
terial, MO film in our case.

In order to implement the setup according to the Figure 4.16, we designed our experimental magneto optical imaging system to be inside the Helmholtz coils test bed on top of the pipe.
In Figure 4.17 we present one of the problems that we encountered during the design of our magneto optical imaging system. Owing to the working distance $d_w$ we made a new concept in such a way that the camera was aligned with the pipe axis.
The next image explains the light travel from the light source facing the polarizer, to the camera facing the analyzer.

Figure 4.19: Light Travel Inside the Magneto Optical Imaging System.

The issued polarized light, 1, will travel from the polarizer to the beam splitter where 50% of the light will be transmitted and 50% will be reflected, 2, to reach the MO film. The light will travel inside the MO film and get reflected back, 3. Arriving a second time to the beam splitter, the light will be equally reflected and transmitted, 4. The beam splitter will reduce the light intensity to the quarter due to this double passing. Once it is reflected by a normal mirror, 5, the light will finally reach the analyzer and be transmitted directly to the camera.

The light source for the experiment must be homogeneous and have the sufficient intensity to light up the magneto optical film. The effect of the 50% transmission 50% reflection beam splitter will reduce the light intensity to \( \frac{1}{4} \) because of the double passing, so we need to take this parameter in consideration for our choice.
In Figure 4.20 the light transfer characteristics is presented as a function of the wavelength. This property is obtained for an angle of 45 deg.

The camera that we chose for this experiment was a AD7013MTL Dino-lite USB microscope camera. It is a small and portable camera, allowing it to fit inside the setup. The external cover is made of aluminum. This property gives the advantage of not affecting
the magnetic field near the defect while doing inspection. This camera has the capability
of 100× magnification with double numerical 2×. This will give us a very close view to the
defect. The 5 MP resolution assures that we have the maximum information with both
video images and recordings. The AD7013MTL microscope camera comes with a built in
LED and connects to the PC with USB cable. Thanks to its DinoCapture software, we
can calibrate the image with the calibration toolbox. The drawing toolbox can also help
to define the size and the shape of the recorded object. This type of microscope was an
essential tool to get the image representing the photo response of the magneto optical film.
This software is useful to enhance the quality of images for an accurate post processing.
Figure 4.22: DinoCapture Recording Software for AD7013MTL Dino-Lite Microscope USB Camera.

After getting the MO photo response, Figure 4.23, we specified the studied zone using the Dino lite software. This gives us the exact dimensions of the real image (2.661x2.379 mm).
The following image, Figure 4.24, is a cut for the zone of study after eliminating the edges of the film.
So far, the zone of study represented in Figure 4.24 is still in the RGB image format. This means that we still have three matrices respectively representing the Red, the Green and the Blue components of the image. Therefore, a gray scale transformation is called so that we can deal with one matrix instead of three. The gray scale transformation, Figure 4.25, is applied to get a variation between brightness and darkness. This is an essential step to normalize the image.

![Figure 4.25: Magneto Optical image, Gray Scale.](image)

The image is still coded with 8 bits, meaning the values are between 0 and 254. So we
need to transform the 8 bits coded image into double, Figure 4.26. This results in plotting the image in three dimensions (x, y and the photo response PR), Figure 4.27.

Figure 4.26: Magneto Optical Image, Post Process Top View.
Figure 4.27: Magneto Optical Image, Post Process.
The above figure demonstrates the great similarity present between the magnetic dipole model and the magneto optical film photo response. The normalized signals show that the two are close in terms of shape. The distances between the maximum and the minimum of each curve are almost identical. This similarity implies that the magneto optical technology has a good chance of describing the MFL signal, along with holding the benefit of the area measurement.

The magnetic dipole model simulation and the Hall Effect scan provide the real values and the distribution of the magnetic field around the defect, but the scan takes a long time to do this task. To have the same capability within a real time response gives the magneto optical imaging sensor huge promise to be a very powerful sensing technology.
4.3 Conclusion

In this chapter we covered both simulation and experimental results. First we proceeded by showing our new experiment setup for Hall Effect sensing. The features of this setup are: (1) capable of making line scan, (2) capable of assembling line scans in a 2D area measurement, (3) takes into consideration the different radius of the under scan pipelines, (4) gives flexibility for the user to set the x-y elementary displacement for the scan.

The Magneto Optical image was derived based on the simulations issued from magnetic dipole models simulations. This first MO image is an expected response for the MO real results. To validate our simulated images we presented in this chapter the Magneto Optical Imaging setup. The component of this setup and the mechanism of extracting images were developed. Finally we presented a post processing result for the MO experimental images showing similarities with the simulated ones. Finally we validated the center line of the MO response with the magnetic dipole models. The following chapter will contain a summery and highlight the results of our study.
Chapter 5

Conclusion

MFL technology has been developed extensively in the field of NDT inspection. The applications of such a technique are present in various domains. In this work, we have presented two different MFL methods: the classic Hall Effect sensing technology, and the new Magneto Optical Imaging technique. We studied the physics behind each sensor so that we can understand the role of every parameter in their equations.

As described, MFL technique is based on the measure of the magnetic field leaking from the defected area. We made a defect inside a cylindrical metallic pipe, and we magnetized the zone of study. Simulations were run to exhibit the different response of each sensor. This first step gave us an initial idea on how to proceed with the experiments. The experimental part is an essential part of this thesis, where we put in to test the validity of the theoretical study and demonstrated the output results of each method.

Hall Effect Sensor: The main advantage of this sensor is that it has been extensively developed throughout the past century. The sensor gained especially a lot of progress with the use of integrated circuits. This small electronic device can easily be interfaced and does not consume much energy (30 mW) with a linear analogue output signal. As a re-
sult, it is a very suitable tool to equip many applications with, such as robotics inspections (PIG). The Hall Effect sensor comes with various sensitivities and ranges, giving a wide band for selecting a convenient sensor with a quick time response (3µs). The robustness is also a great feature allowing for good functioning in hazardous environments (dust, high temperature, humidity).

Thought it has many advantages, the Hall Effect sensor still hold several limitations. One of the main limitations of such a device is that it is a point measurement sensor. It gives the magnitude of the magnetic field for one specific point. Therefore, for the case of an area measurement, this device needs to be equipped in a system allowing the x - y displacement in order to scan all that area. For example, in our experiment, it took 35 minutes to get the area scan for only one of the three components (radial, axial or tangential) of the MFL signal. We needed to shut down the magnetization coil after every scan because of the heat created during this long period of time. We needed to make sure that we provided a constant magnetic field; this required that we monitor the coil excitation current that decreases with time during the 25 minutes of scanning. This was only for one MFL signal component. Three-component Hall Effect sensors were developed recently to overcome this issue. These will be very useful for our setup, taking a third of the time to make the scan. This device is also sensitive to the lift-off distance, separating the sensor from the defected area.

**Magneto Optical Imaging:** Magneto Optical Imaging is a rising technology, and scientists are still discovering its features. The main component of this technology is the garnet magneto optical film. Many efforts have gone into enhancing its properties and maximizing its potential. Unlike the Hall Effect sensor, the MO film is not an end up technology. That is why there are many proposals and many approaches trying to model and characterize the MO film, depending on the applications of such a sensor.
This technique has the powerful capability of making an area measurement in less than a second, allowing us to make real time inspections. This important result is key for future work trying to improve magneto optical imaging technology used to characterize the defected area and extract the maximum of information of it. For the Hall Effect scan, regardless of how small the displacement step size was, we know that we lost some information going from one position to another. This property does not hold for the case of magneto optical imaging, where the MO film covers all of the defected area, making our measurement continuous.

This technology, despite being quick to measure area, is very delicate to deploy in real life. The complexity of this technology comes from the diversity of its components. Magneto Optical Imaging is composed of a homogeneous light source, a polarizer specifically geometrically oriented with respect to an analyzer, a very thin MO film, reflection mirrors, a beam splitter for light guidance, and a high resolution camera. All these different components must be assembled in a very specific way in order to obtain reliable results. The MO film itself is thin and can easily be damaged. This will make it very vulnerable in hazardous environments. The device is also sensitive to the lift-off distance.

To summarize, the MFL inspection technique is a very open research problem that has promising potential. In this project, we tried to study the area scan of the MFL signal with two different sensing technologies: (1) Hall Effect sensing and (2) Magneto Optical Imaging. Linking the classic Hall Effect sensor resulted in a new rising sensor knowing as magneto optical imaging. Implementing this new technology in a robotic device will be a challenging prospective that the field needs to accomplish. Finally, gaining a better understanding of the MO film allows us to customize it to specific applications.
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