Eddy Current Testing Instrument for Online Industrial Quality Control

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
Abstract

Non-destructive testing (NDT) is one of the most used technologies to control the quality and properties of materials in the industry, without causing damage or changing the properties of the test piece. Usually these technologies are applied to validate materials physical properties. Non-destructive testing is also used to check the presence of discontinuities in the test piece, either buried or superficial. Cost reduction, operational readiness and final quality are some of the most important factors that lead companies to employ instruments capable of conducting such inspections.

Eddy current testing (ECT) is a non-destructive electromagnetic testing technique. The principle is to induce an electrical current in a conductive material and analyze its response. This allows the detection of both superficial and depth flaws as well as retrieve different information about conductivity and magnetic permeability.

This work presents the development of a modular instrument that is able to perform online eddy current testing, implement signal detection and classification, operate autonomous and provide monitoring information while being accessed remotely through Ethernet communication. The developed system incorporate eddy current testing front-end modules to analyze the eddy currents response, a processing core to process the data from the front-end ECT modules and allow the remote access functionalities.

**Keywords:** Non-Destructive Testing, Eddy Current Testing, Quality Control, Online Inspection, Embedded System.
Sumário

Ensaios não destrutivos são técnicas utilizadas para controlar a qualidade, assim como as propriedades de um material, nomeadamente na indústria, sem causar danos ou alterar as propriedades da peça testada. Estas tecnologias são utilizadas para medir propriedades físicas assim como verificar a presença de descontinuidades na peça testada, tanto superficiais como em profundidade. Redução de custos, prontidão operacional e qualidade final são alguns dos mais importantes fatores que levam empresas a usar instrumentos capazes de realizar este tipo de inspeções.

O teste por correntes induzidas é uma das técnicas de teste eletromagnéticos. Esta baseia-se na indução de uma corrente elétrica num material condutor e observar resposta da bobine. Assim é possível verificar falhas, tanto superficiais como em profundidade, assim como obter informações sobre a condutividade e permeabilidade do material.

Este trabalho apresenta o desenvolvimento de um instrumento modular capaz de efetuar testes de correntes induzidas em linha de produção, implementar deteção e classificação de sinais, operar autonomamente e fornecer informações de monitorização enquanto acedido remotamente por comunicação Ethernet. O sistema desenvolvido integra módulos electrónicos de teste por correntes induzidas para analisar a resposta destas correntes, um núcleo de processamento para processar a informação proveniente dos módulos de correntes induzidas e que permite as funcionalidades de acesso remoto.

Palavras-Chave: Ensaios Não Destrutivos, Ensaio por Correntes Induzidas, Controlo de Qualidade, Inspeção em Linha de Produção, Sistema Embebido.
# Contents

## Chapter 1  Introduction........................................................................................................... 15
  1.1 Purpose and motivation................................................................................................. 15
  1.2 Goals and challenges................................................................................................. 17
  1.3 Document organization.............................................................................................. 17

## Chapter 2  State of the art ................................................................................................... 18
  2.1 Non-Destructive Techniques....................................................................................... 18
  2.2 Eddy Current ............................................................................................................. 18
    2.2.1 Eddy Current Inspection Principle........................................................................ 19
    2.2.2 Eddy Current Transformer Model......................................................................... 20
    2.2.3 Complex Impedance Plane Analysis..................................................................... 21
  2.3 Electrical Conductivity of the Test Piece, Magnetic Permeability, Magnetization of Ferromagnetic Materials.............................................................. 22
  2.4 Main Variables of Eddy Current Testing, Lift-Off and Fill Factor, Edge Effect, Signal-to-Noise Ratio......................................................................................... 24
  2.5 Frequency and Skin Effect ......................................................................................... 25
    2.5.1 Multi-Frequency Techniques................................................................................ 27
    2.5.2 Pulsed Eddy Current Testing................................................................................. 27
  2.6 Sensors ....................................................................................................................... 29
  2.7 Instrumentation .......................................................................................................... 32

## Chapter 3  System Architecture ......................................................................................... 37
  3.1 System Hardware Architecture .................................................................................. 37
    3.1.1 Processing Core .................................................................................................... 38
    3.1.2 MSP430 ECT Front-end Modules....................................................................... 39
    3.1.3 Power Management............................................................................................. 40
    3.1.4 Printed Circuit Board Design .............................................................................. 45
  3.2 Software Architecture ............................................................................................... 48
    3.2.1 Firmware ............................................................................................................ 48
    3.2.2 Software ............................................................................................................. 53

## Chapter 4  Results and Conclusions .................................................................................. 56
  4.1 Results ....................................................................................................................... 56
  4.2 Conclusions ................................................................................................................ 57
List of Tables

Table 1 - Penetration depth in copper using different frequencies (adapted from [19])........ 26
Table 2 – System connection Beaglebone P8 Header.............................................................. 39
Table 3 - System connection Beaglebone P9 Header. ............................................................. 39
Table 4 – MSP430 FR2355 clock and maximum output frequency ...................................... 49
Table 5 - Commands structure.............................................................................................. 53

List of Figures

Figure 1 - Eddy current on the test piece (adapted from [6]).................................................. 19
Figure 2 - Eddy current transformer model (adapted from [9]).............................................. 20
Figure 3 - Complex Impedance plane (adapted from [10])..................................................... 22
Figure 4 - Curve of magnetization (adapted from [13]).......................................................... 23
Figure 5 - Electromagnetic field penetration inside pure aluminum at frequencies of 200 Hz and
10 KHz (adapted from [18])............................................................................................... 26
Figure 6 - Twenty-five harmonic square wave frequency response (adapted from [22])........... 28
Figure 7 - Typical time domain response in pulsed eddy current testing (adapted from [20]). 29
Figure 8 - Absolute mode probe response (adapted from [17]).......................................... 30
Figure 9 - Differential mode probe response (adapted from [17])........................................ 30
Figure 10 - Output tension according to the applied magnetic field (adapted from [25])......... 31
Figure 11 - Hall voltage creation by a magnetic field (adapted from [25])........................... 31
Figure 12 – SQUID schematic (adapted from[28])............................................................ 32
Figure 13 – Functional block diagram of an eddy current instrument (adapted from [29])...... 33
Figure 14 - System Architecture............................................................................................ 38
Figure 15 - ECT Front-End Module prototype........................................................................ 40
Figure 16 - Step-Down Converter Schematic for +13.5 V .................................................. 40
Figure 17 - TPSS430 Buck Topology (adapted from [30]).................................................... 41
Figure 18 - Step-Down Converter Schematic for -13.5 V ...................................................... 42
Figure 19 - TPSS430 Inverting Buck-Boost Topology (adapted from [30])......................... 42
Figure 20 - LM3940 Schematic used to convert +5 V into +3.3 V ........................................ 43
Figure 21 - LM317 Schematic used to convert +13.5 V into +12 V ........................................ 44
Figure 22 - LM337-N Schematic used to convert -13.5 V into -12 V...................................... 44
Figure 23 - Top PCB Layout. ............................................................................................... 46
Figure 24 - Prototype PCB (Top View). ................................................................................ 47
Figure 25 – Prototype PCB (Bottom View). .......................................................................... 47
Figure 26 – Timer_B set to Up Mode (adapted from [31])...................................................... 48
Figure 27 - Timer in Up Mode output examples (adapted from [31])..................................... 49
Figure 28 – TbxCCRn registers utilization to obtain a quadrature timer.................................. 49
Figure 29 – In-phase and quadrature reference signals........................................................... 50
Figure 30 - SAC Components (adapted from [31])............................................................... 51
Figure 31 - MSP430 SAC's configuration. ............................................................................ 51
Figure 32 - SAC calibration function................................................................................... 52
Figure 33 - Commands structure (adapted from [32])................................................................. 53
Figure 34 - Developed User Interface. ...................................................................................... 54
Figure 35 - Handheld device with the ECT probes ..................................................................... 56
Figure 36 - Real part signal........................................................................................................... 57
Figure 37 - Imaginary part signal................................................................................................. 57
## List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
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<tr>
<td>DAC</td>
<td>Digital-to-Analog Converter</td>
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<tr>
<td>ECT</td>
<td>Eddy Current Testing</td>
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<tr>
<td>ESR</td>
<td>Equivalent Series Resistance</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>HF</td>
<td>High-frequency</td>
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<tr>
<td>IO</td>
<td>Input Output</td>
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<tr>
<td>LDO</td>
<td>Low-Dropout Regulators</td>
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<tr>
<td>LF</td>
<td>Low-Frequency</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
</tr>
<tr>
<td>PEC</td>
<td>Pulsed Eddy Current</td>
</tr>
<tr>
<td>PGAs</td>
<td>Programmable Gain Amplifiers</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
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<tr>
<td>SAC</td>
<td>Smart Analog Combos</td>
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<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<tr>
<td>SPI</td>
<td>Serial Peripheral Interface</td>
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<tr>
<td>SQUIDs</td>
<td>Superconducting Quantum Interference Devices</td>
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<tr>
<td>UI</td>
<td>User Interface</td>
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Chapter 1

Introduction

1.1 Purpose and motivation

Non-Destructive testing (NDT) comprises several analysis techniques both used in science and industry. Those allow the evaluation of the properties of a material, object or system, without causing any damage nor permanently change the tested component. Due to this characteristic, these techniques have been adopted by many manufacturers, proving to be a method to save money and time, both in research, maintenance and manufacturing. Some of the most used NDT techniques are visual test, ultrasonic, liquid penetration and electromagnetic.

Visual testing is the oldest and most common technique. Usually is the first step in the examination process, to inspect a variety of product forms. This technique relies on the human vision aided by mechanical enhancements to sensory inputs such as magnifiers, endoscope and alike. The inspection may be done by looking, smelling, listening, feeling, shaking and twisting the object [1].

Ultrasonic testing is based on the propagation of ultrasonic waves (from 50 KHz up to 20 MHz) in the testing object or material. A transducer is passed over the object being tested, emitting very short pulse-waves to detect internal flaws or to characterize materials. There are two methods of receiving ultrasonic waveforms, reflection and transmission. In reflection, the transducer sends and receives the pulse signal, that reflection comes either from the back wall of the object or from an imperfection within it. In the transmission, a transducer sends the sounds waves through the object, while other transducer receives and detects the amount that has reached the opposite side of it. The presence of flaws reduces the amount of sound detected in the receiver transducer [2].

Liquid penetrant testing is one of the most common and low-cost NDT technique. It utilizes fluorescent or non-fluorescent dyes to flow into narrow spaces to detect surface-breaking flaws. The dye is applied for a certain amount of time and afterwards the excess is removed from the surface, dried and a developer is applied to it. The dye that remains in the flaws is absorbed by the developer, indicating a presence, location and size of the defect. This method has the advantage of being simple, low-cost and independent of flaw orientation, but the disadvantage is that is a slow method [3].
Electromagnetic methods such as magnetic particles introduce electromagnetic waves in the testing material, whereas eddy current testing generate a small electrical current around the test piece in order to extract its properties. With these techniques is possible to detect surface or below surface flaws. In the case of magnetic particles testing, a flaw in the material will interrupt the flow of the magnetic flux, therefore causing the magnetism to spread out from the damaged area. This phenomenon is called flux leakage field. To obtain an approximation of the size and shape of the flaw, metal particles are spread across the component so that the flux leakage from the flaw draw these particles into the damaged area due to the creation of opposite magnetic poles between the points of exit and re-entry of the magnetic lines of force.

In eddy current testing a coil (probe) is excited with a time-varying electrical current, producing a time-varying magnetic field around itself. This field oscillates at the same frequency has the current flowing through the coil. When the probe approaches a conductive material, the magnetic field penetrates the material, generating eddy-currents. The induced currents flowing within the test piece generate a secondary magnetic field, opposite to the primary one. This second magnetic field will affect the primary one, weakening it. By monitoring the resulting magnetic field is possible to detect a flaw in the test piece, has it will change compared to the rest of the piece [4].

ECT can be very useful to measure a large variety of properties, such as the thickness of the coating on the test piece, electrical conductivity, magnetic permeability, corrosion evaluation, distinguish between different alloy compositions, flaw detection, as well as indirectly determine the hardness of the test piece. To improve the reliability, or in some cases to be possible to achieve certain measures, enhancement techniques are used. These techniques may include multiple frequencies used to detect flaws in different depths or probes with multiple coils to increase signal-to-noise ratio (SNR). The advantages of using eddy currents as a non-destructive method is the insensitivity to oils, dust and dielectric materials, the possibility to operate at high temperature range, high speed readings and its reliability. On the other hand, eddy currents testing is limited to materials with electrical conductive properties and unwanted surface variations are sensed. In addition is dependent of flaw orientation and has a limited depth of penetration.

Non-destructive techniques are widely used to reduce costs, ensure quality control even in non-critical areas, leading for a better quality of the final product and operational readiness. This motivate companies to invest in NDT and employ these methods in the production pipeline. Normal systems use a display close to the ECT device, receiving real-time readings and warnings, has well has a history of the measurements. The device developed in this thesis extend these functionalities, allowing remote access to the ECT device, giving the user the possibility to check the state of the quality control. The system employs multiple instances of an electronic front-end module dedicated to ECT measurements. The processing core should be powerful enough to handle multiple ECT front-end modules and its respective provided data. It should also be able to connect to the internet, in order to provide remote access for the user.
1.2 Goals and challenges

The main objective of this work is to develop a system with an expandable approach in mind so that numerous front-end modules can be connected and accessed remotely. This system will have a main processing core, ECT front-end modules and remote access through Ethernet. Alike, the main goals set to this project are:

- Code control firmware for the front-end microcontroller;
- Integrate a modular eddy current testing front-end using a microcontroller and analog circuitry;
- Select a processing core capable of handling multiple instances of the developed front-end at high speed;
- Design electronics hardware including instances of the developed front-end, the chosen processing core and power management;
- Code control, digital signal processing, detection and classification firmware on the processing core;
- Code or integrate a simplified dashboard for display, monitoring and result reporting of multiple devices.
- Produce and employ prototypes of the instrument.

1.3 Document organization

Chapter 2 introduces the fundamentals of non-destructive eddy current testing and provides an overview in state-of-the-art sensors and research. In section 2.1 is explained basic inspection principles, models, measurement possibilities, variables and techniques. The different types of probes are approached in section 2.2, while 2.3 provides a brief explanation of the instrumentation used in these techniques.

Chapter 3 includes both system hardware architecture, as well as software architecture. In section 3.1 is explained the reasoning of choosing of the used hardware as well as tools and techniques that supported the achieved prototype. The developed firmware and software are covered in section 3.2, with some code snippets and explanations behind the developed code.

Chapter 4 covers some of the results obtained using the developed front-end modules, as well as the conclusions of this work.
Chapter 2  State of the art

2.1 Non-Destructive Techniques

Non-destructive testing is one of the most used techniques to inspect, test, evaluate materials, components or monitor discontinuities without destroying the testing piece nor alter its properties.

In comparison, other techniques rely on destroying a lot sampling, a fabricated product piece sacrificed for the required tests. These destructive tests are used to evaluate the physical properties of the material, such as durability, impact resistance, among others. The idea is that in order to achieve a representative sampling, many products have to be destroyed, leading to a decrease in revenue for the company and more time-consuming testing [4].

Eddy current testing is one method of the many NDT methods, relying on electromagnetic testing. Other methods are the magnetic particle testing, liquid penetrant testing, radiographic testing, ultrasonic testing, visual testing, acoustic emission testing, guided wave testing, laser testing methods, leak testing, magnetic flux leakage, neutron radiographic testing, thermal/infrared testing and vibration analysis.

2.2 Eddy Current

In 1851, Leon Foucault, a French physicist discovered the eddy current phenomenon. His discovery was based on a device that used a copper disk moving in a strong magnetic field, showing that eddy currents are generated when a material moves within an applied field, requiring a greater magnetic force to maintain the same rotation due to eddy current effects [5]. This concept was supported by the Faraday Law that states that a current will flow through a conductor, if an altering magnetic field is applied to it, or if a conductor passes through a magnetic field. In both cases, the conductor must have a closed path where the current may flow.

David Hughes, an English scientist discovered, in 1879, that materials with different conductivity and permeabilities change the properties of a coil in contact with the materials. A major advance in the subject was only presented during the World War II, when eddy current was put into practice to material testing.
Eddy current technology was adapted to industrial use in 1933 by the German professor Friedrich Förster, developing instruments for measuring conductivity and for sorting mixed-up ferrous components, founding his, still ongoing company in 1948.

### 2.2.1 Eddy Current Inspection Principle

ECT uses time-varying electrical current to energize a coil, creating a time-varying magnetic field. If an electrically conductive material is in proximity to this electromagnetic field, an eddy current will be induced in the material, as Faraday’s Law shows in

\[
\varepsilon = -\frac{d\phi_B}{dt}.
\]

The electromotive force \( \varepsilon \) is proportional to the time-rate change of the magnetic induction flux density \( \phi_B \).

The induced eddy current in the test piece will generate a secondary magnetic field that tends to oppose the primary magnetic field, generated by the coil. The interaction between the fields causes a weakening effect on the one generated from the coil, therefore an apparent change in the impedance of the coil, as shown in Figure 1.

![Figure 1 - Eddy current on the test piece (adapted from [6]).](image)

It’s possible to monitor the weakening effect on the coil due to how the impedance parameter \( Z_0 \) is characterized, which is a complex number defined as

\[
Z_0 = \frac{V_0}{I_0} = R_0 + jX_0 = R_0 + j2\pi fL_0 = |Z|_\phi,
\]

which represents the voltage-current ratio \( \frac{V_0}{I_0} \) for a single sinusoidal frequency \( f \).

Measuring the coil impedance before approaching the test piece \( Z_0 \) to eddy currents contribution \( Z_C \), by either monitoring the current or the voltage on the signal, is possible to retrieve specific information such as conductivity and magnetic composition on the test piece [7]. This change of the impedance depends on the distance between the coil and the material, the conductivity and the permeability of the material [8], the surface and subsurface geometry. The
presence of a material flaw will disturb or impede induced eddy currents and in response will also change the apparent impedance of the coil [9].

### 2.2.2 Eddy Current Transformer Model

The transformer model represents a basic relationship between the probe and the flaw present in the test piece, as Figure 2 represents. The probe is, usually, a coreless coil placed in the tip of a suitable probe body. The probe body exists to protect the probe from the environment and allow attaching to the mounting fixture.

![Eddy current transformer model](adapted from [9]).

The primary circuit represents the impedance of the probe sensor, namely its induction ($L_0$) and resistivity ($R_0$). The real $R_e$ term in secondary circuit represents the resistance of the loops described by the flow of eddy currents, being consequently proportional to the resistivity of the test piece. The imaginary $jI_m$ represents the leakage inductance of the circuit. The variable $k$ is the coupling coefficient, representing the distance between the sensor and the test piece. As the distance increases, this coefficient decreases, being zero when no test piece is close to the probe, leading to the measured impedance became $Z_0$, as in (2.2).

Based on the analysis of Figure 2, the following equations can be obtained

$$R_0 I + jwL_0 I - jwM_2 I_e = V,$$

$$R_e I_e + jI_m I_e + jwL_1 I_e - jwM_1 I = 0,$$

where $V$ represents the voltage applied to the primary of the transformer, $I$ is the current flowing through the primary of the transformer, $I_e$ is the current flowing through the secondary of the transformer. Also, $w = 2\pi f$, $R_0$ and $L_0$ are the resistance and inductance of the primary coil when no test piece is near it. $R_e$ and $L_1$ represent the resistance and inductance of the induced eddy current loop, where $M_1 = kL_0$ and $M_2 = kL_1$ are the mutual inductance between the two loops.

In the case of a conductive material approaches the probe, the complex impedance of the primary circuit becomes $Z_e$, as
\[ Z_c = R_0 + jL_0w + \frac{k^2 L_0 L_1 w^2}{R_c + jL_1 w + jI_m} \]. \hspace{1cm} (2.5)

From (2.5) is possible to extract
\[ L_c = L_0 - \frac{(wk)^2 L_0 L_1 (L_1 + \frac{I_m}{w})}{(R_c)^2 + (w L_1 + I_m)^2}, \] \hspace{1cm} (2.6)
\[ R_c = R_0 + \frac{(wk)^2 L_0 L_1 R_c}{R_c^2 + (w L_1 + I_m)^2}, \] \hspace{1cm} (2.7)

With equations (2.6) and (2.7) is possible to understand that, when in the presence of eddy currents, the inductance decreases, and the resistivity increases [9] if the material is non-ferromagnetic.

### 2.2.3 Complex Impedance Plane Analysis

By the contents of the two previous section is clear that when a conductor interacts with a coil probe, there are impedance changes in the sensor, making it possible to detect a flaw in the test piece. These changes are analyzed in the complex impedance plane. When there is no test piece near the coil sensor, its impedance is a complex value given by
\[ Z_0 = R_0 + jX_0, \] \hspace{1cm} (2.8)
where \( R_0 \) is the real part, and \( jX_0 \) the imaginary one. \( X_0 = 2\pi fL_0 \) and it’s proportional to the frequency \( f \) and the induction coefficient \( L_0 \).

Once a conductive material approaches the sensing coil, energized by an altering current, eddy currents will appear on the test piece, creating a secondary field that interacts with the primary one. This interaction will change the sensing coil impedance, given by
\[ Z_c = R_c + jX_c. \] \hspace{1cm} (2.9)

In similarity to (2.8) this new value still has both real and imaginary parts, \( R_c \) and \( jX_c \) respectively. \( X_c = 2\pi fL_c \), being \( L_c \) the induction coefficient when a test piece is near the sensing coil.

Once known this value is possible to draw a point in the impedance plane, where the X-axis represents the real part, while the Y-axis the imaginary part, as show in the Figure 3.
The impedance plane diagram is a useful tool to display eddy current data, due to the fact that a variation in the test piece, for instance a crack, will alter the sensing coil impedance, therefore plotting a different result in the complex plane.

2.3 Electrical Conductivity of the Test Piece, Magnetic Permeability, Magnetization of Ferromagnetic Materials

Electrical conductivity is the measure of the amount of electrical current a material can carry, and each material has a different one [11]. This property is one of the key elements in eddy current inspection.

Materials with a high conductivity, such as copper and aluminum, create strong eddy currents and have two advantages over materials that create weaker eddy currents. One is the higher signal levels generated from a crack in the test piece, other is the phase lag between the flaws and the lift-off line is larger. However, there are disadvantages, such as the lower standard penetration depth at a fixed frequency, compared to materials that have a lower conductivity, silicon is a good example of such material. Furthermore, there are factors that may change the conductivity value of the same material, that is the temperature of the test piece, the alloy composition and the crystalline structure. These factors can either be prejudicial to the measures, or can be a key feature, if the objective is to detect small changes in conductivity of the material.

Many industries apply heat treatments to their products, causing a variation on the hardness and their mechanical properties. Thanks to ECT is possible to indirectly identify if the pieces have received a proper heat treatment or not [12].

![Figure 3 - Complex Impedance plane (adapted from [10]).](image)
Magnetic permeability is the measure of the ability of a material to support the formation of a magnetic induction $B$ when a magnetic field $H$ is applied, represented by

$$B = \mu H,$$

where $\mu \; N/A^2$ is the magnetic permeability. Vacuum has a constant permeability of $\mu_0 = 4\pi \times 10^{-7} \; N/A^2$, and in many cases, the permeability of a material is relative to the free space, $\mu, \; N/A^2$.

Magnetic properties affect eddy current testing, leading to a classification in the materials. Paramagnetic materials are softly attracted to magnetic fields, having a relative permeability greater than one $\mu > 1$. An example of these type of materials is the aluminum.

Diamagnetic materials, such as copper, create a magnetic field in opposition to an externally applied magnetic field, causing a softly repulsive effect. In this case, relative permeability is less than one, $\mu < 1$.

Lastly, ferromagnetic materials like iron, cobalt and nickel, are strongly attracted by magnetic fields and concentrate the flux of magnetic field. Their relative permeability is much bigger than one, $\mu > 1$.

Magnetic permeability is an important subject in ECT, due to the fact that the standard depth of penetration is affected by it, decreasing with a material that has higher magnetic permeability. To compensate this effect, ferromagnetic materials are inspected at a lower frequency, while compared to non-ferromagnetic ones.

Magnetization of ferromagnetic materials is a very useful technique used to harmonize measures obtained during testing, and to increasing depth of penetration. This is achieved by saturating the test piece with a strong magnetic field, reducing magnetic permeability variations. When at saturated states, it’s possible to generate eddy currents at a deeper depth. Figure 4 demonstrates that a strong magnetic field (H) will, at a certain point, saturate the magnetization effect ($J$).

![Figure 4 - Curve of magnetization (adapted from [13])](image)
2.4 Main Variables of Eddy Current Testing, Lift-Off and Fill Factor, Edge Effect, Signal-to-Noise Ratio

Lift-off is a change in the impedance that happens when there is a variation in the distance between the test piece, and the coil probe. Usually this is originated by the operator’s movements but can also be caused from irregular sample surfaces and varying coating thicknesses [14]. Lift-off is stronger near the probe because of the stronger magnetic field near the coil. Lift-off can affect eddy current measurements in a way that sabotage the results, being considered a source of noise and undesirable in defect detection [15]. The lift-off effect can appear in the opposite direction has eddy current response from the crack, jeopardizing the measurement.

The previous explanation was considering a coil that has the axis perpendicular with the test piece. Lift-off also occurs on encircling probes, caused by the vibration of the rod or tube inside the probe, leading to difficulties in conducting measurements. This effect can also be called fill factor, which measures how well the test piece fills the coil in this type of probes [16]. Fill factor can be calculated as

\[
fill_{\text{factor}} = \frac{(\text{Diameter}_{\text{test-piece}})^2}{(\text{Diameter}_{\text{coil}})^2},
\]

(2.11)

where \(\text{Diameter}_{\text{test-piece}}\) represents the diameter of the test piece, and \(\text{Diameter}_{\text{coil}}\) represent the coil probe diameter, considering the same measured units. To minimize the fill factor and increasing the response of the probe to crack detection, the coil wires should be as close as possible to the test piece, being \(fill_{\text{factor}} = 1\) the ideal case.

Edge effect occurs when the probe coil is at the end of the test piece, making eddy current flow distorted, as current cannot flow at the edge. To fix this issue, inspections are limited near the edges [17]. Edge effect is present at distances rounding one, up to three times the diameter of the inspection coil in case of encircling probes. In order to overcome this problem, reducing the coil size is a viable solution, as far as the external encircling coil is higher than the inspected materials.

Signal-to-noise ratio (SNR) compares a level of signal power to a level of noise power. Noise sources limit any measurements, especially in eddy current testing, being the main sources temperature variations, lift-off, changes in conductivity or magnetic permeability and changes in speed test.

There are some methods to improve SNR, the most basic being amplifying the signal level. However, amplifiers introduce their own noise and increase the existing, hence a limitation in the amplification stages applied.

Another solution is filtering. The limitation is that the noise is not in the pass band of the desired signal. In addition, if there is a phase difference between the defects and the noise source, phase discrimination techniques may be used [17].

There are different types of coils, and some are less prone to noise sources. Self-compensated differential coil probes are less sensitive to small variations in diameter, conductivity
or magnetic permeability, when compared to absolute coil probes. In the other hand, copper shields cover the probes to decrease the noise picked from external sources, increasing SNR.

Coil size is also an important factor when it comes to increase signal-to-noise ratio. Has presented before, a fill factor close to one is the ideal for encircling probes, and it’s also important that the coil size is the same size, or as close as possible, as the crack size.

The sensor choice can be a key factor when it comes to increase SNR, but it also depends on the application, has each sensor has its own limitations in sensitivity and noise level. For instance, superconducting quantum interference devices (SQUIDs) are used when the magnetic field levels are very low, passing undetected on standard coil probes. The disadvantage of this devices is the requirement of a cryostat to maintain them at very low temperatures.

### 2.5 Frequency and Skin Effect

To detect flaws in eddy current testing, the use of different frequencies on the inspection is crucial. As (2.2) demonstrates, if frequency $f$ is increased, the imaginary part of the impedance also increases.

There are some issues with ECT, and one of the most important is the depth of penetration. The penetration of the eddy currents is limited due to the skin effect, that is the tendency of an alternating electrical current to become distributed within the surface of the test piece such that the current density is largest near the surface of the piece and decreases exponentially with greater depths. Considering the current density flowing along X axis, current flux is represented as

$$
\overline{J} = J_x(z, t) \overline{u_x},
$$

where $\overline{u_x}$ represents the unitary vector along the X axis and $J_x(z, t)$ the magnitude of density current as function of the depth $z$ and time $t$. The phasor of the density along depth (Z axis) is obtained by

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

where $J_{0, \text{max}}$ is the maximum current density at surface and $z$ the depth [18]. The depth at which eddy-current density decreases to a level around 37% of its surface value it’s the standard penetration depth $\delta$. $\alpha_0$ represents the phase at $t = 0$, and $z = 0$ and $-\frac{z}{\delta}$ is the phase lag. Phase lag is the shift in time between the eddy current response from a disruption on the surface of the test piece and a disruption at some distance below the surface. With it is possible to predict the depth of the flaw.

Extracting the real part from (2.13), the variation in the current density phase is 1 radian when the distance traveled from the surface is $\delta$ as
\[ J_x(z, t) = \text{Real}(J_x(z) e^{i \omega t}) = J_{0, \text{max}} e^{-\frac{z}{\delta}} \cos(\omega t + \alpha_0 - \frac{z}{\delta}). \]  

(2.14)

Standard penetration depth can be calculated as in

\[ \delta = \sqrt{\frac{2}{\mu \omega \sigma}}, \]  

(2.15)

where \( \mu \) is the magnetic permeability, \( \omega = 2\pi f \) Hz and \( \sigma \) \( \mu \)S/cm is the conductivity. According to (2.15) it is possible to identify that the standard penetration depth depends on the magnetic permeability, on the frequency and on the conductivity. If any of these variables increase, penetration depth decreases. To illustrate this variation, Table 1 represents the variation in the penetration depth in a copper piece, changing the frequency of the input signal.

\textit{Table 1 - Penetration depth in copper using different frequencies (adapted from [19]).}

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Penetration Depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 Hz</td>
<td>8470</td>
</tr>
<tr>
<td>10 KHz</td>
<td>660</td>
</tr>
<tr>
<td>100 KHz</td>
<td>210</td>
</tr>
<tr>
<td>1 MHz</td>
<td>66</td>
</tr>
</tbody>
</table>

Figure 5 also shows the same phenomena, with a graphical approach that shows the importance of higher frequency for a better resolution.

![Figure 5 - Electromagnetic field penetration inside pure aluminum at frequencies of 200 Hz and 10 KHz (adapted from [18]).](image)

The operational frequency can’t be too low, since the test piece thickness must be two or three times the standard depth of penetration to prevent substantial eddy currents from appearing on the other side of the test piece.

Low frequency tests are usually used in the inspection of ferromagnetic materials to compensate their higher permeability and penetrate the test piece. High frequency tests are used when small discontinuities may occur in the near-surface region, ensuring the maximum eddy current flow at the surface.
2.5.1 Multi-Frequency Techniques

The band of operating frequencies is selected according to the crack morphology, crack position and skin effect. The sensitivity reaches its maximum value at the optimum frequency. In the case of the test piece having more than one flaw, it can be hard to detect all of them, or even impossible when using only one frequency.

Multi-frequency techniques can operate at two or more frequencies using a composite signal. This type of technique save time and expand the single frequency capabilities, by allowing simultaneous tests, analyze in more detail flaws which have complex shapes or canceling undesired signals, to improve signal-to-noise ratio. The undesirable signal is subtracted to the composite one, reducing noise sources such as probe lift-off, temperature variation and geometrical changes in the test piece.

The excitation frequencies can be applied either simultaneously or sequentially. Simultaneous applications will result in a shorter testing time, but each frequency will have less power compared to a sequential approach. Sequential application allows for increased power per frequency, but when applying a new one the system must have time to reach a steady state before initializing the test [20].

These techniques are usually achieved by combining results at different frequencies in the spatial domain. Combining multi-frequency methods with raster scanning is possible to obtain an image of the impedance or the impedance changes in a two-dimensional (2-D) surface. The acquired images are complex values because impedance itself produces complex data. Authors as Bartels and Fisher have researched a multifrequency eddy current image processing techniques for NDT [21]. The 2-D eddy current testing generate a sequence of complex valued images which are linearly combined to maximize the SNR in beneficial situations. This technique consisted of a selection of weights for a linear combination of the images as

\[
d(x, y) = \sum_{i=1}^{2N_f} c_i f_i(x, y),
\]

where \(d(x, y)\) is the linear combination of images, \(N_f\) the number of test frequencies.

Extracting the 2-D images is possible to obtain \(h_1, h_2 \ldots h_{N_f}\) to be used in 

\[
f_1 = \text{real}(h_1), \quad f_2 = \text{imag}(h_1), \quad f_3 = \text{real}(h_2)
\]

and so on. Results on this research shown an SNR improvement up to 1100 percent over traditional two-frequency techniques.

2.5.2 Pulsed Eddy Current Testing

Traditional eddy-current systems use a single sinusoidal frequency. These are limited by the depth of penetration of eddy currents. Because of it, traditional systems are useful for analyzing surface up to a few millimeters below surface cracks. To increase the subsurface
testing, usually reducing the operational frequency shows improvement, increasing the standard depth of penetration. However, in many situations, SNR is reduced.

In order to improve this factor, Pulsed Eddy Current (PEC) instruments are used, being able to generate square, triangle or a saw tooth waveform. These waveforms have a broad, and theoretically infinite (Figure 6), frequencies, allowing pulsed eddy current techniques to provide more information than the traditional ones. Correlating the data at different frequencies allow to obtain the crack depth.

![Image](image.png)

*Figure 6 - Twenty-five harmonic square wave frequency response (adapted from [22]).*

Usually pulsed eddy current instruments are implemented with two coils, one transmitter and one receiver, or a double-function coil. At the same time, the current driving the transmit coil can be made higher in order to improve the reception SNR.

This technique can be used for both crack detection, but also to accurately characterize the permeability and the conductivity of the test piece [21]. Developed systems that use PEC are able to achieve measurements of thickness at very large lift-off distances (up to 100 mm) [20].

These systems permit the detection of flaws, near the surface and in depth, simultaneously, without the need to change the probe or the operating frequency [23]. Each pulse consists in a continuous sequence of frequencies, especially rich in low-frequency components, providing better sub-surface flaw detection. The deeper a signal penetrates, longer it takes to retrieve information to the probe, therefore each component carries information from different depths.

ECT response data can be analyzed in frequency domain, time domain or both. In time domain analysis the peak amplitude is used to determine the size of the defect, while the time to zero crossing the depth of the flaw as shown in Figure 7. The deeper the flaw in the test piece, longer the time to zero crossing.
2.6 Sensors

In eddy current testing, choosing the adequate probe can increase signal-to-noise ratio, and allow different cracks to be detected. The types of magnetic sensors are separated in coil probes, absolute-mode probes, differential-mode probes, reflection probes and hybrid probes. This section presents these different types of sensors.

2.6.1 Coil Probes

Coil probes provide high crack sensitivity when eddy current flow is strongly interfered by the crack. The most basic and most used type of coil probe is the encircling coil. These coils, has the name suggests, encircle the test piece, either externally or internally. Due to the way they interact with the test piece, eddy currents create a radial circumference, making hard to detect defects with the same direction has the eddy currents.

Pancake-type probes are coils that are arranged in a way that the axis is perpendicular to the surface of the test piece. To increase permeability, these coils can use a ferrite-core. These coils are used in flat surface inspection and have a high sensitivity to surface cracks, because of the distortion provoked on the current flow of the eddy currents. The disadvantage of this coils is the high sensitivity to lift-off and the insensitivity to detect laminar flaws.

This type of coils can be found in a variety of electronic configurations, namely absolute or differential mode.

2.6.2 Absolute Mode Probes

Absolute mode probes use, generally, a single test coil to generate the eddy currents and sense the changes in the eddy current field. This type of probes provides an absolute voltage signal, creating a change in amplitude, has Figure 8 illustrates.
Absolute probe coils have the disadvantage of its low sensitivity when not amplified. These probes are sensitive to temperature variations as well. To compensate this factor, a second reference coil can be added, far from the inspected material. This methodology will diminish the effect of temperature variation, as well as an increase the dynamic range of the instrument.

These probes are able to detect long flaws or slow dimensional variations. Furthermore, absolute probe coils can provide hardness and stress measurement of the test piece.

### 2.6.3 Differential Mode Probes

Differential mode probes use two active coils wounded in opposition. When both coils are on a crack free portion of the test piece the differential signal originated is so small that can be negligible and considered null. On the other hand, when one of the coils is over a crack and the other is over a good portion of the test piece, a differential signal is created. This phenomenon can be better understood analyzing Figure 9.

Differential mode probes have the disadvantage of not being able to detect composition nor gradual dimensional variations on the test piece, due to the fact of the coils being close to one another. The advantages of this type of probes is the higher sensitivity to defects and the probe wobble effect is reduced [24].

### 2.6.4 Reflection Probes

Reflection probes also use two coils, as in the differential coil probes, but on this configuration, one of them is used to excite the eddy currents, while the other is used to sense and detect the changes in the test piece. Considering that each coil would have a specific function, the coil design can be optimized. For instance, the coil that oversees exciting the eddy currents,
can be made to produce a strong and uniform primary magnetic field while the sensing coil can be designed to pick up the maximum secondary field. These can be achieved by adjusting the coil size, wire diameter, coil turns and reducing noise sources.

2.6.5 Hybrid Probes

A hybrid probe uses a coil to generate the primary magnetic field and senses the eddy current response with a different technology. In this section, a brief description of different sensors technologies used on hybrid probes are explained.

Magneto resistive is based on the variation of electrical resistance due to the presence of a magnetic field. This type of sensors exhibits a linear change in electrical resistance when exposed to a certain magnetic field strength. Figure 10 illustrates the transference characteristic of a magneto resistive sensor.

![Figure 10 - Output tension according to the applied magnetic field (adapted from [25]).](image)

These sensors are highly sensitive and accurate but are equally highly sensitive to temperature variations. To reduce the temperature sensitivity, differential measurements are usually employed [26][27].

When an electrical conductor has an electrical current flowing, it can create a perpendicular voltage difference (Hall voltage) when a magnetic field is applied. This is called Hall-effect, and Figure 11 illustrates it.

![Figure 11 - Hall voltage creation by a magnetic field (adapted from [25]).](image)

Hall-effect sensors offers highly linear measurements, with the disadvantages of being limited to the silicon sensitivity, large offset and high level of 1/f noise.
Superconducting quantum interference devices (SQUIDs) are, traditionally, the most sensitive magnetometers, designed to measure extremely weak magnetic fields. SQUIDs consist of two superconductors separated by thin insulating layers that form two Josephson junctions, illustrated in Figure 12. These devices can be configured to detect such small magnetic fields that have been used to measure magnetic fields in living organisms.

In eddy current testing SQUIDs have been used since 1980s, thanks to their superior sensitivity, flat frequency response up to 1 MHz, high spatial resolution and high SNR. The disadvantage of these devices is that to achieve and maintain its low noise levels, they must be cooled in a cryogenic chamber, limiting their applications.

![Figure 12 – SQUID schematic (adapted from[28]).](image)

### 2.7 Instrumentation

Eddy current instruments can be found in a wide variety of configurations, from basic to the most advanced equipment, analogic or digital.

For instance, the most basic eddy current equipment is capable of detecting composition in alloys, measure parameters in heat treatments and detect structural variations. Usually they are low-cost devices with one or two physical channels, with time multiplexed frequency capabilities to increase their functionality.

Higher-end equipment can provide higher data processing and more physical channels, when compared to the basic ones. The most advanced instruments allow hot wire testing at speeds up to 15 m/s, while providing very high spatial resolution. When it comes to connections, these high-end eddy current instruments, can support up to 128 inputs and outputs than can be connected to a programmable logic controller (PLC) in order to control automatic systems. Connection to a production process network and multiple frequency operation bands is also possible with these devices.

### 2.7.1 Elements and Architectures
Eddy current instruments must accomplish and integrate elements to produce the desired result from the performed inspection. To achieve it, general purpose eddy current devices, are based in the block diagram presented on Figure 13.

ISO 15548 defines the important characteristics and how to check the overall or specific portions of the system. All units along the block diagram follow simple indications present in the ISO 15548.

The generator unit is entrusted of producing the excitation that will be sent to the coil, so that an inspection can be realized. As demonstrated in previous sections, the output signal of the generated can vary from single sinusoidal excitation, to more complex pulsed and multifrequency signals.

The output from the generator is than sent to the probe unit where is used as an excitation to the test piece and captures the eddy current response. Probes in eddy current testing have many variants and can be design to specific use cases, to detect a specific type of flaws in the test piece.

The input block is where the connection between the probe output and the instrument input happens. Impedance matching, and amplification may be used in this unit, as well as some limits regarding the maximum input voltage.

The balance unit is related with, almost, every unit along the instrument and is where compensation of the signal is performed, in order to achieve a predetermined operation point. For example, the system may be calibrated when the value read by the probe is on a non-faulty portion of the test piece, creating an offset to achieve a zero in the complex impedance plane. This would increase the dynamic range used on the analog-to-digital converters (ADCs), allowing a further increase in gain and reduced noise.

High-frequency (HF) signal and demodulator unit merge the HF filtering, HF amplification and demodulation. The HF filter function is to reduce the input signal frequency, eliminating, or reducing, the undesirable frequencies resulted from the test. The HF amplification is to amplify the signal so that it can be processed in the next units of the instrument. It also allows to
distinguish the desired signal from noise. The demodulation extracts the vector components from the HF signal.

Low-frequency (LF) signal module applies processing techniques to the demodulated signal, such as vector amplification, LF filtering, phase setting, output and signal display. Vector amplification consists in two different channels, originated from the demodulation. The signals flowing through both channels are similar, but each component can be amplified with different gains. After demodulation, the signal is filtered to suit the application frequency. Phase setting allows rotation to the demodulated signal vector on the complex plane display. The output and signal display offer a wide variety of display options, such as complex plane, ellipse, time-synchronous. The output can be analogue, digitized or logical.

The last unit of the block diagram is the digitization. When digitization is performed, it can be either before or after signal demodulation, can use an internal clock or an external encoder. The resolution of the ADC is the nominal value of the converter input voltage corresponding to one digitization bit. The sampling rate represents the frequency at which the ADC operates.

### 2.7.2 Characterization Standards

As mentioned before, eddy current instruments must follow and comply the rules imposed by the ISO 15548. There is a total of three parts, the part one consists in the eddy current instrument characteristics and verification, the part two clarifies the probe characteristics and verification, while the part 3 adds the system characteristics and verification.

In the first part, it’s applied a separation between general-purpose applications, and specific ones. In the general applications, the instrument must be capable of attaching a different variety of probes, while a specific application instrument, it should be design to a specific probe. It’s mentioned that the instrument can have a few variants, such as the power supply, the technology and the physical presentation. Many information’s must be given to user, regarding the many units composing the instrument itself and what do they produce. If the generator produces single or multifrequency signals, that must be mentioned.

In the second part, it’s specified what factors describe a probe, the interconnecting elements, physical characteristics and safety regulations. The external electrical connections to the probe must be clearly identified, explicitly the range of excitation current, voltage and frequencies, probe impedance in air and resonant frequency. Each system must have its own probe functional characteristics, including directionality, response to elementary discontinuities, coverage area and penetration characteristics.

In the third part, it’s specified what the eddy current system implemented techniques. The physical characteristics must include the throughput speed, the scanning path and the mechanical arrangement and settings with their interaction with the test piece. Calibration-related and functional characteristics are also presented.

There are similar topics in all three parts, that being the verification and the measurement of electrical and functional characteristics. In the verification there is a total of three levels
completes the instrument periodic verification. The first one is to check the system global performance, the second is the detailed functional check and calibration and the last level is the check of all the instrument, probe and accessories characteristics. The measurement of electrical and functional characteristics is an agglomerate of tests and procedures to assure the values received and emitted by the system. These tests ensure if the instrument requires further verification or not, based on the obtained results.
Chapter 3  System Architecture

3.1 System Hardware Architecture

The system is composed by a processing core, ECT front-end modules and a power supply. The Beaglebone Black is the processing core of the system and is what makes possible the internet connection and remote access with the included Ethernet port. The processing core needed to be powerful enough to handle multiple ECT front-end modules and its respective provided data, as well as connect to the internet by Ethernet connection.

Four MSP430 from Texas Instruments are used as ECT front-end modules to readout up to four coil elements of a connected probe. The front-ends digital output response is composed by real and imaginary part. They communicate with the processing core through SPI for a fast and reliable connection. This connection will ensure readings from multiple front-end modules and future proof expansion.

The power management module is composed by two stages. The first stage uses DC/DC converters to transform the 20 V DC input voltage into +13.5 V, -13.5V and 5 V. These voltages are then converted into +12 V, -12 V and 3.3 V, respectively, using linear regulators. The +12 V and -12 V are used to drive the operational amplifiers generating or amplifying the probes signals. The processing core uses the 5 V produced by the DC/DC converter for power and the front-end modules use the 3.3 V. The system architecture is present on the Figure 14.
3.1.1 Processing Core

During the process of choosing the right hardware, comparisons between Raspberry Pi2 and Pi3, Beaglebone Black and a BeagleBoard X15 were undertaken. The necessity to connect multiple ECT front-end modules was the main factor to remove the Raspberry modules from the possibilities. Having a parallel communication port alongside multiple SPI pins was the best possible configuration that only the BeagleBoard X15 offered, but the over 200€ cost of this development board made it hard to choose. To round everything, the Beaglebone Black was chosen for the superior number of SPI ports and the larger onboard storage capacity, compared to the Raspberry Pi variants and the more affordable price tag than the BeagleBoard X15.

As mentioned, the Beaglebone Black has a superior number of pins provided to the user, when compared to the Raspberry Pi. Therefore, there are two headers present, the P8 and P9 header, with 46 pins each. The P8 header oversees the various SPI Chip Select signals, as well as the front-end modules interruptions, which signal the almost full condition of the SPI readout buffer. The readout buffer in combination with the mentioned interruption allow to reduce the periodicity at which the processing core needs to read a given front-end. The Table 2 represents the P8 header pinout and the respective connections.
The P9 header holds the different SPI signals provided to the front-end modules, namely the SDO, SDI and CLK. By analysing the Table 3, that represent the P9 header pinout, some UART pins are connected to SPI signals. The reason being a redundancy measure, in case the SPI configuration would give problems during the firmware development phase of the project.

### 3.1.2 MSP430 ECT Front-end Modules

As previously mentioned, the ECT Front-end Modules implement several functionalities, such as probe signaling and calibration, signal processing and storage. The development of the modules’ hardware is not credited to the author. Figure 15 shows one of the used prototypes.

These are based on the microcontroller MSP430 FR2355 from Texas Instruments. The 4 SPI channels, internal 12-bit ADC and 12-bit DAC, the up to 24 MHz internal clock and the built-in programmable gain amplifiers (PGAs) were some of the features that lead to choose this microcontroller has a foundation of the eddy current front-end modules.

The output signal and complementary signals, used in the ECT probes, are internally generated using software. This topic is covered on the Software Architecture section. To increase
the output current, THS3062 high output operation amplifiers are used, allowing a maximum of 100 mA to be sourced through each channel, while the output voltage maintains 16 Vpp.

**3.1.3 Power Management**

To achieve the required supply voltages, circuitry was necessary. For the first stage, TPS5430 step-down converters from Texas Instruments were used. This component was chosen due to the considerable input voltage range, from 5.5 V up to 36 V, meaning that a different power supply may be used in the future. Another important factor was the necessary 3 A continuous output current to power the Beaglebone Black. It also packs some interesting features, such as system protection from overcurrent limiting, overvoltage protection and thermal shutdown. The different voltages were based on the schematic present on Figure 16.

![Step-Down Converter Schematic for +13.5 V.](image)
Analyzing the schematic, it is possible to identify a buck converter, where the output voltage provides the control to the TPS5430 through the VSENSE connection. The schematic on the Figure 17 represents, on a simplified way, how the integrated circuit works. The feedback network voltage signal is compared to a reference voltage value, which, depending on the value, will actuate on the PWM controller, changing the duty cycle of the FET switch on state. Overall, it works as a switch, controlled by the VSENSE signal, providing the desired output voltage.

![Figure 17 - TPSS430 Buck Topology (adapted from [30]).](image)

Analyzing the circuit, and assuming that it is working in continuous mode, when the FET Switch is closed, the current will flow through the inductor, increasing at a rate of \( \frac{di}{dt} = \frac{V_{in} - V_{out}}{L} \), where \( V_L = V_{in} - V_{out} \) is the voltage drop on the inductor. When the switch is opened, the current flow must maintain the same direction, therefore, it goes through the inductor, into the load, and back to the inductor passing the diode. With this, the inductor voltage is reverted in order to keep the current flow, being \( V_L = -V_{out} \).

The input capacitor C23 is decoupling the input voltage from the rest of the circuit, while both the capacitor C26 and inductor L1 are creating a necessary output filter.

Different output voltages can be obtained by changing the R4 resistor value as

\[
R_4 = \frac{R_3 \times 1.221}{V_{out} - 1.221},
\]

where \( R_3 \) is a fixed value of 10 k\( \Omega \) and \( V_{out} \) the desired output voltage. To obtain the 13.5 V \( R_4 = 1 \) k\( \Omega \). To achieve an output voltage of 5 V, the circuitry is the same, the only change being the value of the resistor \( R_4 = 3.24 \) k\( \Omega \).
To obtain -13.5 V a slightly different circuitry was used, as shown on Figure 18. Compared to the previous schematic, the output voltage and ground are switched, making the circuitry behave in a very interesting way in order to achieve negative voltages. When the FET switch on the TPS5430 is closed, the current flows through the inductor, all the way to the ground terminal. Whereas the output capacitor delivers the output current load, maintaining a negative value. When the switch is opened, the diode becomes direct polarized, the current from the inductor splits between the capacitor and the load, charging the capacitor and maintaining the negative value at the load. This charge up the capacitor, inverting the voltage on the terminals of the inductor. Figure 19 helps better understand the previous description.

Similarly, to the previous schematic, the voltage divider defines the output voltage, where \( R_7 = 1k \), having an impact on the duty cycle of the internal TPS5430 switch. The 20 V input voltage is used to achieve a negative voltage using a buck DC-DC converter. Any step-down DC-DC converter can be used as an inverter, simply by changing the label of some pins. The \( V_{OUT} \) pin is labelled as GND in the inverter, and the GND pin as \( -V_{OUT} \). But there are some limitations using this approach. For instance, the voltage difference between the input and output voltages cannot be higher than the buck DC-DC converter’s maximum operating input voltage. Since the used TPS5430 has a maximum input voltage of 36 V, and the desired negative output voltage is -13.5 V, the maximum input voltage would be 23.5 V. In order to avoid the maximum rating, the input voltage was set to 20V.
For the second stage, different Low-Dropout Regulators (LDO) from Texas Instruments were used for each voltage. LM3940 were used to obtain the 3.3 V to power the different ECT modules. The LM317 were used to achieve the 12 V, while the LM337-N the -12 V, both voltages are used on the ECT probes. Each of the mentioned LDO’s have thermal overload protection, as well as short-circuit current limiting protection.

Voltage regulators are used to provide a stable power supply voltage, immune to temperature, input-voltage and load impedance changes. The LDO's have the particularity of having a fast response to input voltage changes, allowing them to drastically reduce the ripple on the voltage signal. Has mentioned in the stage one, switched converters are used and as a result, a higher than desired ripple is introduced into the voltage signal. For this reason, LDO’s were used, to reduce the introduced ripple effect by the stage one converters.

Has mentioned, to achieve the 3.3 V to power the ECT front-end modules, the LM3940 were used, based on the schematic of Figure 20, where the 5 V input signal is provided by one of the previous mentioned TPS5430 step-down converters. This IC can maintain the 3.3 V output voltage, even if the input drops as low as 4.5 V.

![Figure 20 - LM3940 Schematic used to convert +5 V into +3.3 V.](image)

Should be noted that the input capacitor is required if the regulator is located further than 1 inch from the power supply output filter, or a battery cell is used. The output capacitor has a fundamental role on the behavior of the circuit, since it maintains the regulator stability, and must meet the conditions for the equivalent series resistance (ESR) as well as the minimum amount of capacitance, that being 33 µF.

To get the 12 V used in ECT probes, the LM317 LDO was used as a result of the ease of use, only requiring two resistors to achieve the required output voltage. Figure 21 represents the schematic used to convert the 13.5 V input voltage into 12 V.
Analyzing the schematic, the resistor R2 is fixed, and the output voltage is regulated by the resistor R1 as

\[ R_1 = \left( \frac{V_{out}}{1.25} - 1 \right) \times 240. \] (18)

C21 is used to reduce the ripple. The diodes D1 and D2 are used to force the capacitors C21 and C24, respectively, to discharge to the input once it achieves 0 V. When the input voltage reaches 0 V, both diodes are forward biased, therefore, the capacitors discharge through the path imposed, leading to the input of the circuit.

To achieve the -12 V, LM337-N were used. These adjustable negative regulators from Texas Instruments are very similar to the previous mentioned LM317, only requiring two resistors to achieve the desired negative output voltage, as shown in Figure 22.
Similar to the previous schematic, R6 is the fixed resistor, and the output voltage is regulated by the resistor R8 as

\[
R_8 = \left( \frac{V_{out}}{-1.25} - 1 \right) \times 120. \tag{19}
\]

The desired output voltage would be \( V_{out} = -12V \), therefore \( R_8 = 1 \, k\Omega \). The capacitors are used to decouple the circuit input and output.

### 3.1.4 Printed Circuit Board Design

To accommodate the 4 front-end modules, probe connectors, power management circuitry and the processing core, a Printed Circuit Board (PCB) was designed and produced. The software used was Altium Designer. Two layers were used to accommodate the required tracks. The power tracks have 1 mm of width when possible since high current will flow through them. The signal tracks have 0.3 mm of width. The connector pads are 1.5 mm in diameter, with a hole size of 0.9 mm to easily connect jumper wires to both program the front-end modules and check the different signal values. The probe connectors signal pads are 2 mm in diameter with a 1.3 mm hole, while the mounting pads are 3.5 mm in diameter with a 2.4 mm hole size. The power connector pad has 4 mm in diameter with a hole size of 1.8 mm. To attach the Beaglebone Black to the PCB pads with 3 mm in diameter and a 2.5 mm hole where also created. The clearance spacing between tracks and pads is 0.15 mm to prevent any short circuit soldering the components. The components used are surface-mounted, to reduce the PCB footprint. The dimensions of the resistors and capacitors varies between 0603 and 1206 codes. When the capacitance was higher than 1 \( \mu F \), 1206 components were used.

The Figure 23 represents a preview of the PCB layout based on the system architecture, that accommodates the 4 front-end modules, probe connectors, power management circuitry, as well as the processing core.
The power management circuitry is located on the left side of the PCB, outlined by the section 1, along with the power connector. Over to the top right side of the PCB, is located the 4 front-end eddy current modules as well as the necessary connections to program the modules externally, delineated by the section 2. In the lower portion of the PCB are located the probe connectors inside section 3 of Figure 23. In between the modules and the probe connections, are pins to connect jumper wires to check the signal values if needed. Figure 24 and Figure 25 illustrates the prototype PCB where is possible to identify one ECT Front-End module, the required pins to debug and program the module, some required circuitry and the processing core on the back side.
Figure 24 - Prototype PCB (Top View).

Figure 25 – Prototype PCB (Bottom View).
3.2 Software Architecture

As previously mentioned, the eddy current front-end modules are powered by MSP430 FR2355 microcontrollers. To achieve the desired behavior, firmware was produced for these modules. The Beaglebone Black required some software development to communicate with the ECT modules. It also required to manipulate some key variables, such as the frequency at which the eddy current probes would operate and display the information on a user interface. For that matter emerges this section, to explore and overview some key decisions made during the development of the firmware and software of the project.

3.2.1 Firmware

The ECT modules implement four main functionalities: control and deliver the frequency signals to the eddy current probes, improve the ECT modules signal acquisition range using vector amplification, digitalize the probe readouts, and lastly communicate with the processing core.

In order to change frequencies with ease, the MSP430 uses one of the two available timers to generate in-phase and quadrature digital waveforms needed for the hardware demodulator. These signals required to be in quadrature between one another, to accomplish this, the Timer_B is used and set to “Up Mode”. In this mode, the user defines a frequency value that translates to a certain timer increment value, obtained by

\[ M = \frac{Clk}{2^*f}, \]  

(220)

where \( Clk \) represents the clock at which the MSP is set to, and \( f \) the desired output frequency.

When operating, the timer starts from zero and goes to the highest translated frequency value set on the registers (TBxCL0), restarting once that value is achieved. The Figure 26 helps to better understand how the timer is set on the ECT modules.

![Figure 26 – Timer_B set to Up Mode (adapted from [31]).](image)

The Timer_B is able to output up to seven signals, using seven different output modes, presented on Figure 27.
To achieve the desired behavior, the “Toggle” output mode was used, the counterpart to this approach is that the output frequency is reduced compared to other output modes. The maximum output frequency using different clock speeds are represented on Table 4, where the output frequency is a quarter of the set clock frequency.

Table 4 – MSP430 FR2355 clock and maximum output frequency.

<table>
<thead>
<tr>
<th>Clock Frequency (MHz)</th>
<th>Maximum Output frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>24</td>
<td>6</td>
</tr>
</tbody>
</table>

The use of the registers TBxCCRn allows to produce distinct signals using the same timer by setting different points at which each signal reset. The code on Figure 28 helps understand this behavior.

```c
TB1CCR0 = freq-1; // PWM Period
TB1CCCTL1 = OUTMOD_4; // CCR1 reset/set
TB1CCRL1 = freq/2; // CCR1 PWM duty cycle
TB1CCCTL2 = OUTMOD_4; // CCR2 reset/set
TB1CCRL2 = 0; // CCR2 PWM duty cycle
TB1CTL = TBSEL_SMCLK | MC_UP | TBCLR; // SMCLK, up mode, clear TBR
```

This code snippet is extracted from the timer function used in the project to produce the quadrature signals. The approach was that one of the signals resets each time the Timer_B would reach zero, and the other when the timer reaches the half of the set frequency value. Analyzing the code, the register TB1CCR0 is setting the Timer_B period, defining at which value the timer should reset. The register TB1CCR1 configures the timer module to toggle one output signal at 90 degrees thus generating the quadrature reference. The register TB1CCR2 configures the timer
module to toggle one output at 0 degrees thus generating the in-phase reference. The Figure 29 represents the in-phase and quadrature reference signals from the MSP430 using an internal clock of 8 MHz.

![Figure 29 – In-phase and quadrature reference signals.](image)

Each ECT front-end module is connected to one coil, the analog demodulator generates two DC signals corresponding to the real and imaginary components of the coil signal. To read that information separately, the 12-bit analog to digital converter present on the MSP430 FR2355 had to be configured in a way that was possible to capture both signals at the same time. The analog inputs channels A1 and A5, pins P1.1 and P1.5 respectively, were used to capture the signals. The ADC works in an interesting way. In order to read more than one channel at once, the ADCINCHx register needs to be set with the highest analog input channel, in this case, the respective value of the A5 channel. The capture sequence then starts and reads each channel, from the one set on the ADCINCHx register, to the channel A0. It converts and records the value of each channel on the ADCMEM0 register. The sequence stops after the A0 channel is converted [31]. With this behavior, would be better to use the ADC channel A0 and A1, but other required functionalities use these pins, leaving the channel A1 and A5 available. To save the conversion values from the ADC, a temporary integer array is used. The converted readings are then stored in two distinct rotary buffers, one for the imaginary part, and one for the real part. These rotary buffers consist in two integer arrays with the capacity to store 64 values each.

Integrated Smart Analog Combos (SAC) were used. Each SAC is composed by a high-performance low-power operational amplifier, a programmable gain amplifier (PGA) and a 12-bit digital-to-analog (DAC) converter. The Figure 31 represents the components of each SAC.
For both the imaginary and real parts of the signal, two SAC’s were used. One as an inverted, and the other as a DAC. The Figure 32 illustrates this configuration.

The output of the SAC DAC (SAC2) is set with a compensation signal that connects to the negative input of the inverting amplifier SAC (SAC 0). The positive input of the SAC 0 is the post-demodulated DC component (real or imaginary) where the gain is regulated by the PGA.
integrated in the SAC. The readings from the SAC 0 are then used to change the calibration signal of the SAC DAC accordingly. The $V_o$ can be calculated by

$$V_o = V_1 \left(1 + \frac{R_2}{R_1} \right) - \frac{R_2}{R_1} V_2,$$

where $\frac{R_2}{R_1}$ represents the PGA gain, $V_1$ the probe readings signal and $V_2$ the calibration signal from the SAC DAC. In Figure 35, $\frac{R_2}{R_1}$ is simplified to $R$.

Vector amplification is used to maximize the overall sensitivity. For this, a DC reference generated by the MSP430 FR2355 DAC are subtracted from the analog demodulator output. Programmable gain amplification is then applied before digitalizing using the MSP430 FR2355 internal ADC. A binary search function on the DAC output was developed so that the input signal on each of the ADC channels would be on the middle of the acquisition range. Has mentioned before, the MSP430 FR2355 has a 12-bit ADC, therefore, the reading range would be valued between 0x000 and 0xFFF, corresponding to 0 and 2.5V respectively. The best possible reading when no flaw is present is the middle of this range, 0x800. This is due to the fact that a flaw signal on eddy currents, normally translates into symmetrical real and imaginary trajectories. Therefore, if the readings when no flaw was present, are near one of the ADC limits, in a presence of a flaw, it may not be detected. The Figure 30 is a snippet of the developed code to achieve this functionality.

```c
void SAC_Calib()
{
   unsigned int adc_target = 0, dac_mask = 0, dac_final = 0, dac_value = 0, adc_value = 0;

   adc_target = 0x0000;
   dac_mask = 0x0000;
   dac_value = dac_mask;
   dac_final = 0;

   SAC_DAC_Set(dac_value, 0);
   __delay_cycles(500);

   for(i = 0; i < 12; i++)
   {
      ADC_Read();
      adc_value = adcResult[1]; // get Last imaginary read
      FILL_Eot_Buffer();
      if(adc_value < adc_target){
         dac_final = dac_final | dac_mask;
      }
      dac_mask = dac_mask >> 1;
      dac_value = dac_final | dac_mask;
      SAC_DAC_Set(dac_value, 0);
      __delay_cycles(500);
   }
   SAC_DAC_Set(dac_final, 0x0000);
   __delay_cycles(500);
}
```

*Figure 32 - SAC calibration function.*

For the ECT modules to communicate with the processing core, SPI communication was used and configured. This communication protocol is used so that the Beaglebone Black can send and receive data, to and from the front-end modules, as well as change the eddy current
testing parameters. The MSP430 was configured to use 8-bit data length, 4-pin SPI operation and set has a slave. The Beaglebone was configured the same way, with the only difference, it being set as the master. In order to change the configurations on the ECT modules, a control communication protocol was implemented. This protocol uses variable size commands that can include multiple parameters. The structure of a command is composed by four main sections as shown in Figure 33. The Function defines the action or configuration to take or change; the Data is used when a single parameter is required; the Size is zero if no further data is required, otherwise carry the number of data elements to receive further; the Array has multiple parameters when required. The Table 5 includes some of the implemented commands. Both the Function and Size header fields are 32 bits wide, unsigned integers, big endian format. The Data field may use an integer or a floating point 32 bits wide number. The Array elements are 8 bits wide, raw data used to transmit any data format required.

![Figure 33 - Commands structure (adapted from [32]).](image)

<table>
<thead>
<tr>
<th>Function</th>
<th>Action</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00000010</td>
<td>OK acknowledge</td>
<td>None</td>
</tr>
<tr>
<td>0x00000021</td>
<td>Start Acquisition</td>
<td>Channels</td>
</tr>
<tr>
<td>0x00000030</td>
<td>Change output frequency</td>
<td>Output Frequency</td>
</tr>
<tr>
<td>0x00000038</td>
<td>Performs IQ compensation</td>
<td>Channels for compensation</td>
</tr>
</tbody>
</table>

### 3.2.2 Software

A simple user interface (UI) was developed using Python 3.4 and a Python plugin, PyQt, for the Graphical User Interface (GUI). The UI is capable of displaying and transmitting information to the processing core, which will communicate with the ECT Front-Ends using the developed communication protocol. Figure 34 illustrates the developed UI, where is possible to input the frequency and amplitude of one channel. Over to the right side there is a graph that plots the combination introduced on the Real and Imaginary parts inputs. Ideally this graph would plot using the values acquired by the connected probes. There’s also a button to call the developed binary search function that implements a vector amplification to the channel.
Figure 34 - Developed User Interface.
Chapter 4  Results and Conclusions

4.1  Results

The developed hardware and firmware were used to accomplish an operational ECT instrument while collaboration with the FCT-UNL NDT Laboratory. Some tests were carried on Unidirectional Carbon Fiber Reinforced Polymer Composites (UD CFRP) [33]. These are high performance materials for structural components that exhibit low damage tolerance. For that matter, condition monitoring is required for safety-critical applications. For these tests, the carbon fiber rope consists UD CFRP elements, protected by a polyurethane coating with an average thickness of 1 mm, a cross section dimension of roughly 5.0 × 2.5 mm and 100 mm length. The coil was placed 3 mm above the CFRP element, with an additional 2 mm lift-off distance to ensure contactless inspection. The effective lift-off distance is 3 mm due to the fact that the polyurethane coating is 1 mm thick. Different types of defects were induced in the test piece in order to represent natural imperfections or damages to the CFRP element. The defects in the test piece are broken fibers induced by ball-peen hammering (BFH), broken fiber or delamination induced by 3 ptb (3PTB), and 2 lateral cuts, one with 0.2 mm (LC02) and one with 0.5 mm (LC05) length of width. The ECT probe were coupled to a 3D printed handheld chassis with two wheels. The probes are attached to the middle of the chassis, assuring its constant positioning and lift-off distance along the test piece. The Figure 35 represents the mentioned chassis with the ECT probes attached. The CFRP serves as rails for the handheld chassis wheels roll on.

Figure 35 - Handheld device with the ECT probes
Has previously mentioned, the test piece had different types of defects. Figure 36 and Figure 37 shows the output from the ECT probes connected to the developed ECT front-end at a speed of 3.5 m/s with a frequency of 1 MHz. Figure 37 represents the real part, whereas Figure 38 the imaginary part over time. The first and last differential signals were obtained by aluminium marks on the CFRP material to mark the beginning and ending of the inspection. The three indications shown in between were caused by the presence of three fiber break defects with different dimensions.

\[\text{Figure 36 - Real part signal.}\]

\[\text{Figure 37 - Imaginary part signal.}\]

4.2 Conclusions

Eddy current testing is one of the most used methods to inspect conductive materials, but its complexity requires a powerful processing unit. Remote access is an innovative step in the subject, as studies in this area tend to improve ECT efficiency. Incorporate Ethernet connection with an autonomous ECT instrument lead to a more convenient way for the user to access and share information, a key functionality in the present day.

This project presents a modular instrument capable of conducting multiple online eddy current inspections and detect the defects present in the test pieces. The instrument combines ECT front-end modules, each one connected to a probe, capable of analyze an independent eddy current field; a microcontroller Beaglebone Black to process the data sent by the ECT modules via SPI and provide remote access capabilities.
The efforts within this work resulted in the definition of the instrument architecture and the selection of the processing core, the design and validation of the instrument power supply circuitry, the design and prototyping of the instrument printed circuit board and the firmware to implement several functionalities of the ECT front-ends.

For future work, there is aspects that could be improved, predominantly, the software for the Beaglebone Black, defect classification and the remote communication.
References


