Development of a miniaturized electrical conductivity gauge based on eddy currents testing

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Thesis to obtain the Master of Science Degree in Electronics Engineering

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November 2016
Acknowledgments

Firstly, I would like to express my special thanks of gratitude to my supervisor Professor Pedro Ramos and my co-supervisor Luís Rosado for their guidance and advice, which also helped me in doing a lot of research and I came to know about so many new things.

I would like to give a very special thanks to Sr. João Pina dos Santos for all his support, advice and availability at helping in everything he could.

In this project I had the opportunity to use the facilities of the Non Destructive Testing laboratory of Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, where I had the help of Professor Telmo Santos, Patrick Inácio, Miguel Machado and Pedro Riscado. I would like to thank them for the support and time spent helping me.

I would also like to thank my family and friends, specially Soraia Ribeiro and Mário Viegas that helped me in this stage of my college life.
Abstract

Non-Destructive Testing (NDT) of metallic materials is a growing area that requires novel sensing solutions. From the several NDT methods, eddy currents testing is one of the preferred to inspect metallic parts and welding joints searching for flaws and other material discontinuities.

Eddy currents sensors are devices capable of contactless assessment with high-resolution measurements of any conductive target. High resolution and tolerance in dirty environments make eddy currents sensors indispensable in modern industrial operations.

One of the uses of eddy currents sensors is to measure electrical conductivity. The value of the electrical conductivity of a metal depends on its chemical composition and crystalline structure. This work presents the development, implementation and characterization of a compact embedded system for contactless metal conductivity measurements.

In this work was possible to develop a miniaturized handheld contactless electrical conductivity measurement system based on eddy currents. The system performs measurements of various conductivity samples and lift-offs. A user friendly interface with the possibility of changing the signal characteristics, was also developed.

Keywords

Non-Destructive Test, Eddy Current Testing, Metal Conductivity, Contactless, Digital Signal Processing, Embedded System.
Resumo

O teste não destrutivo em materiais metálicos como o alumínio é uma área em crescimento e necessita de novas alternativas para os sensores. Há vários métodos de teste não destrutivos, mas deles todos a utilização de correntes induzidas é o mais utilizado para analisar elementos metálicos, procurar por falhas em pontos de soldadura ou descontinuidades no material.

Os dispositivos que utilizam sensores de corrente induzida, são capazes de realizar medições com elevada resolução sem a necessidade de contacto com o material que é condutivo. A alta resolução e a insensibilidade a ambientes contaminados torna os sensores de corrente induzida indispensáveis à indústria nos dias de hoje.

Os sensores de corrente induzida podem ser utilizados para medir a condutividade elétrica dos materiais. O valor da condutividade elétrica de um metal depende da sua composição química e da pressão a que sua estrutura cristalina está sujeita. Este trabalho apresenta o desenvolvimento, implementação e caracterização de um dispositivo portátil capaz de realizar medidas de condutividade dos metais utilizando o método das correntes induzidas.

Neste trabalho foi possível desenvolver um medidor de condutividade sem necessidade de contacto de pequenas dimensões baseado no método de correntes induzidas. O sistema consegue realizar medições de condutividade elétrica e de distância do sensor de vários metais.

Foi desenvolvida uma interface gráfica que possibilita a variação de alguns parâmetros como a frequência do sinal que estimula o sensor ou a frequência de amostragem por exemplo.

Palavras Chave

Teste Não Destrutivo, Correntes Induzidas, Conductividade de Metais, Sem Contacto, Processamento Digital de Sinal, Sistema Embebido.
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<th>Description</th>
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<td>AC</td>
<td>Alternate Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CDC</td>
<td>Communications Device Class</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide Semiconductor</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analog Converter</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DDS</td>
<td>Direct Digital Synthesizer</td>
</tr>
<tr>
<td>DSCs</td>
<td>Digital Signal Controllers</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>dsPIC</td>
<td>Digital Signal Peripheral Interface Controller</td>
</tr>
<tr>
<td>ECT</td>
<td>Eddy Current Testing</td>
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<tr>
<td>EMF</td>
<td>Electromotive Force</td>
</tr>
<tr>
<td>FDAtool</td>
<td>Filter Design and Analysis Tool</td>
</tr>
<tr>
<td>FSW</td>
<td>Friction Stir Welding</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>GPIB</td>
<td>General Purpose Interface Bus</td>
</tr>
<tr>
<td>HW</td>
<td>Hardware</td>
</tr>
<tr>
<td>IACS</td>
<td>International Annealed Copper Standard</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>IDE</td>
<td>Integrated Development Environment</td>
</tr>
<tr>
<td>IIR</td>
<td>Infinite Impulse Response</td>
</tr>
<tr>
<td>IST</td>
<td>Instituto Superior Técnico</td>
</tr>
<tr>
<td>IT</td>
<td>Instituto de Telecomunicações</td>
</tr>
<tr>
<td>LUT</td>
<td>Look-Up-Table</td>
</tr>
<tr>
<td>MSc</td>
<td>Master of Science</td>
</tr>
<tr>
<td>NCO</td>
<td>Numerically Controlled Oscillator</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
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<tr>
<td>OP-AMPs</td>
<td>Operational Amplifiers</td>
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<td>OTG</td>
<td>On-The-Go</td>
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<tr>
<td>PIC</td>
<td>Peripheral Interface Controller</td>
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<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
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<tr>
<td>SI</td>
<td>International System of Units</td>
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<td>SPI</td>
<td>Serial Peripheral Interface</td>
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<td>SW</td>
<td>Software</td>
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<td>USB</td>
<td>Universal Serial Bus</td>
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<td>VGA</td>
<td>Variable Gain Amplifier</td>
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1 Introduction

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Introduction

1.1 Purpose and motivation

There are many types of NDT techniques such as those based on eddy currents, ultrasound, induction, magnetic flux leakage, and other physical principles. They allow testing of materials, components and systems without limiting future usability and, sometimes, disassembling the parts under test from their original location. NDT products are used to perform acoustic emission testing, interferometry, magnetic leakage testing, magnetic particle testing, radiographic testing, or computed tomography. Such procedures may, among others, can also reveal fatigue or cracks in aircraft parts such as landing gear, or can be used to test raw materials, such as steel during the first stages of production. NDT probes and sensors can also include devices that test for precision thickness and metal-to-metal or other bonds [1].

Some Eddy Current Testing (ECT) are used as electromagnetic comparators to sort components that are manufactured with different metals. Such comparators use coils where an Alternate Current (AC) is applied. When a metal part is brought close to the coil, the coil impedance is affected. Electronic circuitry compare the amplitude, phase, and harmonic distortion of the output voltage to determine component composition.

Since 1950, ECT has developed increasingly in materials testing, especially in the aircraft and nuclear industries. The extensive research and development [2] in highly sensitive sensors and instruments over the last years indicates that ECT is a widely used inspection technique and its applicability is increasing.

There are several work already done in the Instituto Superior Técnico (IST)/Instituto de Telecomunicações (IT) research group in NDT with eddy currents probes. Some of them were developed in previous projects as “NDT Based on Eddy Currents” [3], “Heterodyning NDT Electronic System Based on Eddy Currents” [4] and Electronic System for NDT Using Eddy Currents Array Probes” [5].

The objective of this project is to make a system with smaller dimensions compared to the work previously done and be able to present the results of the acquisition on a graphical user interface. This probe will measure the electrical conductivity and the distance between the probe and the conductive material which is called lift-off.
Electrical Conductivity is the ability of a solution to transfer electric current. It is the reciprocal of electrical resistivity $\Omega$. Its International System of Units (SI) derived unit is the Siemens per meter (S/m), but conductivity values are often reported as percent International Annealed Copper Standard (IACS). Conductivity measurements can be useful since values are affected by such things as a substances chemical composition and the stress state of crystalline structures. Therefore, electrical conductivity information can be used for measuring the purity of water, sorting materials, checking for proper heat treatment of metals, and inspecting for heat damage in some materials.

### 1.2 Goals and challenges

The main objective of this work is to develop a miniaturized handheld contactless electrical conductivity measurement system based on eddy currents. As such, the goals for this project are to develop:

- An embedded measurement system;
- Firmware capable of performing the signal processing to estimate the sensor impedance;
- Communication with the terminal running a graphical user interface to indicate the results;
- Perform measurements of various conductivity samples.
- Define and implement methodologies for correction/conductivity measurement calibration.

The system specifications goal is presented in Table 1.1.

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Conductivity Range</th>
<th>Conductivity Accuracy</th>
<th>Lift-off Range</th>
<th>Lift-off Accuracy</th>
</tr>
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<tbody>
<tr>
<td>1 - 100 kHz</td>
<td>1 - 100% IACS</td>
<td>±1% IACS</td>
<td>0 - 0.6 mm</td>
<td>±0.025 mm</td>
</tr>
</tbody>
</table>

### 1.3 Document organization

This thesis is organized as follows:

- Chapter 1 is an introduction about NDT, specifically of conductivity measurements and on what the project consists.
- Chapter 2 is the state of the art where some theory in ECT is explain. In this chapter some of the work already done in NDT with eddy current probes and applications where NDT are used is also presented.
• In Chapter 3 the architecture of the proposed system is shown.

• Chapter 4 is the software chapter. In this chapter the configurations needed to work with the microcontroller and the used algorithms are explained.

• Chapter 6 presents the thesis the conclusions and suggestions for future work.

1.4 Original contributions

Nowadays there are several solutions to perform conductivity and lift-off measurements but not with this portability. There are some probes that are small but the equipment necessary besides the probe is bigger. With this probe it is possible to use a smartphone or it can be used with a computer, which has other functionalities.

The new contributions of this project were presented [6] in 21st IMEKO TC-4 International Symposium on Understanding the World through Electrical and Electronic Measurement. The symposium covered the broad topics in measurement of electrical quantities and in related fields, with special track on analog-to-digital and digital-to-analog conversion. The aim of the symposium is to serve as a forum for discussions on trends, latest results and to exchange ideas relating different measurement tasks.
## State of the Art

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State of the Art

2.1 Eddy Currents

From the several NDT methods, eddy currents (also known as Foucault currents) is one of the preferred to inspect metal parts and welded joints searching for flaws and other material discontinuities. The main advantage of using this technology is that surface preparation is minimal, it gives instantaneous results and requires no consumables.

The concept of ECT is based on the principles of electromagnetic induction. Maxwell’s Ampere law, proves that an alternating current running through a wire sets up a time varying magnetic field, which is known as a primary magnetic field. Electromagnetic induction occurs when a conductor is near a time varying magnetic field and ultimately results in the induction of electrical voltage within the said conductor. Currents are induced in planes perpendicular to the vector of the magnetic induction and are called eddy currents (because their shape is reminiscent of a whirlpool). Eddy currents sensors have a driver that creates an alternating current in a coil which in turn generates an alternating magnetic field that induces eddy currents in the target material. The eddy currents create an opposing magnetic field which resists the field being generated by the coil, as shown in Figure 2.1.

![Figure 2.1: Basic eddy current theory.](image-url)
The interaction of the magnetic fields is dependent on the distance between the coil and the target material and also on the actual material composition. If the distance between the coil and the material changes, the electronic measurement system senses the change in the field interaction (either through the same coil or another sensing coil) and produces a voltage output that depends on the change in distance between the probe and target [7]. When the material target is different there is also a change in the field interaction that produces a change in the voltage output. These effects will make possible to distinguish between different materials.

2.1.1 Principles of Eddy Current Testing

In 1824, Oersted discovered that an electrical current passing though a coil creates a magnetic field capable of shifting a compass needle. In 1830, Faraday and Henry discovered that a moving magnetic field would induce current in an electrical conductor. This process of generating electrical current in a conductor by placing the conductor in a changing magnetic field is called electromagnetic induction. Faraday also noticed that the rate at which the magnetic field changed also had an effect on the amount of current or voltage that was induced [8].

Eddy currents phenomena can be explained based on Ampere’s (2.1) and Faraday’s (2.3) laws. The generalization to any closed loop of arbitrary shape that involves many magnetic field lines is known as Ampere’s law [9],

\[ \oint_S \vec{B} \cdot d\vec{s} = \mu_0 I, \] (2.1)

where \( \mu_0 \) is the permeability of free space and \( I \) is the electric current flowing through the surface bounded by the closed path. Considering a long straight wire of radius \( r \) carrying a current \( I \) of uniform current density, the magnetic field \( B \) is given by

\[ B = \frac{\mu_0 I}{2\pi r}, \] (2.2)

Faraday’s law [10] implies that a changing magnetic flux will induce a non electrostatic electric field that can vary with time,

\[ \oint_S \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}. \] (2.3)

where \( \Phi_B = \int \vec{B} \cdot d\vec{A} \).

Lenz’s law states that induced currents produces magnetic fields that tend to oppose the change in magnetic flux that induces such currents. The relationship between Electromotive Force (EMF), \( \varepsilon \), and changing magnetic flux, \( \frac{d\Phi_B}{dt} \), is

\[ \varepsilon = -\frac{d\Phi_B}{dt}. \] (2.4)

Magnetic field \( B \) is generated by a probe coil and a electrostatic current is generated on a conductive
material. This electrostatic current generates an opposite magnetic field from the original one that affects the coil impedance. Cracks or different material conductivities affects the induced currents and the opposite magnetic field so the coil impedance also changes. This allows to characterize or detect different conductive materials.

In a purely resistive circuit current and voltage are in phase, but when capacitors or inductors are present the current and voltage do not peak at the same time [11]. The fraction of a period difference between the peaks, expressed in degrees, is the phase difference. This leads to a positive phase for inductive circuits since current lags the voltage in an inductive circuit Figure 2.2(a). The phase is negative for a capacitive circuit since the current leads the voltage, Figure 2.2(b).

![Inductive circuit](image1.png) ![Capacitive circuit](image2.png)

**Figure 2.2:** Inductive and capacitive circuits and phases.

Inevitably, all inductive circuits have some amount of resistance. AC current will lag somewhere between a purely resistive circuit, and a purely inductive circuit [11]. The exact amount of lag depends on the ratio of resistance and inductive reactance. The more resistive a circuit is, the closer it is to being in phase. The more inductive a circuit is, the more out of phase it is. In Figure 2.3, resistance and inductive reactance are equal and the current lags the voltage by 45 degrees.

![Inductive circuit when reactance is equal to resistance](image3.png)

**Figure 2.3:** Inductive circuit when reactance is equal to resistance.

Electrical Impedance, $Z$, is the total opposition that a circuit presents to alternating current. Impedance is measured in ohms and may include resistance, $R$, inductive reactance, $X_L$, and capacitive reactance, $X_C$. Every coil is characterized by the impedance parameter $Z$, which is a complex number defined as
The impedance magnitude in a circuit with resistance and inductive reactance can be calculated using

\[ |Z| = \sqrt{X_L^2 + R^2}. \] (2.6)

The impedance phase in a circuit with resistance and inductive reactance can be calculated using

\[ \phi = \arctan \frac{X_L}{R}. \] (2.7)

Using these two relations, one can estimate \( R \) and \( X_L \) based on \( |Z| \) and \( \phi \) measurement.

The magnetic field that is created on the conductive material, has a weakening effect on the primary magnetic field. The new imaginary part of the impedance of the coil decreases proportionally when the intensity of eddy current in the conductive material increases [12]. Eddy currents also contribute to the increasing of the power dissipation of energy that changes the real part of the coil impedance. Measuring this coil impedance variation from \( Z_0 \) to \( Z_C \), by monitoring the voltage and the current signal, can reveal specific information such as conductivity or chemical composition of the piece [13].

The impedance plane diagram [14] is a useful way to display eddy current data. As shown in the Figure 2.4, the strength of the eddy currents and the magnetic permeability of the material cause the eddy current signal on the impedance plane to react in different ways.

![Impedance plane diagram](image)

**Figure 2.4:** Impedance plane diagram.

If the eddy current circuit is in the air and then placed on a piece of aluminium, the resistance component will increase (eddy currents are being generated in the aluminium and this takes energy away from the coil, which shows up as resistance) and the inductive reactance of the coil decreases...
(the magnetic field created by the eddy currents opposes the coil’s magnetic field and the net effect is a weaker magnetic field to produce inductance). If a crack is present in the material, fewer eddy currents will be able to form and the resistance will go back down and the inductive reactance will go back up. The changes in conductivity will cause the eddy current signal to change in a different way.

When a probe is placed on a magnetic material such as steel, something else happens. As the previous example, eddy currents form, taking energy from the coil, which shows an increase in the coils resistance. Also, the eddy currents generate their own magnetic field that opposes the magnetic field of the coil. However, from the diagram of Figure 2.4, the reactance increases. This is because the magnetic permeability of the steel concentrates the magnetic field of the coil. This increase in the magnetic field intensity completely overshadows the magnetic field of the eddy currents. The presence of a crack or a change in the conductivity will produce a change in the eddy current signal similar to that observed with aluminium.

2.1.2 Depth of Penetration and Current Density

Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil. Eddy current density decreases exponentially with depth, such phenomenon is known as the skin effect [15]. The skin effect arises when the eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing the net magnetic flux and causing a decrease in current flow as the depth increases.

Magnetic permeability $\mu$ quantifies the degree of magnetic induction $B$ of materials when a magnetic field $H$ is applied

$$B = \mu H.$$  \hfill (2.8)

High magnetic permeability makes the penetration depth decrease. In order to compensate for this effect and explore the material internally, ferromagnetic materials are inspected at lower frequencies than non-ferromagnetic ones.

The lift-off is the distance variation between the inspection coil probe and the test piece. The lift-off can be caused by varying coating thickness, irregular sample surfaces or the operator’s movements [16]. The lift-off effect is shown Figure 2.5.

Fill factor is the ratio of the cross sectional area of the test piece and area of the coil section. It is necessary that the coil wires be as close as possible to the test piece, in order to have a greater response potential to cracks.

Edge effect is a phenomenon that occurs when an inspection coil is at the end of the test piece. In these instances, eddy current flow is distorted as currents cannot flow at the edge. So, to avoid problems with flaws, inspection is avoided near edges.
Figure 2.5: Lift-off effect. When the probe is closer to the target eddy currents are stronger.

When setting a frequency, the initial coil impedance $Z_0$ is adjusted. When inspection frequency $f$ is increased, the imaginary part of the impedance is increased

$$Z_0 = R_0 + j2\pi f L_0.$$  \hfill (2.9)

Eddy current flow is not uniformly distributed throughout the entire volume of the test piece. Current flow is stronger at the surface, decreasing exponentially in relation to the distance from the surface. Assuming that the current density flowing along X axis is

$$\vec{J} = J_x(z,t) \ast \vec{u}_x$$  \hfill (2.10)

where $\vec{u}_x$ is the unitary vector along X axis and $J_x(z,t)$ is the magnitude of density current as function of depth $z$ and time $t$.

The phasor of the current density along depth $Z$ axis is given by

$$J_x(z) = J_{0,\text{max}} e^{-(\frac{z}{\delta})} e^{j(\alpha_0 - \frac{z}{\delta})}$$  \hfill (2.11)

where $J_{0,\text{max}}$ is the maximum current density at surface and $Z$ is depth. The standard penetration depth $\delta$ is the depth at which the eddy current density decreases to a level of about 37% of its surface value. The term $\alpha_0$ is the phase at $t = 0$ and $z = 0$ and $-\frac{z}{\delta}$ is the phase lag.

The penetration depth can be calculated by
\[ \delta = \sqrt{\frac{2}{\mu 2\pi f \sigma}} \]  

(2.12)

where \( \mu \) is the magnetic permeability in \( H m^{-1} \) and \( \sigma \) is the conductivity in \( \Omega m^{-1} \).

Phase lag makes possible to obtain information about the depth of a defect within a material. Phase lag is the shift in time between the eddy current response from a disruption on the surface or a disruption at some distance below the surface.

2.2 Probes

The eddy current probe is what detects the difference between the test material and air, and sends the differential measurement to the handler. Design and development of eddy current probes \[17\] is very important as it is the probe quality that dictates the probability of detection and the reliability of characterization. Appropriate selection of probe coil is important in eddy current testing, as even an efficient eddy current instrument cannot achieve much if it doesn’t get the right information from the coils. The shape, cross-section, size and configuration of coils are varied to design an eddy current probe for a specific application.

2.2.1 Absolute Probes

Absolute probes \[18\] generally have a single coil that generates eddy currents and senses changes in the eddy currents. Absolute probes provide an absolute voltage signal and can be used for flaw detection, conductivity measurements, lift-off measurements and thickness measurements. The disadvantage of these coil probes is their low sensitivity and temperature drift.

Absolute probes may have a voltage compensation using an additional reference coil that is far from the inspected material as shown in Figure 2.6. A lower voltage signal is measured when there is no defect which increases the probe sensitivity and performance with limited dynamic range electronics. Furthermore, they are less sensitive to temperature changes than non-compensated probes.

2.2.2 Differential Probes

Differential probes \[19\] consist of two active coils that compare two adjacent parts of the inspected material. The detecting coils are wound or wired in opposition to one another in order to equalize the induced voltages originated by the excitation primary field. When there is no defect, the output voltage of the differential coil probe is zero because the voltage in each coil is identical. However, when one coil is over a defect in the test material alter the balance and a differential signal is produced, as is shown in Figure 2.7. It is very sensitive to defects yet relatively insensitive to slowly varying properties such as
gradual dimensional, lift-off, or temperature variations. A disadvantage using differential probes is that the signals may be difficult to interpret.

![Diagram of compensated absolute probe.](image)

**Figure 2.6:** Example of a compensated absolute probe.

2.2.3 Reflection Probes

Reflection probes consists of two coils, one coil is used to excite the eddy currents and the other is used to sense changes in the test material. These probes are often referred as driver/pickup probes. The advantage of this probes is that the driver and pickup coils can be separately optimized for their intended purpose. The driver coil can be made so as to produce a strong and uniform flux field in the vicinity of the pickup coil, while the pickup coil can be made very small so that it will be sensitive to very small defects [20].

![Diagram of differential probe behavior.](image)

**Figure 2.7:** Differential probe behavior.
2.2.4 Reflection-Differential Probes

Split D [21] is an example of a reflection-differential probe. It has a driver coil that surrounds two D shaped sensing coils as shown in Figure 2.8. It operates in the reflection mode but additionally, its sensing coils operate in the differential mode. This type of probe is very sensitive to surface cracks.

![Design of a Split D probe.](image1)

![Real Split D probe.](image2)

Figure 2.8: Split D probe.

2.2.5 Geometries

Eddy currents probes can also be classified accordingly to their geometry [20]:

- Surface probes [22] generally consist of a coil enclosed in a protective housing. The dimensioning of the coil depends on the intended application. Most of the coils are wound so that the axis of the coil is perpendicular to the test surface. The advantage of this configuration is that is good for detecting surface discontinuities that are oriented perpendicular to the test surface. The disadvantage is that discontinuities that are in a parallel plane to the test surface will not be detected. Figure 2.9 shows a person with a surface probe checking a welding joint.

![Surface probe used to scan welding joints.](image3)

Figure 2.9: Surface probe used to scan welding joints.
• Bolt hole probes are a special type of surface probe that is designed to be used with a bolt hole scanner. They have a surface coil that is mounted inside a housing that matches the diameter of the hole being inspected. The probe is inserted in the hole and the scanner rotates the probe within the hole. In Figure 2.10, a U.S. Air Force Sgt. uses a bolt hole eddy current probe to scan the inside of a fuse plug hole on a wheel.

![Bolt hole eddy current probe](image1.jpg)

**Figure 2.10**: Bolt hole eddy current probe used to scan the inside of a fuse plug hole on a wheel [23].

• ID probes or Bobbin probes [24], are inserted into hollow products, to inspect from the inside out. The ID probes have a housing that keep the probe centred in the product and the coil orientation constant relative to the test surface. The coils are most commonly wound around the circumference of the probe so that the probe inspects an area around the entire circumference of the test object. Figure 2.11(a) shows how the coils in the probe are placed and the magnetic flux. Figure 2.11(b) shows how the eddy currents flow and its effect when a defect is detected by the probe.

![ID probe configuration and magnetic flux](image2.jpg)

**Figure 2.11**: ID probes.

(a) ID probe configuration and magnetic flux.  
(b) Eddy currents flow of a ID probe.

• OD probes [25] are similar to ID probes except that the coil encircle the material to inspect from the outside in. OD probes are commonly used to inspect solid products, such as bars. Figure 2.12
shows a OD probe around a metallic tube.

![OD probe around a metallic tube](image)

**Figure 2.12:** OD probe checking for defects on a metallic tube.

The probe configuration that is used in this project is a surface absolute probe with compensation as shown in Figure 2.6. This configuration helps with the dynamic range because when the probe is in air, the voltage signal is close to zero. This configuration is less sensitive to temperature changes, highly sensitive to lift-off, signal interpretation is simpler and is more sensitivity on plane measures.

2.3 Eddy Current Inspection

2.3.1 Advantages

Compared to other non-contact sensing technologies such as optical, laser, and capacitive, high-performance eddy current sensors have some distinct advantages [26]. Eddy current sensors are sensitive to surface defect being able to detect defects with 0.5 mm length. It can also detect defects in multi-layer structures with minimal interference from planar interfaces.

These sensors are able to detect defects through non-conductive surface coatings up to 5 mm thickness, can be used in autonomous systems and do not require a very strict maintenance. Inspection with these sensors can give immediate results with minimum part preparation required. The test probe does not need to contact the material and can test hot samples. They also allow the inspection of complex shape and size of conductive materials. These systems although complex may be portable.

One example is the NORTEC 500C [27], Figure 2.13, from Olympus that has a weight of 1.72 kg, including lithium-ion battery and an overall dimensions of $241 \times 140 \times 92$ mm. Its operating frequency is from 10 Hz to 12 MHz and uses absolute or differential probes. The conductivity measurement range is from 0.9% to 110% IACS with an accuracy of $\pm 0.5\%$ IACS until 62% IACS and $\pm 1\%$ IACS above that conductivity value. Can measure non-conductive coating thickness from 0 mm to 0.381 mm with an accuracy of $\pm 0.025$ mm over a 0 mm to 0.64 mm range.
2.3.2 Limitations

Eddy current probes [28] are very susceptible to magnetic permeability changes. Small changes in permeability have a pronounced effect on the eddy currents and this makes testing difficult but not impossible.

This method is only effective on conductive materials and will not detect surface parallel defects. The flow of eddy currents is always parallel to the surface. If a planar defect does not cross or interfere with the current then the defect will not be detected. A large area scanning can be accomplished, but requires an extra scanning device.

2.4 Applications

Eddy currents equipment can be used for a variety of applications [29] such as the detection of cracks (discontinuities), measurement of metal thickness, detection of metal thinning due to corrosion and erosion, determination of coating thickness, and the measurement of electrical conductivity and magnetic permeability. Eddy current inspection is an excellent method for detecting surface and near surface defects when the probable defect location and orientation is well known.
2.4.1 Surface Crack Detection Using Sliding Probes

Fastener holes are found to be the most prevalent sources of cracking in aircraft structures, and corner cracks at fastener holes are particularly important in aircraft structures [30]. Many commercial aircraft applications involve the use of multiple fasteners to connect the multi-layer skins. In order to inspect the fastener holes in an adequate amount of time, sliding probes are an efficient method of inspection.

Sliding probes have been named so because they move over fasteners in a sliding motion. There are two types of sliding probes, fixed and adjustable, which are usually operated in the reflection mode.

2.4.2 Tube Inspection

Eddy current testing uses electromagnetic induction to identify defects in tubing [31]. A probe is inserted into the tube and pushed through the entire length of the tube. It is often used to detect corrosion, erosion, cracking and other changes. Heat exchangers and steam generators, which are used in power plants, have thousands of tubes that must be prevented from leaking. This is especially important in nuclear power plants where reused, contaminated water must be prevented from mixing with fresh water that will be returned to the environment.

2.4.3 Conductivity Measurements

One of the uses of eddy current instruments is for the measurement of electrical conductivity. The value of the electrical conductivity of a metal depends on several factors, such as its chemical composition and the stress state of its crystalline structure. Therefore, electrical conductivity information can be used for sorting metals, checking for proper heat treatment, and inspecting for heat damage.

Electrical Conductivity is the ability of a solution to transfer electric current. It is the reciprocal of electrical resistivity $\Omega$. Its SI derived unit is the Siemens per meter (S/m), but conductivity values are often reported as percent IACS. IACS is an acronym for International Annealed Copper Standard, which was established by the 1913 International Electrochemical Commission. Conductivity values in Siemens/meter can be converted to % IACS by multiplying the conductivity by $1.7241 \times 10^{-6}$ [32].

2.4.4 Thickness Measurements of Non-conducting Coatings on Conductive Materials

Thicknesses of non-metallic coatings on metal substrates can be determined simply from the effect of lift-off on the sensor output. This method has widespread use for measuring thickness of paint and plastic coatings. The coating serves as a spacer between the probe and the conductive surface. As the
distance between the probe and the conductive base metal increases, the eddy current field strength decreases because less of the probe’s magnetic field can interact with the base metal [20].

2.4.5 Position Measurement/Sensing

Precision eddy currents non-contact measuring systems have been used for more than 30 years for displacement, vibration, thickness, alignment, dimensioning, and parts sorting applications. All these can be classified as variations on displacement because in each case the parameter being measured is the distance from the target to the sensor [33].

Eddy Current outputs can indicate the size of the gap between the probe and the target. When the probe is stationary, any changes in the output are directly interpreted as changes in position of the target. This is useful in automation requiring precise location, machine tool monitoring, final assembly of precision equipment such as disk drives and precision stage positioning [34].

2.4.6 Dynamic Motion

NDT has become an effective mean for identifying, understanding, and simulating dynamic behaviour and responses of structures [35]. Has contributed essentially in improvement of structural health monitoring procedures. Measuring the dynamics of a continuously moving target, such as a vibrating element, requires some form of non-contact measurement. Eddy Current sensors are useful whether the environment dirtiness and the motions are relatively small.

2.5 Recent NDT Projects within IST/IT Research Group

In the past years there were some projects with NDT with current probes in IT research group. All the Master of Science (MSc) and PhD projects developed had different goals but the purpose was the same, inspecting a metallic area to search cracks, defects or different materials.

2.5.1 NDT Based on Eddy Currents

A NDT system based on eddy currents [3] was developed with the purpose of being highly reconfigurable allowing operation with several probes configurations. This was achieved through a special architecture that enables multiple combinations of peripherals for signal generation or acquisition and the characteristics of the processing core.
2.5.2 Heterodyning NDT Electronic System Based on Eddy Currents

This NDT system based on eddy currents \cite{4} was proposed as a portable solution to an existing NDT system which uses the same planar eddy currents probes with the purpose of inspection Friction Stir Welding (FSW) joints. The developed system was able to perform the division multiplexed multi-frequency inspections and characterize the defects by applying an heterodyne down conversion on the analog front-end.

2.5.3 Electronic System for NDT using Eddy Currents Array Probes

The NDT system using eddy currents Array Probes \cite{5} makes use of a new pulsed stimulus block that allowed the simplification of the driving circuit and testing different harmonic frequencies in simultaneous depths with a single signal. This concept is applied to the expansion of the previous probe to an array layout while maintaining the same working principle of the planar eddy current probe.
3
Hardware

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Hardware

The objective of this project is to develop a portable embedded measurement system to perform contactless metal conductivity and lift-off measurements.

The final system size of the Printed Circuit Board (PCB) is $110 \times 15$ mm. The handler size is $45 \times 15$ mm and the probe size is $25 \times 15$ mm. The handler and the probe are in a different PCB to be possible to change the probe without changing all the electronic circuit. To simplify the connection between the system and the host, a mini-USB interface to the handler was added. The PCB and design system is shown in Figure 3.1.

Figure 3.1: Projected system design and PCB system.
The measurement system must generate synchronous sine signals using a dsPIC external Hardware (HW) Direct Digital Synthesizer (DDS) a Software (SW) mirror DDS implemented within the dsPIC. The objective is to perform heterodyning between the stimulus signal and the acquired signal. The external DDS output is one sine wave that will be used to stimulate the probe. The probe is a bridge where each arm is an RL series circuit. One of the inductances is the coil that generates the magnetic field in the material under test, while the other coil is identical but is placed away from the material. The bridge output is also a sine signal which is amplified by a Variable Gain Amplifier (VGA) before being digitized with an Analog-to-Digital Converter (ADC). This voltage has a phase shift and different amplitude when compared with the stimulus signal but keeps the same frequency. After the ADC conversion, the samples will be processed in the microcontroller. This signal processing includes heterodyning the acquired signal with the two quadrature outputs of the SW DDS to obtain the in-phase and in-quadrature components of the measured signal. From these two components, the system estimates the electrical conductivity of the material and the probe lift-off. The complete system block diagram is shown in Figure 3.2.

![Figure 3.2: Block diagram.](image)

In these systems is common to do the heterodyning in HW, but to get a smaller size the heterodyning is done in SW. Due to the complexity of passing through analog to digital and to have better flexibility and repeatability, a better ADC is used. This system performs conductivity and lift-off measures, but is also capable of doing crack detection measures. Due to that fact, it is possible to generate frequencies up to 10 MHz.

The final version of the system (with its casing) with a mini-USB interface is shown in Figure 3.3.
3.1 Microcontroller

Microchip’s dsPIC33E family of Digital Signal Controllers (DSCs) features a 70 MIPS dsPIC® DSC core with integrated Digital Signal Processor (DSP) and enhanced on-chip peripherals. These DSCs can be used to control brushless DC, permanent magnet synchronous, AC induction and stepper motors. These devices are also ideal for high-performance general purpose applications [36].

In this project, a dsPIC is a good trade-off between the required signal processing operations, the necessary multiple external communications protocols (e.g., SPI, USB) and low power consumption. The internal DDS generates sine and cosine signals. These have exactly the same frequency as the external HW DDS output and there is a deterministic phase difference between the SW and HW signals. The deterministic phase difference is obtained by controlling the time difference between the HW DDS startup and the first ADC acquisition (the SW DDS signals are generated and stored before the measurement process starts). The difference between the two sines is the sampling frequency, 70 MHz for the external DDS and 300 kHz for the internal one. Inside the dsPIC heterodyning methods will be used to estimate the probe impedance. To obtain the in-quadrature of the measured signal a phase shift of 90° is done. To remove the images that are centered in two times the original signal frequencies, a low pass filter after the down-converting is used.

3.2 USB and Power

Universal Serial Bus (USB) interface has a 5 V output that is the input of the Linear Regulator (ADP124-3.3). The ADP124 is low quiescent current, low dropout linear regulator. It is designed to operate from an input voltage between 3.5 V and 5.5 V and to provide up to 500 mA of output current.
Due to the system portability and the need for low consumption, the hardware has a unipolar source.

The USB needs a 48 MHz frequency clock to work [37]. The 48 MHz is made with dsPIC PLL. The system crystal has a output of 60 MHz and the dsPIC PLL will synthesize 48 MHz from the 60 MHz crystal frequency. The dsPIC configuration to generate the USB working frequency is selected based on the dsPIC internal clock options [36] shown in Figure 3.4.

To achieve 48 MHz in Figure 3.4(b) output, the configuration shown in Table 3.1 was used.

<table>
<thead>
<tr>
<th>$F_{IN}$</th>
<th>$N_1$</th>
<th>$F_{REF}$</th>
<th>$M$</th>
<th>$F_{VCO}$</th>
<th>$N_2$</th>
<th>$F_{OSC}$</th>
<th>$N$</th>
<th>$F_{USB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 MHz</td>
<td>10</td>
<td>6 MHz</td>
<td>32</td>
<td>192 MHz</td>
<td>2</td>
<td>96 MHz</td>
<td>4</td>
<td>48 MHz</td>
</tr>
</tbody>
</table>

With the introduction of Microchip’s microcontroller with USB On-The-Go (OTG) peripheral, imple-
menting an embedded host has became easier. The USB specification defines an architecture that is capable of supporting most communication devices which use the USB Communications Device Class (CDC). USB CDC is a composite Universal Serial Bus device class. The class may include more than one interface, such as a custom control interface, data interface, audio, or mass storage related interfaces. CDC supports a wide range of devices that can perform telecommunications and networking functions.

### 3.3 Probe Driver

To stimulate the probe, the sine wave synthesized in the DDS (AD9834) is used. In this DDS, a sine wave with an output frequency up to 37.5 MHz can be generated. After the DDS, an anti-aliasing filter removes the images that are centred at multiple frequencies of sampling frequency, (60 MHz), and the DC component from the DDS. This bandpass filter is dimensioned to allow frequencies from 1 kHz up to 10 MHz. The filter is shown in Figure 3.5.

![Figure 3.5: Filter circuit.](image)

The sine amplitude is controlled with a digital potentiometer (AD5160) to enable a further degree of control in the driver block without degrading the DDS amplitude resolution. The final element in the driver is a high-speed rail-to-rail amplifier (ADA4891-A) which will supply the current into the probe bridge circuit. Figure 3.6 shows the simulated bode diagram of the driver circuit where it is possible possible to see that between 1 kHz and 15 MHz the gain is maximum and this is the operating bandwidth of the probe.

A digital oscilloscope Tektronix TDS5034 with a bandwidth of 350 MHz and a sample rate of 5 GS/s to confirm the frequency response obtained in this circuit was used. The measurements were done after a rail-to-rail amplifier that has a slew rate of 170 V/µs. The results are shown from Figure 3.7 to Figure 3.10.

After the filter, there is a circuit that will set a DC component in the output signal because the driver
Figure 3.6: Simulated bode diagram of the driver circuit.

Figure 3.7: 1 kHz sine wave with 10000 samples and a sampling frequency of 50 kHz.

Figure 3.8: 100 kHz sine wave with 10000 samples and a sampling frequency of 5 MHz.
Figure 3.9: 1 MHz sine wave with 10000 samples and a sampling frequency of 50 MHz.

Figure 3.10: 10 MHz sine wave with 10000 samples and a sampling frequency of 500 MHz.

has to work with positive voltages due to the unipolar source. The signal output will be a sine wave with a DC component of 1.6 V. Figure 3.11 shows the circuit.

When an unipolar supply design is used, it is common to use rail-to-rail Operational Amplifiers (OP-AMPs) because these amplifiers can output voltage very near the power supply voltages. The ADA4891-1 is a Complementary Metal-Oxide Semiconductor (CMOS), high speed rail-to-rail amplifier that offer high performance at a low cost. The amplifier feature true single-supply capability, with an input voltage range that extends 300 mV below the negative rail. The ADA4891-1 has a gain-bandwidth of 220 MHz. The maximum output current of the ADA4891-1 is 37 mA, this gives an output voltage of 2.2 V with a load of 60 Ω, that is the load with the probe included.

Figure 3.12 shows the whole driver circuit.

3.4 Probe

In this project a first approach with a PCB that simulate the signal that it will be acquired with the probe was made. This circuit helped setting the acquisition working properly, since it was known the stimulus and the output.

DRV is the output of the Driver module, so, this is the sine wave generated by the DDS. The output of the probe is the SNS. In SNS_P it will be half the AC and DC voltage of DRV_P. In SNS_N the signal will
be almost the same but with a smaller amplitude. This difference is small, in order of 1 mV to be possible to test if the acquisition module was working. Figure 3.13 shows the circuit to simulate the probe.

The proposed probe is an absolute probe that has a coil near the surface to inspect the material and another one that is away from the material. The second coil is called compensation coil, and it generates a signal near to the measurement coil when the probe is in the air. The signal obtained will be the difference between the two coil voltages. The probe is a inductive circuit as is shown in Figure 3.14.

The coils that were tested in this project have 2 mm, 3 mm and 4 mm of diameter. All of them have a encircling of 100 turns. To choose the best pair of coils a program in Matlab and a HIOKI 3522-50 LCR HITESTER where used to compare the impedance of each coil. The HIOKI was controlled by General Purpose Interface Bus (GPIB) to sweep a range of frequencies from 100 Hz to 100 kHz. The characteristics of the pair that were chosen are listed in Table 3.2.

**Table 3.2:** Pair of coils characteristics used in the probe at 100 kHz. Diameter is 3 mm and the encircling turns are 100.

<table>
<thead>
<tr>
<th></th>
<th>$Z$ ($\Omega$)</th>
<th>$\phi$ (°)</th>
<th>$RS$ ($\Omega$)</th>
<th>$LS$ ($\mu H$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil 1</td>
<td>28.552</td>
<td>86.9</td>
<td>18.46</td>
<td>45.4</td>
</tr>
<tr>
<td>Coil 2</td>
<td>25.291</td>
<td>86.87</td>
<td>18.29</td>
<td>40.2</td>
</tr>
</tbody>
</table>

Figure 3.15 shows the final probe design.
3.5 Acquisition

The acquisition channel consists on the VGA (AD8338) and on the ADC (AD7915). The VGA differential input suits the bridge measurement setup. However, as the VGA input impedance is relatively low (500 Ω), two amplifiers as buffers are used (AD8028). Notice that the sensor signals have a considerable DC component set by the driver (an option made to simplify power management on the whole system that uses a single unipolar DC power source), so it is possible to use buffers without adding any additional DC components. The VGA gain is controlled by a programmable DAC (AD5660). After the VGA, the ADC is fully differential input with 16-bit resolution and is capable of up to 1MS/s.
3.6 3D Design

In this project a Computer Aided Design (CAD) program to develop a case for the PCB and a Prusa i3 Hephestos to print it were used. One concern of the design was to be small but solid, especially in the socket area because it could be too thin and break. The other concern was not allowing the movement of the PCB inside of the case. The probe side has a hole to insert the ferrite coil and, on the opposite side, a hole with a mini-USB size to perform the interface with the host device was included. Some of the printed cases are shown in Figure 3.16 and the final design performed in CAD program SW is shown in Figure 3.17.
Figure 3.16: Final case for the system.

Figure 3.17: Final design for the system case.
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Firmware

In this project to control the peripherals by SPI and to do the signal processing C code in MPLAB-X Integrated Development Environment (IDE) was developed. MPLAB is a proprietary freeware IDE for the development of embedded applications on Peripheral Interface Controller (PIC) and dsPIC microcontrollers and is developed by Microchip Technology.

To communicate between the host device and the dsPIC a datapacket structure was defined as in Table 4.1.

<table>
<thead>
<tr>
<th>Command Type</th>
<th>Size</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 byte</td>
<td>4 bytes</td>
<td>Variable size</td>
</tr>
</tbody>
</table>

Table 4.1: Datapacket structure to send instructions to dsPIC.

Command type is a character that defines the operation between the two devices. From the host device to the dsPIC instructions to program the peripherals or to begin the system processing are sent. To program the peripherals, signal frequency and phase, timer prescale, to define sampling frequency, and number of acquisitions are sent.

First of all the program sends the input parameters to generate the signal. The parameters are the signal frequency and phase, timer prescale, to define sampling frequency, and number of acquisitions.

4.1 SPI

The microcontroller that is used in this project has an internal Serial Peripheral Interface (SPI) that will control all the peripherals that need adjustments. To control every module as desired, firmware to control them was developed.
4.1.1 DDS and Potentiometer

As it was specified in Chapter 3 the driver module generates a sine wave. To define the frequency and amplitude of the sine wave, a DDS and a digital potentiometer are used. With a 60 MHz clock rate, a resolution of 0.22 Hz can be achieved. The word that defines the frequency is obtained as

\[ F_{\text{code}} = F_{\text{req}} \times \frac{2^{28}}{F_{\text{MCLK}}} \]  \hspace{1cm} (4.1)

where \( F_{\text{req}} \) is the value of the frequency, 28 is because frequency registers are 28 bits wide and \( F_{\text{MCLK}} \) is 60 MHz. Two consecutive writes to the same address must be performed. The first write contains the 14 LSBs, and the second write contains the 14 MSBs [38].

With this DDS it is possible to control the phase shift with

\[ \text{Phase}_{\text{code}} = \text{Phase} \times \frac{2^{12}}{360} \]  \hspace{1cm} (4.2)

where \( \text{Phase} \) is the value of the phase in degrees, 12 are the phase registers width and 360 is the degrees of a full circle.

To control the amplitude of the sine wave, the AD5160, a 256-position digitally controlled variable resistor device is used [39]. To assure that there is no saturation in the driver circuit the AD5160 is used. The word code to send to the AD5160 is defined with

\[ \text{Potentiometer}_{\text{code}} = R_x \times \frac{256}{10 \times 10^5} \]  \hspace{1cm} (4.3)

where \( R_x \) is the value of the desired resistance of the digital potentiometer. 256 is because this digital potentiometer has an 8 bit register and 100 k\( \Omega \) is the maximum value.

4.1.2 DAC and Gain Amplifier

The gain amplifier has a differential input and the nominal gain range spans from 0 dB to 80 dB for control voltages between 0.1 V to 1.1 V [40]. To control the AD8338 gain to assure that there is no saturation in acquisition circuit the AD5660, 16 bit register wide nano Digital-to-Analog Converter (DAC), is used. DAC is controlled with

\[ V_{\text{out}} = 2 \times V_{\text{REFOUT}} \times \frac{D}{2^N} \]  \hspace{1cm} (4.4)

where \( V_{\text{OUT}} \) is the output that is needed \( V_{\text{REFOUT}} \) is 1.25 V, \( D \) is the decimal equivalent of the binary code that is loaded to the DAC register and \( N \) is the number of bits, 16 [41].
4.1.3 ADC

To acquire the signal after the effect of the metal target and the signal conditioning, the AD7915 is used. When a command to start the acquisition is sent, a dsPIC timer is set to define the ADC sampling frequency. The timer will set the reading of the dsPIC from the ADC through SPI, this has to be a quick process to have a high sampling frequency. A buffer stores the ADC values to use in the signal processing. A 10 kHz signal sampled at 300 kHz is shown in Figure 4.1.

![Figure 4.1: ADC acquisition made with a frequency sampling of 300 kHz and a signal frequency of 10 kHz.](image)

4.2 Signal Processing

After acquiring the amplified probe output signal, signal processing enables the estimation of the desired material parameters. The real and imaginary components of the acquired signal are obtained by demodulating the acquired signal with the internal DDS signals. The internal SW DDS computes a sine and cosine with the same frequency of the sine produced with the external DDS (AD9834) taking into account that the external DDS operates at 60 MHz and the internal SW DDSs must operate at the sampling frequency at which the ADC operates. The necessary synchronization is controlled by setting a deterministic delay between the external DDS start-up and the start of the first ADC conversion. To get the average value of the multiplied signals, the result of the multiplication passes through lowpass IIR filters. The outputs of the multipliers and the filters are

\[
X_{Re} = \frac{V_{\text{probe}}V_{\text{ref}}}{2} \cos(\Theta_{\text{probe}} - \Theta_{\text{ref}}) \quad (4.5)
\]
\[ X_{lm} = \frac{V_{\text{probe}} V_{\text{ref}}}{2} \sin(\Theta_{\text{probe}} - \Theta_{\text{ref}}) \] (4.6)

where \( V_{\text{probe}} \) and \( \Theta_{\text{probe}} \) are the amplitude and phase of the acquired signal (i.e., the amplified probe output). \( V_{\text{ref}} \) and \( \Theta_{\text{ref}} \) are the known amplitude and phase of the internal SW DDS. From these two components, the magnitude and phase can be obtained.

### 4.2.1 Software DDS

The HW DDS [38] has 28 bits of phase accumulator but the Numerically Controlled Oscillator (NCO) truncates that value by 12 bits. Due to the 12 bits of the NCO the Look-Up-Table (LUT) has 4096 entries. Each index has a size of 10 bits that are defined by the DAC that has 10 bits of resolution. Figure 4.2 shows the HW DDS block diagram.

![Figure 4.2: Hardware DDS (AD9834) block diagram.](image)

To generate a sine and cosine to heterodyning with the acquired signal, a SW DDS was implemented. The SW DDS has a LUT with 4096 entries but each entry has 12 bits size. The number of entries is equal to the HW DDS to have a good match between the two DDS. The 12 bits resolution of each entry is to have a signal better define at the output because the HW DDS has a filter at the output but the software do not.

The LUT is programmed before the program starts as

\[ LUT(k) = \sin \left( \frac{2\pi k}{4096} \right) \] (4.7)
where \( k \) is the index of the table. The LUT that is built is shown in Figure 4.3.

![Programmed LUT built in SW with 4096 positions.](image)

**Figure 4.3**: Programmed LUT built in SW with 4096 positions.

With the programmed LUT equivalent with the external DDS and knowing the timer and frequency configurations, the SW generates a sine and a cosine. This step has to be similar to the external DDS with the same number of bits of the phase accumulator. With this configuration, it is possible to index the LUT and generate a sine and a cosine. As the NCO has 12 bits, this gives 4096 positions to index in the LUT. To perform a sine, the step that is made in each iteration in LUT is calculated and a buffer with the calculated values is filled. The step accumulator is

\[
\text{accumulator step} = \frac{2^{28}}{f_s \times f}
\]

where \( f_s \) is the sampling frequency and \( f \) the desire sine frequency. In every iteration the accumulator value is added to the previous one. To perform a cosine a phase difference of 90° is given by adding 1024 positions on the sine index. The sine and cosine are stored in buffers to use in the signal processing. The sine and cosine that are generated in the software DDS are shown in Figure 4.4.

### 4.2.2 Multiplication

The first step to achieve the real and imaginary component of the acquired signal is the multiplication with a sine and a cosine. When two signals with the same frequency are multiplied, the output signal has two times that frequency.

All the signals are in buffers and then the sine and the cosine are multiplied by the acquired signal.
Figure 4.4: Sine and cosine with a frequency of 10 kHz with a sampling frequency of 300 kHz and 400 samples generated in SW DDS.

The result of the multiplication between the acquired signal shown in Figure 4.1 and the sine and cosine of Figure 4.4 are shown in Figure 4.5.

4.2.3 Low Pass Filter

To obtain the average value of the real and imaginary part of the ADC signal, a fourth order Lowpass Butterworth digital IIR filter with two biquad sections is used. This filter was designed using Filter Design and Analysis Tool (FDATool) with a cut-off frequency of 0.05 of the sampling frequency. The filter structure is shown in Figure 4.8.

The equations of the first section of this filter are

\[ d(n) = s_1 \times x(n) - a_1 \times d(n-1) - a_2 \times d(n-2) \]  \hspace{1cm} (4.9)

and

\[ e(n) = d(n) + 2 \times d(n-1) + d(n-2) \]  \hspace{1cm} (4.10)

\( e(n) \) is the entry of the second stage of this filter and his equations are

\[ f(n) = s_2 \times e(n) - a_3 \times f(n-1) - a_4 \times f(n-2) \]  \hspace{1cm} (4.11)
The Lowpass Butterworth digital IIR filter coefficients are shown in Table 4.2.

Table 4.2: 4th order lowpass filter coefficients.

<table>
<thead>
<tr>
<th>a1</th>
<th>a2</th>
<th>a3</th>
<th>a4</th>
<th>s1</th>
<th>s1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.44×10^{-4}</td>
<td>-1.98</td>
<td>0.976</td>
<td>2.40×10^{-4}</td>
<td>-1.94</td>
<td>0.944</td>
</tr>
</tbody>
</table>

The filter frequency response is shown in Figure 4.7.

When the signals in Figure 4.5 passes trough the lowpass filters, only the average value of each one is at the output of the filter. The filter output is shown in Figure 4.8.

### 4.2.4 Module and Phase

In this work there are two different methods to achieve a conductivity and liftoff measure, by the real and imaginary component of the signal, or the module and phase. With the real and imaginary component it is possible to achieve the module with

\[ |Z| = \sqrt{R^2 + I^2} \]  (4.13)
and phase with

\[ \phi = \arctan \left( \frac{\text{Im}}{\text{Re}} \right) \]

(4.14)

where Re and Im are the real and imaginary components of the signal respectively. These calculations are done in the host program.

### 4.2.5 Conductivity and Lift-Off measure

There are relations [42] that define the real and imaginary components of the coil impedance for a given material conductivity, probe configuration and lift off. However, they are not easily inverted (see Appendix B). The theoretical solution for a frequency of 63.3 kHz with a 1 mm radius and length coil is shown in Figure 4.9. Each curve represents a different metal with different lift-offs. Table 4.3 has the electrical conductivity and magnetic permeability of each sample.

**Table 4.3:** Electrical conductivity (\( \sigma \)) and relative magnetic permeability (\( \mu_R \)) of each metal used in the simulation.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma ) (MS/m)</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>( \sigma ) (%IACS)</td>
<td>1.67</td>
<td>1.67</td>
<td>16.7</td>
<td>16.7</td>
<td>33.3</td>
<td>66.7</td>
<td>100</td>
</tr>
<tr>
<td>( \mu_R )</td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

In theory it is possible to achieve the real and imaginary part from the lift-off and the conductivity of a material [42]. Since the system acquires the real and imaginary part of the signal, it should be possible to estimate the conductivity and lift-off using this relation.
Figure 4.7: 4th order lowpass butterworth digital IIR frequency response with a sampling frequency of 100 kHz and a cut-off frequency of 500 Hz.

Figure 4.8: Output of the lowpass filters. From the input signals in Figure 4.5 only remains the average value.

A program that generates the results of Figure 4.9 solution for different conductivities and lift-offs was made and the result is shown in Figure 4.10.
Figure 4.9: Theoretical predictions of variations of $\delta(w_L)/w_{L0}$ and $\delta R/w_{L0}$ from balance position at 'infinite' lift-off plotted versus height of lift-off in millimeters for a surface-scanning coil. The coil, radius 1 mm and length 1 mm, is excited at a frequency of 63.3 kHz for detect-free metal samples with values of electrical conductivity $\sigma$ and relative magnetic permeability $\mu_R$. Each letter represents a metal with different conductivity and permeability.

Figure 4.10: Simulation of the theoretical predictions of variations of $\delta(\omega)L/\omega L_0$ and $\delta R/\omega L_0$.

4.2.6 Send Packets

To send the data to the Host program segmented packets as defined in Table 4.4 are sent. This segmentation is required/used when sending large amounts of data.

The packet has an identification field that allows to know what kind of data is sent. In this program
eight different packets are sent, but only the packet with the conductivity and lift-off measure are really needed. The other packets, that have the data of the sine, cosine, ADC, the result of the multiplication between the ADC with the sine and cosine, and the output of the real and imaginary part of the signal after the filter, were used to debug the project. The packet contains a size field that specifies the amount of data in the packet. For data larger than the maximum packet size, the data is split into different packets and an identifier is used to specify the data order.

4.3 Interface

To debug the connection between the dsPIC and the host of the application, a Matlab and a labVIEW program is used, but the final interface is in labVIEW. The idea of the host interface is to control the signal characteristic and to display the measured conductivity and a lift-off. Figure 4.11 shows the Graphical User Interface (GUI) of this project in labVIEW.
4.4 Android Application

Due to the physical size of this project and considering that this should be much portable as possible, an interface in Android was developed. With this add on, it is possible to use this probe without a PC using only an Android Smartphone. The system is powered by the mobile phone USB connection, so, an extra battery is not needed.

Figure 4.12 shows the final interface of this project in Android.

![Figure 4.12: Final design for the system case.](image)

Figure 4.12: Final design for the system case.
Results
Results

When a target material approaches the probe, it produces a voltage output that depends on the material conductivity, so, it is possible to identify different materials. Figure 5.1 shows the histogram of the normalized real and imaginary components of the processed signal for three different materials.

![Histogram of the real (a) and imaginary (b) outputs varying the tested materials with 1000 repetitions, without lift-off and a frequency of 60 kHz.](image)

**Figure 5.1:** Histogram of the real (a) and imaginary (b) outputs varying the tested materials with 1000 repetitions, without lift-off and a frequency of 60 kHz.

In Table 5.1, the mean and standard deviation values of the real, imaginary, magnitude and phase
components obtained with 1000 repetitions are shown.

Table 5.1: Mean and standard deviation values of the real, imaginary, magnitude and phase components obtained with 1000 repetitions.

<table>
<thead>
<tr>
<th>Material</th>
<th>Copper</th>
<th>Aluminium</th>
<th>Aluminium Alloy 6082</th>
<th>Aluminium Alloy 5083</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{X}_{Re}$</td>
<td>-2.54</td>
<td>-2.47</td>
<td>-2.39</td>
<td>-2.24</td>
<td>-1.78</td>
</tr>
<tr>
<td>$\sigma(\bar{X}_{Re})$ [%]</td>
<td>0.573</td>
<td>0.567</td>
<td>0.582</td>
<td>0.507</td>
<td>0.793</td>
</tr>
<tr>
<td>$\bar{X}_{Im}$</td>
<td>1.12</td>
<td>1.18</td>
<td>1.20</td>
<td>1.27</td>
<td>1.42</td>
</tr>
<tr>
<td>$\sigma(\bar{X}_{Im})$ [%]</td>
<td>0.673</td>
<td>0.598</td>
<td>0.625</td>
<td>0.692</td>
<td>0.503</td>
</tr>
<tr>
<td>$</td>
<td>\bar{X}</td>
<td>$</td>
<td>1.66</td>
<td>1.66</td>
<td>1.64</td>
</tr>
<tr>
<td>$\sigma(</td>
<td>\bar{X}</td>
<td>)$ [%]</td>
<td>0.411</td>
<td>0.385</td>
<td>0.383</td>
</tr>
<tr>
<td>arg($\bar{X}$) [°]</td>
<td>-87.8</td>
<td>-85.9</td>
<td>-84.2</td>
<td>-81.0</td>
<td>-71.2</td>
</tr>
<tr>
<td>$\sigma(\text{arg}(\bar{X}))$ [°]</td>
<td>0.256</td>
<td>0.247</td>
<td>0.264</td>
<td>0.266</td>
<td>0.278</td>
</tr>
</tbody>
</table>

The tested materials characteristics [42] are shown in Table 5.2.

Table 5.2: Conductivity of the materials tested.

<table>
<thead>
<tr>
<th>Material</th>
<th>Copper</th>
<th>Aluminium</th>
<th>Aluminium Alloy 6082</th>
<th>Aluminium Alloy 5083</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(%\text{IACS})$</td>
<td>100.83</td>
<td>56.4</td>
<td>43.29</td>
<td>28.7</td>
<td>8.25</td>
</tr>
</tbody>
</table>

The output components change with the distance between the probe and the target material. Figure 5.2 shows the different output for five materials where the distance between the probe and the target is changing. It is shown, in Figure 5.2, that different materials at different lift-off values from the probe exhibit a specific phase and module value, so, it is possible to distinguish between different materials and different lift-off values. Figure 5.3 shows the same results but with the real and imaginary components of the signal.

In theory it is possible to achieve the real and imaginary part from the lift-off and the conductivity of a material [42]. Since the system acquires the real and imaginary part of the signal, it should be possible to estimate the conductivity and lift-off using this relation.

A fit with with the measured values to obtain an estimation of the conductivity and lift-off based on those measurements was done with cftool, a Matlab tool that fit curves and surfaces to data and view
Figure 5.2: Normalized phase and magnitude output with different distances between the material under test and the probe. \( Z_0 \) is the system measurement when the probe is far from the test sample.

Figure 5.3: Normalized real and imaginary outputs with different distances between the material under test and the probe. \( Z_0 \) is the system measurement when the probe is far from the test sample.
plots.

To estimate the conductivity and lift-off of non-magnetic samples, polynomial functions are used. A third degree polynomial with a coefficient of determination, \( r^2 \), of 0.995 to estimate samples conductivity is

\[
\sigma = p_{00} + p_{10} \text{Re}(Z) + p_{01} \text{Im}(Z) + p_{20} \text{Re}(Z)^2 + p_{11} \text{Re}(Z) \text{Im}(Z) + p_{02} \text{Im}(Z)^2 \\
+ p_{30} \text{Re}(Z)^3 + p_{21} \text{Re}(Z)^2 \text{Im}(Z) + p_{12} \text{Re}(Z) \text{Im}(Z)^2 + p_{03} \text{Im}(Z)^3
\] (5.1)

where coefficient values of the conductivity fit are listed in Table 5.3.

### Table 5.3: Coefficient values of the conductivity fit with a \( r^2 \) of 0.982.

<table>
<thead>
<tr>
<th>( p_{00} )</th>
<th>( p_{10} )</th>
<th>( p_{01} )</th>
<th>( p_{20} )</th>
<th>( p_{11} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-5.39 \times 10^2)</td>
<td>(-1.10 \times 10^4)</td>
<td>(-2.51 \times 10^2)</td>
<td>(-8.25 \times 10^2)</td>
<td>(-3.33 \times 10^2)</td>
</tr>
<tr>
<td>( p_{02} )</td>
<td>( p_{30} )</td>
<td>( p_{21} )</td>
<td>( p_{12} )</td>
<td>( p_{03} )</td>
</tr>
<tr>
<td>(-6.90)</td>
<td>(-5.58 \times 10^3)</td>
<td>(-3.48 \times 10^2)</td>
<td>(-9.28)</td>
<td>(-9.42 \times 10^{-2})</td>
</tr>
</tbody>
</table>

To estimate the distance between the probe and the material another fit is used. The third degree polynomial with a \( r^2 \) of 0.995 to estimate the distance between the coil and the target material is

\[
d = p_{00} + p_{10} \text{Re}(Z) + p_{01} \text{Im}(Z) + p_{20} \text{Re}(Z)^2 + p_{11} \text{Re}(Z) \text{Im}(Z) + p_{02} \text{Im}(Z)^2 \\
+ p_{30} \text{Re}(Z)^3 + p_{21} \text{Re}(Z)^2 \text{Im}(Z) + p_{12} \text{Re}(Z) \text{Im}(Z)^2 + p_{03} \text{Im}(Z)^3
\] (5.2)

where coefficient values of the conductivity fit are listed in Table 5.4.

### Table 5.4: Coefficient values of the lift-off fit with a \( r^2 \) of 0.995.

<table>
<thead>
<tr>
<th>( p_{00} )</th>
<th>( p_{10} )</th>
<th>( p_{01} )</th>
<th>( p_{20} )</th>
<th>( p_{11} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.46 \times 10^1)</td>
<td>(-1.38 \times 10^1)</td>
<td>(2.07 \times 10^{-1})</td>
<td>(5.08)</td>
<td>(-6.18 \times 10^{-2})</td>
</tr>
<tr>
<td>( p_{02} )</td>
<td>( p_{30} )</td>
<td>( p_{21} )</td>
<td>( p_{12} )</td>
<td>( p_{03} )</td>
</tr>
<tr>
<td>(2.18 \times 10^{-3})</td>
<td>(2)</td>
<td>(1.80 \times 10^{-1})</td>
<td>(3.39 \times 10^{-3})</td>
<td>(3.31 \times 10^{-5})</td>
</tr>
</tbody>
</table>

With this fitting coefficients a maximum absolute error of 0.04 mm for lift-off and 1.5% IACS for electrical conductivity were achieved. Figure 5.4 shows the lift-off absolute error and Figure 5.5 shows the electrical conductivity absolute error for five different conductivity samples with different lift-offs. In
Figure 5.4 the highest lift-off absolute error was obtained in a sample with 42% IACS and a lift-off of 0.3 mm.

In Figure 5.5 the highest electrical conductivity absolute error was obtained in a sample with 28% IACS and a lift-off of 0.3 mm.
Figure 5.5: Conductivity absolute error.
6 Conclusions

Contents

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Conclusions

Eddy currents based NDT systems are one of the most used today to inspect metallic parts in searching for flaws and other material discontinuities. This is because it is a quick, simple, and reliable inspection technique to detect surface and near-surface defects in conductive material. It can be used also to measure material electrical conductivity and non-conductive coating thickness. Currently, this technique is quite evolved and there are some portable options in the market which are ideal for technicians inspecting installed parts.

In this project a special importance on the system size is given. The system is as small as possible to be portable. Its pen-like casing dimensions which can be easily handled by technician. The final system size is 150×20×15 mm with the 3D printed case included. The host interface controls and presents the estimated conductivity and lift-off data in labVIEW and in an Android Smartphone.

The system specifications are listed in Table 6.1 and the final system working with an Android Smartphone in 6.1.

<table>
<thead>
<tr>
<th>Conductivity Range</th>
<th>Conductivity Accuracy</th>
<th>Lift-off Range</th>
<th>Lift-off Accuracy</th>
<th>Weight</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-100% IACS</td>
<td>1.5% IACS</td>
<td>0 - 0.6 mm</td>
<td>0.04 mm</td>
<td>21 g</td>
<td>150×20×15mm</td>
</tr>
</tbody>
</table>

6.1 Future work

The presented results validate the proposed measurement system but some improvements in hardware and software are still possible. As such, some of the proposed future work is:

- Include the mini-USB interface in the PCB handler to reduce the system size;

- The system can perform a signal frequency between 1 kHz to 10 MHz, but the conductive and lift-off measure is only calibrated for 60 kHz. An algorithm prepared to frequency variations should be implemented.
Figure 6.1: Final system working with a smartphone.
Bibliography


Appendix - Hardware Circuit
Figure A.1: Final circuit of the hardware.
Appendix - Real and imaginary components of the coil impedance
Real and imaginary components of the coil impedance

The parameters affecting the values of the normalized components of impedance of the coil are the normalized frequency \( f_0 \) and normalized lift-off \( k_0 \), as defined below.

\[
f_0 = \beta^2 = \omega \mu \sigma r_0^2
\] (B.1)

\[
k = \frac{h}{r_0}
\] (B.2)

where \( \omega \) is the angular frequency, \( \mu \) is the absolute magnetic permeability, \( \sigma \) is the electrical conductivity, \( r_0 \) is the effective radius of the coil and \( h \) the absolute lift-off.

The total potential difference across the coil of length \( l_0 \) is

\[
V = \int_{l=h}^{m} \int_{z=h}^{m} dV = j\omega \pi \mu_0 n_0^2 \int_{l=h}^{m} \int_{z=h}^{m} J^2(\alpha r_0)(2l_0/\alpha) - (2/\alpha)^2[1 - e^{-\alpha l_0}] + [(\mu_2 \alpha - \alpha_1)]e^{-2\alpha h}[1 - e^{-\alpha l_0}]^2 d\alpha dz dl
\] (B.3)

where \( n_0 \) is the number of turns within a length \( dz \), \( \mu_0 \) is the magnetic permeability of free space and \( \alpha_1^2 = \alpha^2 + j\omega \mu_1 \sigma \).

For convenience, \( r_0 \alpha = X \) and \( r_0 \alpha_1 = X_1 \) so that

\[
X_1^2 - X^2 = j\beta^2
\] (B.4)

Normalizing the length \( k_0 = l_0/r_0 \) and substituting \( I = i_0 n_0 l_0 \)

\[
V = j\omega KI(2k_0 I_1 - 2I_2 + 2I_3 + I_4)
\] (B.5)
where

\[ K = \frac{\pi \mu_0 n_0}{l_0} \]  

(B.6)

and

\[ I_1 = \int_0^\infty \frac{J_1^2(X)}{X} dX \]  

(B.7)

\[ I_2 = \int_0^\infty \frac{|J_1(X)|^2}{X} dX \]  

(B.8)

\[ I_3 = \int_0^\infty \frac{[J_1(X)/X]^2 e^{-k_0 X}}{X} dX \]  

(B.9)

\[ I_4 = \int_0^\infty \frac{[J_1(X)/X]^2 e^{-2kX} [1 - e^{-k_0 X}]^2 f(X)}{X} dX \]  

(B.10)

where

\[ f(X) = \left( \mu_r X - X_1 \right) / \left( \mu R X + X_1 \right) \]  

(B.11)

and \( J_1(X) \) is a first-order Bessel function.

\[ Z \approx \frac{V}{I} = j \omega K (2k_0 I_1 - 2I_2 + 2I_3 + I_4) \]  

(B.12)

For infinite lift-off, \( k \) is infinite and \( I_4 \) vanishes

\[ Z_0 = j \omega L_0 = j \omega K (2k_0 I_1 - 2I_2 + 2I_3) \]  

(B.13)

\[ \frac{Z}{Z_0} = \frac{R + j \omega L}{j \omega L_0} \]  

(B.14)

\[ \frac{\omega L}{\omega L_0} - \frac{jR}{\omega L_0} = 1 + \frac{I_4}{(2k_0 I_1 - 2I_2 + 2I_3)} \]  

(B.15)

where \( I_1 \) and \( I_1 \) are standard integrals given by \( I_1 = 1/2 \) and \( I_2 = 4/3 \pi \) but the evaluations \( I_3 \) and \( I_4 \), hence of \( \omega L/\omega L_0 \) and \( R/\omega L_0 \), have to be performed numerically using a computer. The expression \( B.15 \) is separated into real and imaginary parts

\[ \frac{R}{\omega L_0} = [(\mu_r X)^2 - G]/N \]  

(B.16)

\[ \frac{\omega L}{\omega L_0} = \mu_r X [2(G - X^2)]^{1/2}/N \]  

(B.17)
where

\[ G = (X^4 + \beta^4)^{1/2} \]  \hspace{1cm} (B.18)

and

\[ N = (\mu_r X)^2 + G + \mu_r X [2(G + X^2)]^{1/2} \]  \hspace{1cm} (B.19)