## **Electromagnetic Methods for**

## **Landmine Detection**

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## Abstract

The removal of Explosive Remnants of War (ERW) such as Anti-personnel (AP) mines is a problem that affects countries and communities as a lasting legacy after many armed conflicts around the world, with more than an estimated 110 million landmines still alive. The mines can still indiscriminately injure or kill civilians for decades after the conflicts or wars end. The Ottawa Mine Ban Treaty in 1997 has banned the use of mines because of their significant effect on communities and set targets for the decontamination of mine-affected areas. Current metal detectors used for humanitarian demining struggle with a high False Alarm Rate (FAR) during the landmine clearance operations, and this research project is aiming to characterise a measurement system to identify specific metal or landmines to reduce FARs with the better demining efficiency and the operation cost.

This thesis considers the electromagnetic polarizability tensor as a concise representation of a metal object in an AC magnetic field. A measurement system has been researched and developed to measure the spectroscopic characteristics of the polarizability tensor for metal objects of the type and size that would be relevant for humanitarian demining. To verify the operation of the system, simulation and experimental results of a set of US coinage are presented and compared.

As part of the development of the tensor measuring system, an optimised coil configuration was proposed, and the comprehensive description of the coil design with corresponding manufacturing process was provided. AP landmines up to 13 cm diameter can fit into this coil configuration and the magnetic fields of the transmitter and receiver coils are substantially uniform which lead to better measurement results of the tested objects. Both analytical calculation and experimental measurement validated the suitableness of the coil array. The methodology of determining the coil arrangements has assisted the future coil configuration.

Finally, a new method of modelling metal detector applications in the time domain using a pulsed eddy current metal detection system is proposed and presented. This simulation has been validated by the corresponding modelling method in frequency domain, and the results showed the method is capable of simulating landmine detection systems with a much faster simulation speed.

## **Declaration**

No portion of the work referred to in this thesis has been submitted in support of an application for another degree of qualification of this or any other university or other institution of learning.

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# **Glossary of Terms**

AP	Anti-Personnel
ALIS	Advanced Landmine Imaging System
ATR	Aided Target Recognition
CAD	Computer-aided Design
CAE	Computer-aided Engineering
COTS	Composed of an Off-the-shelf
DPM	DCD Protected Mobility
DRES	Defence Research Establishment Suffield
DSP	Digital Signal Processor
EIT	Electrical Impedance Tomography
EOD	Explosive Ordnance Disposal
ERW	Explosive Remnants of War
FAR	False Alarm Rate
FEM	Finite Element Method
FFT	Fast Fourier Transform
FMCW	Frequency Modulated Continuous Wave Radar
FPGA	Field Programmable Gate Arrays
GICHD	Geneva International Centre for Humanitarian Demining
GPR	Ground Penetrating Radar
HSTAMIDS	Handheld Standoff Mine Detection System
ICBL	International Campaign to Ban Landmines
IMAS	International Mine Action Standards
IR	Infrared
LWIR	Long Wave IR
MAC	Mine Action Centres
MBT	Mine Ban Treaty
MD	Metal Detection

#### ELECTROMAGNETIC METHODS FOR LANDMINE DETECTION

MIMO	Multiple Inputs Multiple Outputs
MWIR	Medium Wave IR
NDT	Non-Destructive Testing
NGO	Non-governmental Organisations
NMAS	National Mine Action Standards
NPA	Norwegian People's Aid
NQR	Nuclear Quadrupole Resonance
РСВ	Printed Circuit Board
PID	Proportional-Integral-Derivative
RF	Radio Frequency
SHA	Suspected Hazardous Area
SNR	Signal to noise Ratio
STEMD	Systematic Test & Evaluation of Metal Detectors
STMR	Single Transmit Multiple Receive
ТРА	Time to Peak Amplitude
TZC	Time to Zero Crossing
UN	United Nations
UNDP	United Nations Development Programme
USB	Universal Serial Bus
UXO	Unexploded Ordnance
VAMIDS	Vehicular Array Mine Detection System
VMMD	Vehicle Mounted Mine Detector
VMS	Vehicle Mounted System
WWI	World War One
WWII	World War Two

# **List of Constants**

Symbol	Description	Value
π	Pi	3.141592
k	Boltzmann's constant	1.38 x 10 <sup>-23</sup> m <sup>2</sup> kgs <sup>-2</sup> K <sup>-1</sup>
$\mu_0$	Permeability of free space	$4\pi \ge 10^{-7} \text{mkgs}^{-2} \text{A}^{-2}$

The following constants are used in this thesis:

## Preface

Peipei Hu was born in Wuhu, China in 1992. He studied BEng in 'Electrical and Electronic Engineering' at the University of Manchester, United Kingdom and was awarded the first class degree with honours in July 2014. During the undergraduate study period, he undertook two major projects within the School of Electrical and Electronic Engineering, under the supervision of Dr. Aspley Judith and Professor Wuqiang Yang respectively. He has begun studying for the degree of 'Doctor of Philosophy' at the University of Manchester, UK, in July 2014 with the project title 'Electromagnetic Methods for Landmine Detection' under the supervision of Professor Anthony Peyton.

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## **1.** Introduction

Landmines and other explosive remnant of war (ERW) have a great impact on many countries and communities as a lasting legacy after numerous wars and conflicts around the world. Landmines can be defined as munitions created to explode from approach, contact or just the presence of a vehicle or an individual. Landmines are indiscriminate and victim-activated: i.e., the person who triggers the mine turns into its victim; this can be civilian adults or children, not just military personnel. ERW can still injure or kill civilians even for decades after the conflict ends (see section 2.1).

Landmines can have a significant impact on the daily lives of people in mine affected communities, for instance they can deny residents access to cultivatable land, limit available transport routes, such as to schools and places of work, and instil a climate of fear, restricting routine activity.

### **1.1 Aims and Objectives**

One of the most important features of good detectors is their abilities to locate landmines correctly. Current landmine detectors, which rely on metal detection, have a significant weakness in their high false alarm rate (FAR). FAR is a rate of false positive indications, when either there is no mine present, typical a result of mineralisation in the soil or noise or interference affecting the detector, or caused by an innocuous piece of metal, known as metallic clutter. Reducing the FAR would help to increase the effective speed of detection. The higher FAR during the demining operations, the more time and effort will be spent and the higher the probability of injury to deminers and, potentially, civilians. Therefore, the main motivation of this research is to produce landmine detector technology which can reduce the FAR to increase the efficiency and safety of the demining operation. This will have added benefit of reducing cost because it will take less time, and the ability to lower FAR without significantly increasing detector cost has the potential to reduce the economic cost of demining operations.

The general aim of this research is to reduce the FAR based on current metal detector systems and this thesis focuses on the improvement and development of the metal detection technology. The research includes the design and creation of a new measurement system to determine the spectral and spatial electromagnetic characteristics of target objects such as landmine replicas and small items of metallic clutter, which may give a false signal in the field. The electromagnetic characteristic of objects is noted as the electromagnetic polarizability tensor (shortened to tensor over the rest of this thesis, see chapter 3) which relates to the target's shape, size, material and orientation. Each metal object has its own specific tensor according to its characteristics. Furthermore, the tensor is also a function of frequency and consequently the concept of tensor spectroscopy can also be applied to further represent the response of the metal object. Many landmines are mass produced and usually there is a small quantity of metal components within the landmine, such as a metallic detonator cap, a steel stab pin or spring element; therefore one type of a landmine can be represented by a unique tensor. Similarly, the metallic objects found buried in a minefield, which are considered to be clutter also contain different electromagnetic characteristics, i.e., different tensors. Therefore, the different tensors between landmines and other metal clutters items allow, in theory, a detector to discriminate between the metal content of landmines and clutter items. In addition, the researcher also studies the pulsed system applied to metal objects in time domain and frequency domain to obtain information of the modelled metal (see chapter 7).

The main objectives of this research are as follows:

- To design and construct a sensor coil array, which is appropriately sized to measure the tensor spectra of typical AP mines and clutter items.
- To design and implement front-end amplifiers which can amplify the detector signal to a sensible level with suitable signal to noise ratio (SNR).
- To use the system to determine the tensor spectra for a range of metallic objects of interest.
- To simulate the response of metal objects in the time domain and frequency domain in Ansys Maxwell, which is a commercial finite element electromagnetic field solver, in order to match these two responses via the Fourier transform.

### **1.2 Statement of Originality**

There are three main novel contributions of the research described in this thesis. Firstly, the research proposed, designed and constructed a novel sensor coil for the tensor measurement system. The combination between the transmitter coil and receiver coil produces a uniform electromagnetic field within the coil. The coil provides the possibility to measure different objects of various dimensions. A detailed review of available literature (see chapter 4) strongly indicates that no analytical solution to the studied coil geometry exists. Secondly, it is to the

author's best knowledge that no comprehensive tensor library describing AP landmines and clutter items exists. This is not surprising since very little is reported in the literature regarding the tensor of small objects. It is outside the scope of this project to produce such a library due to the availability of real AP mines, so instead a library for US coinage has been produced. US coinage was chosen because it is widely available and the values can be later verified by other workers. Lastly, the research has proposed and investigated a novel approach to modelling of a pulsed system magnetic detection system in a commercial simulation package. The pulse signal contains a great range of frequencies which can provide frequency information of the tested objects. The pulse signal simulation result has also been verified by comparison with frequency domain simulation. There has been little research on the analysis of modelling of pulsed metal detection systems; therefore this research has successfully filled this knowledge gap.

### **1.3 Thesis Outline**

This chapter has introduced the motivation, aims and objectives of this research, stressing the main novelties of the project. Following this introduction, the thesis is organised as follows:

Chapter 2 describes the main demining challenges globally and introduces the organizations and partners working on humanitarian demining. The chapter reviews current research efforts on landmine detection technology. In addition, this chapter also describes the salient aspects of existing metal detection technology.

Chapter 3 presents the electromagnetic theory behind this research, including the Biot-Savart Law, Faraday's Law and magnetic dipole moments. The definition of the electromagnetic polarizability tensor is introduced and the relationship between the tensor and the properties of the metal are also described. In addition, this chapter provides a literature review on the current state of the art of metal detection technology and research.

Chapter 4 focuses on the design and construction of the transmitter and receiver coils which are a key part of the tensor measurement system. It describes the simulation results and the analytical solution, which is a multi-paradigm numerical computing environment. The simulation methodology and analytical solution have been experimentally validated, and the experimental process and the result are also described. The chapter goes on to describe the manufacturing procedure and includes the impedance characteristic of the coil. Finally, the chapter depicts the measuring area of the testing objects within the coil. Chapter 5 describes an overview of the measurement system including the front-end electronics, the design and manufacturing of the transmitter amplifier and a discussion of the SNR performance. The chapter has also discussed one of the main sources of error, which is baseline drift in the measurement system.

Chapter 6 describes the measurement and simulation results from US coinage using the tensor measurement system. It also presents the measurement and simulation results for similar-sized copper disks.

Chapter 7 concentrates on the simulation of a pulsed metal detection system, using the Ansys Maxwell simulation package. The chapter describes the concept of the pulsed system, and continues with the modelling methodology of the system. Afterwards, the chapter discusses the simulation results in the time and frequency domains. Finally, the two simulation results are compared and validated by applying the Fourier transform.

Chapter 8 concludes with a summary of the research work and presents the main areas for future work.

### **1.4 Publications**

1. John L Davidson, Omar A Abdel-Rehim, Peipei Hu, Liam A Marsh, Michael D O'Toole and Anthony J Peyton, "On the magnetic polarizability tensor of US coinage," Measurement Science and Technology, vol. 29, no. 3, Feb. 2018.

2. Mingyang Lu, Qian Zhao, Peipei Hu, Wuliang Yin, Anthony J Peyton, "Prediction of the asymptotical magnetic polarization tensors for cylindrical samples using the boundary element method," 2015 IEEE Sensors Application Conference, Croatia.

3. Tiemei Yang, Guang Chen, Wuliang Yin, Peipei Hu, Qian Zhao, "A high frequency digital induction system for conductive flow level measurements," Flow Measurement and Instrumentation, vol 37, pp 83-91, June 2014.

# **2.Background**

In this chapter, the global landmine challenge is introduced. The chapter continues with a description of the main demining organisations and partners, emphasising the key research work and the impact on various communities globally. The chapter goes on with a discussion of metal detectors and some of their limitations. Finally, a description of existing landmine detection technologies is provided to set the scene for the research subsequently described in the thesis.

### 2.1 Global Landmine Challenge

Landmines, which are placed near, on or under the ground, have been used in wars and area conflicts for decades [1]. Landmines are filled with explosive and can be activated by either victims walking or vehicles driving over the trigger mechanism. Landmines were initially created during World War One (WWI) and later used extensively in World War Two (WWII); and one of the primary motives for their use is to provide a 'force-multiplier' [1]:

- Counter sudden ambushes and attacks.
- Reduce the threat of opponent troops and vehicles.
- Provide a barrier to the movement of enemy troops and vehicles.
- Divert enemy troops and vehicles to an unmined but vulnerable place.

Depending on the intention of the landmine planter, some mined areas can be marked to inform the enemy, whereas an alternative technique is to rely on surprise. Due to the nature of conflicts, less well-equipped military forces have routinely employed this 'surprise' planting technique as opposed to the more regular minefield marked area method [1]. Additionally, landmines can be used as weapons of terror by less conventional forces. For instance, to terrorise a civilian population to force them to flee or discourage them from returning back, post conflict. As such, they can be effective weapons to help enforce an illegal policy of ethnic cleansing. For example, the Myanmar army is reported to have planted landmines along the border with Bangladesh to pose a deadly threat to the escaped Rohingya population in September 2017 [2].

In addition, there is the burden of care to the surviving victims of landmines, with resources spent on the health and medical systems to take care of victims of the mines. There is therefore reduced resource for health and other investments such as education within countries that are affected by mines. Therefore, the mines not only cause huge pain to victims, but also create significant barriers to post-conflict reconstruction [3-6].

Landmines are regarded as a particularly malicious type of weapon as they indiscriminately kill or injure people during conflict. However, the influence of landmines outlasts the conflict as they remain dangerous for decades as a threat to future generations in the areas where the landmines are buried. It is difficult to find reliable audit figures on the scale of the problem, but some reports suggests there are around 110 million landmines still buried in the ground in 64 countries worldwide. Landmines have already killed over 1 million people since 1975 [7]. In addition to landmines, explosive remnants of war (ERW), which includes non-AP mines *e.g.* unexploded bombs, cluster munitions, anti-vehicle mines etc., are also a threat to the affected regions. Figure 2.1 shows the countries and districts affected by landmines and ERW around the world.



Figure 2.1: Countries affected by landmines and explosive remnants of war globally adated from [7].

Figure 2.2 shows the number of mine/ERW casualties per year between 1999 and 2015. After several years of steady decline in the casualty rate, there was a steep rise in the number of the casualties in 2015 which recorded 6461 casualties in 61 states and other districts according to the report published by International Campaign to Ban Landmines (ICBL); this being significantly higher than the 3695 casualties recorded by ICBL in 2014. The main reason for this sharp increase is the armed conflicts in Ukraine, Syria, Ukraine, Yemen, and Libya during 2015 [8].



Figure 2.2: Number of mine/ERW casualties per year from 1999 to 2015, derived from [8].

Figure 2.3 shows that child causalities account for at least 38% of all civilian casualties, and male casualties made up 86% of all casualties where the gender was known in 2015. It also shows that civilians account for 78% of casualties in 2015 for which the military/civilian status was revealed. There were at least 1,600 deminers who were injured or killed while delivering landmine clearance operations between 1999 and 2015 [8], underlining the inherently dangerous nature of this critical work.

**(a)** 38% Child **62%** Adult **(b)** 14% Male Female 86% (c) 2% 20% Military & security forces Civilians 78% Deminers

Figure 2.3: Distributions of mine/ERW causalities by (a) age, (b) gender, and (c) civilian/military in 2015 [8].

NB: this only includes the civilian casualties where the age was known.

Once planted, landmines do not go away until they are dug out or destroyed in situ and they do not obey any peace agreements or ceasefires. The cost of removing existing landmines and preventing manufacturing and planting around the world has been estimated to be \$2 billion per year [9-10]. Buried landmines can have significant adverse social and economic effects on society [11]. These include:

- Slow down the repatriation of a displaced population.
- Hamper the delivery of aid and activities of relief organisations
- Kill or injure landmine clearance operators.
- Burden health-care system with further causalities.
- Restrict land use where defined as a suspected hazardous area (SHA).
- Prevent land from being used for agriculture and other productive purposes.

### 2.2 Global Contributions of Humanitarian Demining

In 1996, the International Committee of the Red Cross concluded that AP mines are unnecessary weapons due to their limited military advantages. One of the most successful humanitarian demining organisations is the ICBL and its main aim is to ban any individual or organisation from manufacturing, stockpiling, transferring and planting landmines [11]. The ICBL managed to propose a treaty named as the Mine Ban Treaty for tackling the global landmine challenge. The treaty was adopted in 1997 and officially took effect on 1 March 1999. All treaty member states commit to [12]:

- Never use landmines.
- Offer technical support to developing countries which lack landmine detection technology.
- Clear landmines in their stockpiles in no more than four years.
- Clear mined areas within their territory in less than ten years.
- Deliver education on mine risk and ensure that no civilians live in the mined areas.

More than 80% of the world's states have joined the treaty and are executing their duties according to the MBT stipulations. The countries that have not yet joined the treaty include the USA, China, and Russia. However, this does not weaken the importance of the treaty since an important role of ICBL is to apply diplomatic pressure to countries to comply with treaty even without legally abiding to it. For instance, the USA is the world's greatest contributor into clearing landmines via research investment, landmine risk education and government regulation and has not planted AP mines anywhere after 1991 or exported AP mines since 1992. Additionally, in 2014, it was

announced that the USA would no longer manufacture or import AP mines and would speed up destroying stockpiles of landmines held by the US government. The ICBL and United Nations (UN) continue to lobby countries who have not yet adopted the treaty [13].

Currently, there is a significant reduction in the numbers of landmine producers and of existing landmines. A great amount of land has been freed and changed to productive use since the treaty came into effect [13]. It has been marked that over 51 million AP mines have been successfully cleared from arsenals and completed destroyed. Additionally, there has been increased support and recognition for landmine survivors [13].

The ICBL continues supervising the treaty states in order to ensure that they fulfil their responsibilities. Additionally, the ICBL plays an important role in actively encouraging more countries to join the treaty. However, it is estimated that it would take over 1,000 years and 30 billion US dollars to clear all existing landmines using current technology [7]. The UN and many states are now conducting more actions to address the landmine issue. This global challenge still requires more help from different organisations to develop humanitarian demining technology.

### 2.3 Demining Organisations

A number of organisations play important roles in developing landmine detection technology and corresponding websites which provided the basic information of mine action are displayed:

- International organisations tackling the landmine problem, i.e. the United Nations Mine Action Service (www.mineaction.org), the national Mine Action Centres (MAC) in Croatia, Cambodia, Laos, etc. and the Geneva International Centre for Humanitarian Demining (GICHD, www.gichd.ch). The main purpose of the GICHD is to support national authorities, international and regional organisations to improve the relevance, performance and sustainability of mine action [14]. The standards were retitled as the International Mine Action Standards, known as IMAS specifies the clearance depth in IMAS 09.10 [15]. More information of GICHD and IMAS can be found in section 2.4.2.
- Find Non-governmental Organisations (NGO). such as A Better Wav (www.findabetterway.org.uk), focus on research aspects of detecting landmines, supporting education and humanitarian benefits to improve conditions for people living in conflict regions. There are also very large NGOs involved in humanitarian demining. For example, Mines Advisory Group (MAG, Halo Trust www.mag.org.uk), (www.halotrust.org) and Norwegian People's Aid (NPA, www.npaid.org).

 Academic organisations, such as the University of Manchester, UK, known for landmine detection and GPR technology. The related projects are funded by FABW, and the charity also funded various projects across Imperial College, University of Bath, and University of Zagreb etc.

Colin King, served in Explosive Ordnance Disposal (EOD) department in the British Army, described existing mines in a report [16]. Andy Smith, works as chief technical advisor for United Nations Development Programme (UNDP) for demining groups, makes effort on humanitarian demining [17]. The final reports of the project MIMEVA from DG Joint Research Centre [18] and EUDEM [19] produced by European Union (EU) in Humanitarian Demining are recommended as a starting point to initiate knowledge of this research.

### 2.4 The Role of Metal Detectors

Although landmines can be visible to the naked eye when planted on the surface, it is more usual for landmines to be laid sub-surface or over time become more discretely buried. Several methods can be used to detect and destroy landmines. These include mechanical methods, manual demining and the use of dogs [20]. The mechanical approach is fast but cannot fully achieve the humanitarian demining accuracy required by international safety standards. Additionally, mechanical methods are not well-suited to all in terrains and are not regarded as environmentally friendly with the risk of AP mines being pushed to one side or buried deeper or becoming partially damaged making them more dangerous. Although many technologies have been applied for manual demining *e.g.* electromagnetic methods, biological methods and acoustic/seismic methods, metal detectors continue to be used as the primary detection tool used by deminers. Metal detection (MD) is a mature technology which over time metal detector manufacturers has improved sensitivity in efforts to detect minimum metal landmines [21]. The humanitarian community's reliance on metal detectors is due to several factors. First, there is a good understanding of how the detectors operate and several companies compete to bring the most effective detectors onto the market. Second, the technology is relatively inexpensive. Third, current procedures are based on ensuring the ground is free of all metal, and while zero-metal mines exist, most have now been removed so they are hardly ever found. So, effective, safe operating procedures and quality controls can be put in place based on the assumption that no metal mines. However, metal detectors have the serious limitation of detecting metal clutter such as fragments of shell and bomb cases, wasting significant time excavating items that are not dangerous. Ideally, deminers would like to be able to ignore harmless metal items so that they can concentrate on explosive devices.

Consequently, metal detection technology has been combined with other modalities such as ground penetrating radar as described in section 2.6.1.

#### 2.4.1 Background to International Mine Action Standard

A set of international standards for humanitarian mine clearance were first put forward in March 1997 by the UN; these standards were updated in 2000. This resulted in changes to operational clearance procedures, personnel training, landmine risk education, and stockpile decommissioning methods. IMAS developed with support from the Geneva International Centre for Humanitarian Demining (GICHD). These standards are under continual review by governmental and non-governmental organisations in order to take into account new technological and methodology developments. The main purpose of IMAS is to propose a common and consistent way to clear mines / ERW safely and efficiently [22].

IMAS are involved in all stages of demining including locating mined fields, determining landmine positions, mine clearance and providing confirmation of freed land. IMAS also provide the regulation of occupational health, risk education and aid for victims. IMAS are routinely updated after being reviewed regularly with the support of GICHD which functions as a member of Secretary of the Review Board [23].

The GICHD plays a key role in managing and developing IMAS in different ways. For example, the GICHD may be requested to draft updated version of IMAS once the decision was made by the IMAS review board. Additionally, the scientists and engineers at the GICHD can also put forward their suggestions and opinions in IMAS review board. Also, the GICHD provides a consultation service to relevant authorities or stakeholders in the review of IMAS [23].

The International Mine Action Standards are applied to three main areas. Firstly, IMAS are regarded as a guide to any landmine detection community to ensure its work is adheres to relevant standards and professional codes of practice. Secondly, they provide a structure for developing National Mine Action Standards (NMAS), which are typically country-specific. Thirdly, the IMAS may be taken as the national standards before the NMAS are generated [24]. This thesis will only focus on certain relevant standards, such as the location and clearance of the landmines.

According to the United Nations, there are five defined stages of demining, and metal detectors can be used in stages 1, 2, 3, and 5 [23].

- 1. Find the mined fields.
- 2. Determine the location of the landmines within mined area.
- 3. Confirm the individual landmine / ERW.
- 4. Remove each suspected object.
- 5. Confirm the area is safe and open to civilians.

Additionally, there are significant differences exist between military mine clearance operations and humanitarian demining. Humanitarian demining sets out to detect, remove and completely destroy all mines in a non-military area, whereas military procedures are far more strategic, requiring rapid clearance of path through a mine field.

#### 2.4.2 Specifications of Clearance

There are some critical specifications of clearance provided by IMAS. Before clearing a mined area, a technical survey or other trustworthy information should be provided. One of the most important details of the technical survey is the specified depth of clearance. An evaluation of the suspected mines and ERW hazards determines the default depth of clearance. Normally, the depth is more than 130 mm below the initial surface level for mines and ERW [25]. The value of the depth is concluded by the effective detection depth of most metal detectors. The depth of the clearance also depends on the future function of the land. In addition, the required clearance depth may be changed and the clearance process should be repeated if there is any change in the land's usage [25].

### 2.4.3 Categories of Mined Areas

The use of a metal detector will be various according to the area where the landmines are located. There are in total of 12 scenarios of mined areas which represent the full range of operational environments. Table 2.1 shows the detail of the scenarios accompanied with corresponding characteristics [26].

Categories	Characteristics	
Grassland	Open (flat or rolling) land	
Woodland	Heavily wooded land	
Hillside	Open hillside	
Routes	Unsurfaced roads and tracks, including 10 m on each side	
Infrastructure	Surfaced roads and railway tracks, including 10 m on each side	
Urban	Large town or city	
Village	Rural population centre	
Mountain	Steep and high altitude	
Desert	Very dry, sandy environment	
Paddy field	Land allocated for growing of rice	
Semi-arid savannah	Dry, open and flat, little vegetation	
Bush	Significant vegetation and possible rock formations	

Table 2.1: Categories of mined areas with corresponding characteristics adapted from [26].

GICHD classifies the disturbance of metal detectors for different scenarios. The disturbance is defined as 'none', 'low', 'medium' and 'high'. The disturbance of 'none' or 'low' means there is no or insignificant influence on the metal detector. The disturbance of 'medium' represents a reduction of the possibility of detecting minimum metal mines and causing safety issue of clearance. The disturbance of 'high' denotes the scenario where the metal detection can fail. These four situations can happen in any of the 12 categories shown in Table 2.1 [27].

#### 2.4.4 Demining Procedures using Metal Detectors

Several stages of the demining process *e.g.* initial assessment, surveying, clearance and confirmation of cleared areas all use metal detectors. Basic operational detector tests are performed prior to scanning the region of interest. These include checking the general condition and functionality of the metal detector at the start of the day, along with adjusting the detector to local ground conditions. Such checks are also repeated for any changed conditions during scanning and at the end of each scanning session. Additionally it is necessary to check the user manual of the metal detector manufacturer prior to setting the detector up. Carrying out comprehensive checks ensure the correct operation of the detector and crucially, the safety of the operator. An example summary of the minimum checks required prior to surveying is given below [27]:

- Check the general condition of the detector such as wire connections, visible damage, and battery etc.
- Check if the detector is functional. This process is called the 'warm up' or 'set up' and usually lasts for a few minutes.
- Adjust the parameters of the detector according to the local conditions.
- Check if the detector can target a known object. This is a critical step of checking the detector because it can make the work safe and successful. This process can be conducted by checking that the detector has the ability to locate known objects in similar ground conditions. Normally, the known target is chosen to be a minimum metal mine at the maximum clearance depth to verify the best performance of the detector. The targets for routine checks will be described further in section 2.4.6.
- Repeat 'warm up' if the mine area's condition is changed.
- The last step of the check list is to disassemble the metal detector and check the general condition again.

Among this check routine, the battery check is important and each detector is equipped with specific batteries. The detector manufactures tend to design the product based on the physical dimensions of the batteries. In addition, detectors usually contain a battery-check and system failure circuitry to warn of any issues with the detector. Finally, it is usual for a detector to give confidence clicks in the audio signal to give assurance to the operator that the detector is operating correctly.

The deminer should take every signal generated by a metal detector as the response of a mine even if the signal strength changes and does not reliably discriminates from background signals. If the signal generated at one place is consistent with signal responses of nearby mines already positively targeted, the operator could have more confidence to suspect there is a mine underground. For any other situations, the deminer should take changing detector response as a potentially mined area. This is why metal detector operators need to take considerable effort in order to locate mines. Additionally, mine detection possess an inherent weakness since virtually all mined areas are within regions of previous of previous conflicts containing significant metal contamination. This gives rise to significant FAR with the deminers routinely finding up to 100 innocuous objects for every positively identified mine [28]. This significantly hinders throughput, increases clearance cost and impacts on the safety of the deminer.
It is of the greatest importance to find the location of the metal item accurately using the detector. "Pinpointing" is defined as the process that the deminer delivers a fine test after the metal object is detected. This technique uses a greater number of measurements over a smaller area in order to pinpoint the target. Essentially, the deminer changes directions of the scans of the head of the detector in order to increase the accuracy of determining the location of the mine. This involves sweeping the head of the detector at different orientations and angles approaching the target in such a way as to better-estimate the size and location. It has been shown that it is significantly safer and quicker to excavate landmines if the location is identified to within better than 10 millimetres [29]. Figure 2.4 shows the signal area produced by the detector from the weakest to strongest area [29]. The deminer determines the boundary of the signal area and starts to dig towards the mine from the sides.



Figure 2.4: The method used to find the precise location of the mine adapted from [29].

Using the described pinpointing technique, the deminer marks the closest boundary where the detector signals for excavation. The excavation process involves lateral probing of the ground from the sides of the marked boundaries along with digging and advancing sideways towards the estimated target centre. If the probing technique suggests a mine-like object, further excavation is used to expose the mine from its side to confirm its nature. Subsequent exposure of the mine enables an informed decision to be made on the most effective demolition or disarming option. There are some concerns about risks of manual lateral probing especially for deeper mines have been discussed in [30], while the probing technique is still be used by some deminers.

#### 2.4.5 Targets for Metal Detector Checks

The targets used to check the correct operation and sensitivity of the metal detector can be real examples of the mines (with their active non-metallic parts removed) or mine surrogates. The calibration test pieces such as ferrite rode or titanium cube are used for calibrating detectors. These

surrogates may not have exactly the same metal components of the equivalent mines; the intention is that they produce an equivalent response from the metal detector.

Figure 2.5 shows metal components of several AP mines. The number of the metal components does not necessarily determine the difficulties of locating the landmines. For example, the GYATA 64 contains coil- and leaf springs, a small piece of lead, a detonator, a circlip and a large firing pin; the R2M2 contains a ball bearing and a stainless steel spring; Type 72a contains two tiny metal-alloy detonator shells, a small spring and a metal pin; the PMA-2 contains a small aluminium-alloy detonator; The PMN contains a piece pf chopped lead, a larger firing pin springs and a circlip [27].



Figure 2.5: The metal content of some target objects reproduced from [27].

# 2.5 Metal Detectors for Humanitarian Demining

The following subsections will be devoted to an introduction of the current metal detectors which are used for humanitarian demining. The role of the metal detectors has already been described in section 2.4. The research and further development of metal detection technology are complicated due to following [21]:

• **Target objects and metallic clutter variability:** Significant variation in shape, size and metal content of AP mines exist as described in section 2.4.6. Additionally, many modern AP mines are plastic caused and only contain a minimum amount of metal giving rise to weak electromagnetic responses and making metal detection difficult. The problem is

further complicated by the presence of clutter items which vary greatly in size and composition making distinguishability from the target object difficult [31].

- Soil properties: The soil is usually regarded as non-cooperative soil, however, it should be pointed out that this is a first-order approximation, which will get less accurate when the test object becomes deeper, smaller, permeable or less conductive, and when the soil gets more permeable, conductive or heterogeneous. For example, in magnetic soils it can be very hard to detect target objects [21].
- **Incomplete scientific knowledge:** Most metal detector manufacturers are small to medium-sized enterprises, which protect their investment critically and publish the technical details very carefully. There are some patents describing the technology in a certain degree collected in [32].

Additionally, repeatability, settling time, sensitivity drift, and ergonomics including weight and ease of handling/operation are also increasing the complexity of the problem; it appears that there is no current metal detector for the humanitarian demining manufacturer that has disclosed quantitative information on the target items with full analysis, at least to the author's knowledge.

#### 2.5.1 Overview of Metal Detector Manufacturers

There is a limited literature on the technical details from the metal detector manufactures, with the exception of the relevant patents. The military market is the main destination of metal detector production. Most of the manufacturers also create other applications using inductive sensors, such as non-destructive testing (NDT), magnetometers, and security devices.

The USA and European metal detector manufacturers play important roles in this industry at the international level, including US Army, Britain (Guartel), Austrian (Schiebel), German (Vallon, Foerster and Ebinger), and Italian (CEIA). In addition, an Australian company (Minelab) is one of the world's largest manufacturers of hand held metal detector products [33].

The total number of metal detectors sold for humanitarian demining is possibly less than a few thousand every year, which indicates that sales would be approaching ten million Pounds Sterling [21]. This provides a rough idea of the market in this industry while the importance of the related military markets cannot be ignored [19].

Literature in the area of absolute metal detector performance from the Institute for the Protection and Security of the Citizen carried out a project named Systematic Test & Evaluation of Metal Detector (STEMD) in 2006, and they compared the performance of different metal detectors including speed tests, repeatability on set-up, sensitivity drift, detection capability of specific targets in-air, minimum target detection curves in-soil and power consumption [29]. The project found that the measured detection depth of realistic targets with full-sized mine items can be trusted only in-soil measurements, and it also recommended that demining organizations could employ different landmine detector according to their own priority, such as some users prefer high sensitivity, others concerned more about detector ergonomics and handling [29]. Some technical issues when evaluating the performance of the metal detectors were raised and discussed in [34-35].

### 2.5.2 Portable Metal Detection Systems

Metal detectors for humanitarian demining are very sensitive inductive sensors, which can detect a small amount of metal at a shallow depth in the ground. Frequency domain systems have been widely used due to the good performance of detecting small target objects, but pulse systems have become more and more popular in recent years due to their ability to reject the effects of the ground and allow simple coil geometries to be used [36]. Human-portable systems all have similar characteristics, as follows [19]:

- **Price:** between 2000 and 4000 Pounds Sterling as of 2017.
- Weight: No more than 2 kg.
- Size: Most detectors have a round, rectangular or oval sensor head. The diameter of the head is normally in the 20 30 cm range, to achieve enough depth and a good performance of scanning speed; the thickness is around a few centimetres.
- **Electrical/Power:** suitable for cell batteries and can last tens of hours. Ergonomics is an important concern for the demining teams instead of pure performance of the detectors.
- Operating depth: shallow, from the surface of the ground to about 10 15 cm for small metal items, 20 30 cm for mines with an considerable metallic content and 50 70 cm for large targets (*e.g.* UXO and unexploded bombs).
- **Output:** normally, an audio alarm sounds when detecting a metal object. Every alarm should be carefully checked until it has been wholly analysed and/or its source cleared.

There are some large metal detectors, which are produced by Ebinger and Vallon in Germany, created to detect larger metallic items, such as UXO. They can be used in the magnetic soil areas where magnetometers cannot be employed [19]. The magnetometer is an instrument which can measure magnetism and a new biaxial magnetometer sensor has been proposed to improvement the sensitivity comparing to a conventional fluxgate magnetometer [37].

There are a number of critical limitations of existing metal detectors such as high FAR (100:1 to 1000:1) because of the metallic clutter [19] or the mineralized soils of mined areas which can reduce the sensitivity.

### 2.5.3 Arrays (Vehicle Based Systems)

The majority of metal detector arrays are developed from a single metal detector and their width is usually one to several meters such as the Minelab Single Transmit Multiple Receive (STMR) metal detector array. The main advantages of the arrays include fast scanning of the suspected area, providing information not only on the location of the metallic items but on their approximate shape and buried depths. These types of systems are mainly used for detecting large targets such as unexploded bombs. In addition, some vehicle-based systems keep the height constant to ensure the sensor head is parallel to the ground [19].

European manufacturers occupy the biggest market of metal detector arrays. For example, Schiebel Vehicular Array Mine Detection System (VAMIDS) has been employed in different projects; it contains eight separate sensors within 1 m wide segmented arrays [19]. Also, TZN in Germany has been produced AMOS Unexploded Ordnance Detection System, which structures a two-layer coil system and relies on a pulse induction system [19]. In general, vehicle based systems are only good at detecting UXO and struggle with AP mine detection.

Figure 2.6 shows the data acquired by the Schiebel metal detector array VAMIDS on a dirt road at Defence Research Establishment Suffield (DRES). There are 9 equidistant strips standing for the full width of the array because the detector travels along the road with the same speed. The black area represents a strongly negative signal and white area means a strongly positive signal. The array has detected some mines circled in lane 2, lane 7 and lane 9 in Figure 2.8, a number of metallic items and false alarms [38].



Figure 2.6: Signal image of Schiebel VAMIDS adapted from [38].

There are also some other vehicle based systems adopted the same principles, such as vehicle mounted system (VMS) invented by Vallon and Husky Vehicle Mounted Mine Detector (VMMD) produced by DCD Protected Mobility (DCD), and a baseline performance evaluation of the system has been described in [39].

## 2.6 Review of Alternative Technologies to MD

Metal detection technology has become a mature method for humanitarian demining over the past 50 years. The main enhancements of metal detectors concentrate on improving background rejection to deal with different soil conditions, and increasing sensitivity. This section introduces some alternative sensor technologies for landmine detection, including Ground Penetrating Radar (GPR), Infrared (IR), Electrical Impedance Tomography (EIT), and Nuclear Quadrupole Resonance (NQR). Additionally, manual (prodders and probes), mechanical excavation (mechanical machines), and biological methods *e.g.* dogs, rats or bees are also alternative technology to MD.

### 2.6.1 Ground Penetrating Radar (GPR)

GPR technology has been applied in geology, civil engineering, and archaeology for soil study and detecting buried items over the last 25 years. Today, many organisations are putting effort into different parts of the GPR technology, and landmine detection is one application area, since plastic mines can potentially be detected by radar [16, 29]. In addition, GPR has been combined with the traditional metal detector in dual sensors to reduce FAR and improve the detection capability [41]. The principle of GPR is similar to that of radar, an electromagnetic wave is emitted and the subsequent reflected wave is measured. However, in the case of GPR, the wave propagates into the ground using an antenna not requiring ground contact. The air-ground interface and any subsurface objects cause wave reflections due to the different electrical properties (*e.g.* dielectric constant) at material boundaries. A second antenna or antennas are used to pick up these reflections and carry out subsequent processing. The GPR system can potentially determine the position and shape of target objects according to the received waves [42]. Generally, higher frequencies for GPR systems will provide theoretically higher spatial resolution but higher frequencies also limit the penetration depth, thus a compromise between image quality and penetration depth resulting in the range of operating frequencies for GPR systems is between several hundred MHz and a few GHz. There is little risk of harm for system operators because most systems are carried out with low power [19].

#### 2.6.1.1 Categories of GPRs

GPRs can be divided into three different categories according to their operating principle as follows [19]:

- **Time domain GPR with an impulse system:** The GPR system emits a pulse signal with a carrier frequency and is modulated using a square envelope.
- **Chirp Radar:** The system emits a pulse signal and the carrier frequency is changed quickly along the pulse width.
- Frequency domain GPRs: The system transmits a waveform and the carrier frequency is changed across a selected frequency range. For instance, stepped frequency radar with a fixed-step-changed carrier frequency and Frequency Modulated Continuous Wave Radar (FMCW) with a linear-changed carrier frequency.

The performance of different types of GPRs is related to how each method is implemented and the difference between the target objects and other clutter. The clutter in GPRs includes more than the term "clutter" from the point of view of metal detectors, it also includes inhomogeneities such as rocks, vegetation roots, pockets of water etc. The amount of energy returned to the antenna depends on the characteristics of the objects, such as size, shape, and materials. Operating frequency determines the spatial resolution and wide frequency bands are necessary for the system to provide a good resolution for small items. The condition of the soil has a big influence on reflected signals, *e.g.* clay, especially wet clay, can significantly attenuate the receiver signals.

### 2.6.1.2 Configuration of GPR Systems

GPR systems for humanitarian demining provide either detection warning, such as an audio alarm, or image data. The majority of handheld detectors simply use an audible alarm; however, more recent versions are beginning to include visualisation of GPR data.

The alarm method requires that enough information of the target item is obtained from the reflective signal, which should be then analysed in order to detect the target objects and categorize them. The challenge lies in determining exactly how to extract and analyse the information accurately.

In the data imaging method, the demining area should be well-understood so that the radar's position can be acquired correctly in real time. In practice, it is difficult to design a tracking system for a portable GPR probe due to the required accuracy and the coverage of the scan area. B-scans (vertical slices), C-scans (horizontal slices) and full 3D volume are commonly used as a spatial structure of received data. The antennas should be scanned stably to keep the level of spatial resolution [19].

Depending on the application, the imaging method may be preferred; however, it requires a highlevel of high speed data analysis and processing, image reconstruction and visualisation, which may be costly. In addition, some organisations and manufacturers use GPR arrays to reduce the scanning time but further increase the complexity and cost of the system. There are two types of visualisation i.e. an image of the reconstructed scene and an image of the classification of the target objects [19]. Figure 2.7 shows an image of scene reconstruction, and area A represents a plastic cased landmine target and area B stands for a metal packaged target. The image also shows the precise location and the depth of the landmine targets.





#### 2.6.1.3 Limitations of GPR

GPR is a technique which measures the contrast between target objects and the ground. Any contrast will create a reflected signal to the receiver antenna, therefore the technique lacks specificity. Furthermore, the characteristic of the soil plays an important role when detecting metal-based or plastic mines. For example, the presence of a metal mine in a far-less conducting soil would generate a significant reflected signal. Conversely, a plastic mine within sand or sandy soils would be far more difficult to detect [44]. The situation can be further complicated if multiple dielectrics are present within the target mine. Additionally, the same GPR system can perform very well or very poorly depending on the condition of the soil. Therefore factors such as rain, humidity or conductivity of the soil can affect the performance of GPR systems.

A significant limitation of GPR is the effect known as "ground bounce" [44]. This is due to the large reflection received from the ground surface itself which is normally the area of greatest dielectric constant. This can become an issue for GPR systems if there are small plastic mines planted at very shallow depths (*e.g.* a few cm) because the reflected signals from the surface of the ground can 'hide' the mines' waveforms. However, the effect can be significantly reduced using GPR systems with higher-bandwidth and very short pulses with negligible ringing resulting in increased resolution [42]. In addition, non-metallic clutter items are another challenge for GPR

as they generate spurious reflected signals from heterogeneous subsurface features, such as roots, rocks and water bags etc. The briefly described limitations and challenges are the main sources of FAR for GPR [42]. Despite such limitations, a number of detectors are now available commercially most notably the Handheld Standoff Mine Detection System (HSTAMIDS) and the MineHound system. The following subsections describe each system.

#### 2.6.1.4 The AN/PSS-14 Detection System

The AN/PSS-14 detection system, HSTAMIDS, is an innovative landmine detector manufactured by CyTerra. The system according to CyTerra represents a step change in detection technology and combines advanced data fusion algorithms, highly sensitive metal detection technology and GPR which enables a reliable, consistent and effective detector for detecting low-metal AP mines and anti-tank mines. The manufacture also claims that the system can adapt to all different soil types, such as frozen, dry, wet, sand, clay and laterite with an exceptionally low FAR [45].

There are two audio alarms installed in the sensor, one for the GPR system and the other for the MD, and they are reported to the system operator simultaneously. The audio signal built in to the metal detector varies in volume and pitch according to the detected items' size, type, and depth. Moreover, the data fusion algorithm, Aided Target Recognition (ATR) provides another sharp beep signal when both MD and the GPR detect a mine-like item. The audio signals can be turned off by the operator when necessary. This function helps the operator inspect high-metal anti-tank mines which generate a constant high volume of audio alarm [45]. The HSTAMIDS-AN-PSS-14 has been deployed in Cambodia, Afghanistan, and Thailand for the US army. Figure 2.8 shows an operator investigating a mined area using this detection system.



Figure 2.8: The HSTAMIDS-AN-PSS-14in operation [45].

### 2.6.1.5 VMR3 MineHound



Figure 2.9: Deminers in Cambodia are taught how to use the Vallon VMR3 system [49].

MineHound is a handheld detector which combines both metal detection and GPR with the aim to reduce FAR and thus improve the detection rate of low-metal mines [46-48]. The system combines a custom GPR developed by Cobham (ERA Technology, UK) with a pulse induction metal detector produced by Vallon (Germany) and is shown in Figure 2.9. The GPR implements time-domain radar emitting 1 ns duration pulses continuously at the frequency of 1 MHz. A digital signal processor is embedded in the system to control and deliver signal processing functions [45]. For example, an adjustable start search point can be used to remove noise from the soil surface along with a second adjustable limit to remove noise from bedrocks and water tables. Additionally, the GPR provides accurate target position and depth information due to bespoke single receiver and transmitter antennas with directly mounted front-end and controlling printed circuit boards (PCBs).

The MineHound is to use and the operator can judge the different detection situations via two audio signals. The GPR and MD audio signals can work separately or simultaneously. The information of the target object, such as size and position, can be obtained by the detector once the audio signal or signals occur. The system is capable of detecting minimum metal AP mines and the diameter of the smallest detectable buried mine can be small as 5 cm; it can also reject metal fragments of considerably larger size than landmines [40, 45].

MineHound has been used for humanitarian demining in Cambodia from 2010-2013 and deployed to Afghanistan during 2012-2013 [49]. In Cambodia, demining teams used MineHound to clear 573,109 square metres and came across 661,890 audio signals, and 92% of the signals were regarded as metal clutter. Furthermore, 845 real landmines and other threats were successfully identified. In Afghanistan, MineHound investigated 197,044 metal signals and 99% of them were marked as clutter. In total, an area of 432,082 square metres was cleared [49]. In conclusion, the MineHound system has improved productivity and reduced labour for humanitarian demining in mined fields, although the initial investment is more expensive than the conventional metal detector [49].

#### 2.6.1.6 Summary Evaluation

GPR for humanitarian demining has been investigated and developed considerably in recent decades, and the technology is becoming the most important supplement to metal detection. Instead of cueing entirely off the metal components, it focuses on the variation of the dielectric constant of the mines [42]. The biggest disadvantage of GPR lies in its response to clutter (section 2.6.1.3.).

The combination of GPR and MD provides the most promising results for humanitarian demining with reduced FAR and improved detecting capability. The successful applications of HSTAMIDS and MineHound systems have verified this combined technology. Finally, it is meaningful to monitor the innovations of GPR, such as image reconstruction in real time and new design of antennas; so that humanitarian demining tests can be conducted once the technology is mature.

### 2.6.2 Infrared (IR)

Figure 2.10 shows the operation principle of infrared detection. Differences in thermophysical properties of landmines and soil form the basis of IR thermography [50]. Namely, that mines retain or release heat at a rate different from the surrounding soil. This difference in thermal capacitance leads to measureable IR emissions (or signatures). The technique depends on factors that affect

the formation of thermal signatures, such as the depth and size of the burried mine, soil properties and the time of day the measurement is carried out. The method uses infrared camers to measure the difference in the wavelength spectrum of the infrared radiation between the soil and any other buried landmines. The measurement devices usually operate in the  $3-5 \,\mu\text{m}$  or  $8-12 \,\mu\text{m}$  wavelength ranges individually or simultaneously, which are named as Medium Wave IR (MWIR) and Long Wave IR (LWIR) respectively. It is assumed that the change in the surface temperature is the same as the change in the radiation. The former change may disappear after a while, but the latter one will be stable unless the device settings are modified. There is no difference in surface temperature if a mine is buried below 0.1-0.2 m since thermal diffussion effects do not extend over these distances. However, a mine still releases heat to the nearby soil at various rates, so the thermal difference between mine-containing soil and mine-free soil can still be used for mine location [38].



Figure 2.10: Operating principle of infrared detection of buried landmines [38].

The maximum detecting depth can be reached by enough spatial resolution instead of implementing the most sensitive sensors. In addition, natural solar heating and cooling over buried items and soil between daytime and night is different, so environmental conditions play an important role for passive infrared imagery. The technology will be unsuitable for mine detection when the thermal difference is negligible. There are other problems related to the history of the target items, uneven surfaces, vegetation and clutter, which can introduce secondary effects, *e.g.* the magnetic field introduced by clutters. Two main methods to increase the IR efficiency are as follows [19]:

- The investigation of IR image sequences, presenting the dynamic behaviour due to the time variant heating, such as solar radiance has been studied by German BGT and Belgian VUB [19].
- The IR system polarisation of the emitted and reflected signals of the man-made items, namely the deployment of another physical parameter has been studied by the UK DERA, French Thomson-CSF and German Daimler Benz. The IR system can produce periodical image sequence by changing the polarisation orientations [19].

Both approaches generate contrast between man-made items and the environments via analysing image sequences and conjugating them into a parametric image, and the approaches increased the detection speed and reduced FAR.

IR systems for landmine detection have been extensively studied by some research centres and companies, such as the LOTUS project (Multi-sensor Remote Controlled Vehicle) and EC DG VIII pilot project (Airborne Minefield Detection in Mozambique). LOTUS is a project which integrates and demonstrates a multi-sensor system for humanitarian demining. The system combines a MD array developed by Foerster (Gemany), and IR camera from TNO-EFL (The Netherland), and GPR developed by EMRAD (United Kingdom). The system has been used in field trials in Bosnia in 2002 [51]. The detail of the project will be described in the following section as an example of this research.

### 2.6.2.1 The Infra-red Detector in LOTUS

The IR landmine detection system of the project LOTUS is composed of an off-the-shelf camera which is shown in Figure 2.11, a digital processing subsystem and a host PC. The IR camera is supported by a Matrox Genesis board, which functions as a frame taker to digitize the camera output and perform the signal processing of the DSP. The principle of the IR detection system relies on the temperature difference between the landmines and surrounding soils. In addition, the approach uses local contrast enhancement to make the background temperature more stable and reduce the FAR by analysing the detection hotspots in the processed images [51].



Figure 2.11: The IR camera used in LOTUS [51].

The IR processing contains four main steps which are shown in Figure 2.12. In the first step, the IR camera collects 256 x 256 data points describing a 1.16 m square. This corresponds to 4.5 mm individual square pixels. Subsequent resampling involves searching 25 mm squares and assigning a pixel value found in this smaller search to grid cell positions. The grid cell will be filled with highest pixel value once the position is detected as a 25 mm square rather than 4.5 mm square. The second step is known as a "blob search", whereby areas with the high contrast are potential target landmine locations and they are searched and marked with digital ones. During the third step, a local contrast enhancement algorithm is applied to each grid cell. The intensity of each cell is presented based upon the analysed results. Finally, the fourth step involves a fusion process giving the regions of the interest shown in the second step and the intensity values produced in the third step to give a final processed output [51].



Figure 2.12: Four IR processing steps: (a) re-sampling; (b) blob search; (c) local contrast enhancement and (d) final processing result adapted from [51] and the circle regions clearly show the image enhancement providing by the processing steps.

The main purpose of the LOTUS project is to detect and locate AP mines in real time. The system was tested during a field trial [51] in the Northeast of Bosnia and Herzegovina. The trial site was within a suspected mined area of flat farmland which had been previously cleared and divided into five 50 m long test lanes. Several deactivated targets including PMA2 and PMA3 were surface laid and buried to depths ranging from 1 cm to 21 cm to the top of each AP mine. The results acquired by the IR detection system were promising. It detected various metal objects including PMA 1A, 2 & 3, No 4 and PROM buried in the field with different depths. The successful rate of detecting the metal objects is 100% in the first three lanes, 93% in the fourth lane and 69% in the fifth lane. The conclusion from this project is that the IR sensor is suitable for detecting minimum metal AP mines with a maximum detecting depth of 8 cm [51].

#### 2.6.2.2 Summary Evaluation

IR systems have been developed in last two decades and are becoming more accepted by the landmine community. The biggest feature of the systems is their imaging capability. Although the signature variations with different environment conditions are still a problem for thermal IR detecting systems, a better understanding of the tested objects and the metallic clutter could improve their performance. In addition, the innovation of the sensor and the time-history information will help to understand the variations of the thermal signatures [52].

### 2.6.3 Electrical Impedance Tomography

EIT has been used in the areas of biomedical [53-55], geophysics [56] and in process engineering [57] to image inaccessible regions of interest. The technology is low cost and the electrical conductivity distribution can provide the direct information of the conductive medium. It can be applied to detecting buried objects because the ground is conductive to a certain degree. Particularly, the technology can be used for landmine detection as mines are normally buried at shallow depths and result in a discontinuity of the soil conductivity [58].

Electrical potentials are measured across different electrodes for various current injection sites in EIT. The measurement results are then applied to solve the relevant quasi-static inverse problem to image the electrical conductivity distribution. For ground probing, the electrical conductivity distribution is produced by the results of an array of electrodes, which is located on the surface of the ground. The landmine buried in the ground causes an anomaly, which disturbs the conductivity distribution [59]. The signal contains the target's information, such as the size, shape, conductivity, and the buried depth [58-61].

Figure 2.13 shows an experimental system used to study the feasibility of this approach for landmine detection, used at DRDC Suffield [58]. The instrument consists of an electrode array, a data acquisition system and a data processing segment. For this application, there are 64 electrodes in total with a stimulation current of 1 mA and an operating frequency of 1 kHz.



Figure 2.13: EIT landmine detector during a field test at DRDC Suffield adapted from [58].

Church *et al* [60] tested the system using anti-tank mine surrogates buried in ground at various depths from 6.4 cm to 21 cm. The detector response for the replica and the real response received from the measurement produce a correlation. The position where largest correlation occurs is considered as the position of the target object. Figure 2.14 shows the detector response of a mine-like object buried in a sandy soil at a depth of 14 cm. The graph presents the accurate position of the target items in terms of the original point in metres [60].



Figure 2.14: Detector response of a mine-like item buried at a depth of 14 cm in a sandy soil. The vertical axis is the detector response in arbitrary units and the horizontal axes units are the horizontal distance from the centre of the object (0, 0) in metres [60].

At present, EIT landmine detection technology can work well down to a depth of 15-20 cm for detecting large targets *e.g.* tank mines, where the depth is defined between the surface of the ground and the top of the target object; and EIT is difficult to detect minimum metal AP mines. The proper filter method is critical to reduce the FAR produced by different sizes of the target objects [60].

#### 2.6.3.1 Summary Evaluation

EIT technology can detect metallic and non-metallic landmines because the technology only detects the disturbance of the soil electrical conductivity distribution. EIT performs well in wet environments, such as marshes beaches. This is because damp condition makes good electrical contact. The components of the EIT detection system are relatively simple and inexpensive which is one of the advantages of this approach [58].

However, there are some severe limitations for EIT technology for landmine detection. First of all, electrical contact between the electrodes and the soil is required for this technology. The straight contact could detonate a mine. Secondly, EIT cannot perform well in non-conductive environments, such as rock covered places and deserts [58].

EIT technology for humanitarian demining can be improved significantly from different aspects. For example, a better understanding of the receiver operating characteristic curve in different environments [60], a better deployment method of the system, and a fast data processing unit [58].

### 2.6.4 Nuclear Quadrupole Resonance (NQR)

NQR methods of humanitarian demining depend on the analysis of radio frequency (RF) signals from the N<sup>14</sup> nuclei within the mines [61-63]. RDX and TNT are widely used as explosive fills of landmines and they can be used to NQR landmine detection due to the solid crystal structure and existence of nitrogen. The frequencies of the RF signals are between 0.5 and 6 MHz, and they are one of the features of an explosive. The positive identification, the estimate of quantity of the explosive and their depths are provided by the signals. In addition, signals can only be observed in solid or solid-like materials, avoiding false alarms from other materials which are nitrogen contained in the surrounding area or the mine casing [65].

Figure 2.15 shows a block diagram of a typical NQR detection system and Figure 2.16 shows the corresponding laboratory apparatus of the system. RF excitation signals, which are generated by a spectrometer, are applied to a tuned antenna after amplified by an RF power amplifier. The

principle of NQR is shown in Figure 2.15. A search coil transmits a train of RF pulses which perturb the orientation of the nitrogen nuclei within the explosive material. After each excitation at the applied frequency, the nuclei rotate back with lower energy. However, since the nuclei possess a magnetic moment, the motion of rotation induces a small detectable voltage in a tuned antenna which after amplification gives rise to a spectral output [65]. Normally, analytical experiments prefer a solenoid antenna, while practical landmine detection experiments use a single-sided antenna [65]. Furthermore, the NQR signal received by the same antenna or another receiver antenna is amplified by a low noise preamplifier and digitalized into the spectrometer.



Figure 2.15: Block diagram of a typical NQR detection system [65].



Figure 2.16: Laboratory apparatus of the NQR detection system [65].

NQR data is collected as a range of different frequencies in the time domain and is normally processed by a Fourier analysis. The four highest NQR frequency spectrums of TNT are shown in Figure 2.17, and they are closely spaced which can potentially be tested sequentially to reduce detection time [64].



Figure 2.17: NQR frequency spectrum of TNT sample [64].

#### 2.6.4.1 Summary Evaluation

NQR has been used in humanitarian demining. The detection process is specific to the chemical nature of the encased explosives and consequently, it detects different types of landmines with a high possibility of detection and a low FAR. This technology can discriminate between various explosive types and even can identify the structures within the same explosive.

However, there are some limitations of NQR for landmine detection. Firstly, NQR cannot detect landmines which are fully enclosed in a metal case because RF radiation cannot penetrate the case. Secondly, the noise of RF signal and the interference within the field can significantly affect the performance of the NQR detector. Finally, the most challenging perspective of NQR is to reduce the times needed for detecting TNT. At present, the detection times are on the order of several minutes, which is inefficient and generally not regarded as practicable [64]. Therefore, the most important development of NQR for humanitarian demining is to reduce the detecting time.

### **2.7 Conclusions**

In this chapter, the background of the research has been introduced including describing the global landmine challenge and the main demining individuals and organisations. The role of the metal detector for humanitarian demining has also been discussed and described in detail. Additionally,

the chapter has reviewed metal detectors for humanitarian demining. Finally, alternative landmine detection technologies have been presented, i.e. GRP, IR, EIT, and NQR.

# **3.** Theoretical Background

This chapter describes the main electromagnetic theory that supports the research described in this thesis and, in particular, explains the definition of the tensor and the usefulness of this quantity in terms of describing the response landmines and small items of metallic clutter. Maxwell's equations are introduced first. Afterwards, the Bio-Savart Law is presented and there is a discussion of how to determine the magnetic field produced by a coil configuration using this Law. The chapter then describes the magnetic dipole moment. Further, the chapter explains the concept of the tensor and how this relates to the characteristics of the tested object. Finally, the chapter concludes with an introduction to the forward model and the inverse model, which are essential components of the solution to the inverse problem presented by determining the tensor of metal objects from inductive measurements taken from the surface.

### **3.1 Maxwell's Equations**

Electromagnetic fields play a significant role in engineering and physics. The fields can be represented concisely by a set of equations – Maxwell's equations which comprise Gauss's Law for electrical fields, Gauss's Law for magnetism, Faraday's Law of induction and Ampere's Circuital Law. Gauss's Law states that electric fields are caused by electric charges. Gauss's Law for magnetism asserts that there are no magnetic charges in a magnetic field; i.e., lines of magnetic flux are continuous. Faraday's Law describes how an electric field is generated by a time-varying magnetic field. Finally, Ampere's Law with Maxwell's addition shows that magnetic fields can be formed by electrical current or time-varying electric fields. The four differential Maxwell's equations are written below [66-69]:

- Gauss' Law:  $\nabla \cdot \overline{\mathbf{D}} = \rho$  (3.1)
- Gauss' Law for magnetism:  $\nabla \cdot \overline{\mathbf{B}} = 0$  (3.2)
- Faraday's Law of induction:  $\nabla \times \overline{\mathbf{E}} = -\frac{\partial \overline{\mathbf{B}}}{\partial t}$  (3.3)
- Ampere's Circuital Law:  $\nabla \times \overline{\mathbf{H}} = \overline{\mathbf{J}} + \frac{\partial \overline{\mathbf{D}}}{\partial t}$  (3.4)

Where  $\mathbf{\overline{E}}$  (V/m) represents electric field intensity,  $\mathbf{\overline{D}}$  (C/m<sup>2</sup>) stands for electric flux density,  $\rho$  (C/m<sup>3</sup>) is electric charge density,  $\mathbf{\overline{B}}$  (T) represents magnetic flux density,  $\mathbf{\overline{H}}$  (A/m) stands for magnetic field strength, and  $\mathbf{\overline{J}}$  (A/m<sup>2</sup>) is electric current density.

There are constitutive relationships between electric field intensity ( $\overline{\mathbf{E}}$ ), electric flux density ( $\overline{\mathbf{D}}$ ), magnetic flux density ( $\overline{\mathbf{B}}$ ), magnetic field intensity  $\overline{\mathbf{H}}$  and electric current density  $\overline{\mathbf{J}}$ .

$$\overline{\mathbf{D}} = \varepsilon \overline{\mathbf{E}} \tag{3.5}$$

$$\overline{\mathbf{B}} = \mu \overline{\mathbf{H}} \tag{3.6}$$

$$\bar{\mathbf{J}} = \sigma \bar{\mathbf{E}} \tag{3.7}$$

Equations (3.5)–(3.7) describe the macroscopic characteristics of the medium associated with electric permittivity  $\varepsilon$ , permeability  $\mu$ , and conductivity  $\sigma$ . Additionally, relative permeability, denoted as  $\mu_r$ , is the ratio of the permeability of a specific medium to the permeability in free space  $\mu_0$ .

A set of integral forms of Equations (3.1)-(3.4) exist and they are equivalent mathematically. Figure 3.1 illustrates an open surface S and corresponding boundary contour C for the integral form of Maxwell's equations.



Figure 3.1: The contour C and surface S of Maxwell's integral equations.

The integral form of Maxwell's equations is stated below:

- Gauss' Law:  $\oint_{\Omega} \overline{\mathbf{D}} \cdot d\overline{\mathbf{S}} = \int_{\mathbf{V}} \rho \, d\Omega$  (3.8)
- Gauss' Law for magnetism:  $\oint_{\Omega} \overline{\mathbf{B}} \cdot d\overline{\mathbf{S}} = 0$  (3.9)
- Faraday's Law of induction:  $\oint_{\mathbf{C}} \mathbf{\bar{E}} \cdot d\mathbf{\bar{L}} = -\oint_{\mathbf{S}} \frac{\partial \mathbf{\bar{B}}}{\partial t} \cdot d\mathbf{\bar{S}}$  (3.10)
- Ampere's Circuital Law:  $\oint_{C} \overline{\mathbf{H}} \cdot d\overline{\mathbf{L}} = \int_{S} (\overline{\mathbf{J}} + \frac{\partial \overline{\mathbf{D}}}{\partial t}) \cdot d\overline{S}$  (3.11)

Equations (3.8)-(3.9) illustrate that the total magnetic flux is zero for closed surface S, but the integral of  $\overline{\mathbf{D}}$  within the closed surface S is equal to the total charge enclosed by the surface in the volume  $\Omega$ .

Equations (3.10)-(3.11) show that the line integral of electric and magnetic field intensity within corresponding boundary contour C. Equation 3.10 describes Faraday's Law and reveals how an induced voltage is generated by a varying magnetic flux through a closed loop. Transmitter and receiver coils are deployed in this research, so a varying induced voltage will be produced in one coil (the receiver) due to a varying current flowing in another coil (the transmitter). The form of the law is sometimes named as the transformer induction equation and describes the total electrical field induced within a closed circuit due to the total magnetic flux linking to the circuit at a specific time decreasing rate [70].

### **3.2 Biot-Savart Law**

The magnetic field strength ( $\overline{\mathbf{H}}$ ) and the magnetic flux density ( $\overline{\mathbf{B}}$ ) at any point generated by an electric current in free space can be deduced from the Biot-Savart Law [71]. The Biot-Savart Law is a special case of Ampere's Law, which is applicable to free space only.



Figure 3.2: The magnetic field strength ( $\overline{H}$ ) produced at *P* because of wire segment  $d\overline{L}$  with a current (*I*) flowing through it.

The law can be written concisely as [71]:

$$\overline{\mathbf{H}} = \frac{l}{4\pi} \oint \frac{d\overline{\mathbf{L}} \times \hat{\mathbf{r}}}{|\mathbf{r}|^3} \tag{3.12}$$

Where  $\hat{\mathbf{r}}$  is the vector between the point *P* and the conductor element, and *I* is the current flow through the filament part,  $d\overline{\mathbf{L}}$ . Including the units of the values, it can be deduced that the unit of  $\overline{\mathbf{H}}$  is A/m.

Three assumptions have been made for this law, viz.:  $d\overline{\mathbf{L}}$  can be negligible short; the expression applies in vacuum, and the wire is filamentary. In addition, the current form in the equations is non-extant due to the impossibility of an isolated segment with current flowing.

Combining this with Equation (3.6), the law can be used to describe magnetic flux density ( $\overline{\mathbf{B}}$ ) as:

$$\overline{\mathbf{H}} = \frac{\mu_0 I}{4\pi} \oint \frac{d\overline{\mathbf{L}} \times \hat{\mathbf{r}}}{\hat{\mathbf{r}}^2}$$
(3.13)

The Biot-Savart Law can be applied to calculate magnetic fields of different shapes, such as a finite length of straight wire, a circular loop and solenoids.

The magnetic fields calculation for a straight wire at the point of P can be described by an equation [72]:

$$\bar{\mathbf{H}} = \frac{I}{4\pi r} (\cos \alpha_1 - \cos \alpha_2) \hat{\mathbf{k}}$$
(3.14)

where  $\hat{\mathbf{k}}$  is a unit vector of the azimuth direction. The wire is assumed to be stationary in a vacuum space.



Figure 3.3: Magnetic field calculation for a straight wire at the point *P*.

The sensor employed in this research contains by a number of circular transmitter and receiver coils (see chapter 4). The coils can be decomposed into a different number of circular loops.

Figure 3.4 shows the magnetic flux in one circular loop, the whole magnetic flux of the coils can be accumulated.



Figure 3.4: Magnetic flux due to a circular loop carrying a steady current [73].

In cylindrical Cartesian coordinates, the differential current element located at

$$\overline{\mathbf{r}'} = R(\cos\phi'\hat{\mathbf{i}} + \sin\phi'\hat{\mathbf{j}}) \tag{3.15}$$

where  $\hat{i}$  and  $\hat{j}$  are unit vectors of the azimuth direction.

The current element  $I d\vec{s}$  can be written as:

$$I \, d\bar{\mathbf{s}} = I(d\bar{\mathbf{r}'}/d\phi') \, d\phi' = IR \, d\phi'(-\sin\phi'\hat{\mathbf{i}} + \cos\phi'\hat{\mathbf{j}}) \tag{3.16}$$

The position vector of the point *P* is  $\bar{\mathbf{r}}_P = z\hat{\mathbf{k}}$  due to *P* being on the axis of the loop at a distance z from the centre. The relative position vector is given by

$$\bar{\mathbf{r}} = \bar{\mathbf{r}}_{\boldsymbol{P}} - \bar{\boldsymbol{r}'} = -R(\cos\phi'\hat{\mathbf{i}} + \sin\phi'\hat{\mathbf{j}}) + z\hat{\mathbf{k}}$$
(3.17)

Its magnitude can be written as:

$$\mathbf{r} = |\bar{\mathbf{r}}| = \sqrt{(-R\cos\phi')^2 + (-R\sin\phi')^2 + z^2} = \sqrt{R^2 + z^2}$$
(3.18)

Thus, the corresponding unit vector from  $I d\vec{s}$  to P can be written as:

$$\hat{\mathbf{r}} = \frac{\bar{\mathbf{r}}}{r} = \frac{\bar{\mathbf{r}}_{p} - \bar{r'}}{\left|\bar{\mathbf{r}}_{p} - \bar{r'}\right|}$$
(3.19)

The cross product  $d\bar{s} \times (\bar{\mathbf{r}}_{P} - \bar{\mathbf{r}'})$  is:

 $d\bar{\mathbf{s}} \times (\bar{\mathbf{r}}_{P} - \bar{\mathbf{r}'}) = R \, d\phi'(-\sin\phi'\hat{\mathbf{i}} + \cos\phi'\hat{\mathbf{j}}) \times (-R(\cos\phi'\hat{\mathbf{i}} + \sin\phi'\hat{\mathbf{j}}) + z\hat{\mathbf{k}})$ 

$$= R \, d\phi'(z\cos\phi'\hat{\mathbf{i}} + z\sin\phi'\hat{\mathbf{j}} + R\hat{\mathbf{k}}) \tag{3.20}$$

According to the Biot-Savart Law, the contribution of the current element to the magnetic field at *P* is

$$d\overline{\mathbf{B}} = \frac{\mu_0 I}{4\pi} \frac{d\overline{s} \times \hat{\mathbf{r}}}{r^2} = \frac{\mu_0 I}{4\pi} \frac{d\overline{s} \times \overline{\mathbf{r}}}{r^2} = \frac{\mu_0 I}{4\pi} \frac{d\overline{s} \times (\overline{\mathbf{r}}_P - \overline{r'})}{|\overline{\mathbf{r}}_P - \overline{r'}|} = \frac{\mu_0 I R}{4\pi} \frac{z \cos \phi' \hat{\mathbf{i}} + z \sin \phi' \hat{\mathbf{j}} + R\hat{\mathbf{k}}}{(R^2 + z^2)^{\frac{3}{2}}} d\phi'$$
(3.21)

So the magnetic field at *P* is

$$\overline{\mathbf{B}} = \frac{\mu_0 I R}{4\pi} \int_0^{2\pi} \frac{z \cos \phi' \hat{\mathbf{i}} + z \sin \phi' \hat{\mathbf{j}} + R \hat{\mathbf{k}}}{(R^2 + z^2)^{\frac{3}{2}}} d\phi'$$
(3.22)

The x and the y components of  $\overline{\mathbf{B}}$  can be readily shown to be zero,

$$B_{\chi} = \frac{\mu_0 I R z}{4\pi (R^2 + z^2)^{\frac{3}{2}}} \int_0^{2\pi} \cos \phi' \, d\phi' = 0 \tag{3.23}$$

$$B_{y} = \frac{\mu_{0} I R z}{4\pi (R^{2} + z^{2})^{\frac{3}{2}}} \int_{0}^{2\pi} \sin \phi' \, d\phi' = 0$$
(3.24)

But the z component is:

$$B_{z} = \frac{\mu_{0}IR^{2}}{4\pi(R^{2}+z^{2})^{\frac{3}{2}}} \int_{0}^{2\pi} d\phi' = \frac{2\pi\mu_{0}IR^{2}}{4\pi(R^{2}+z^{2})^{\frac{3}{2}}} = \frac{\mu_{0}IR^{2}}{2(R^{2}+z^{2})^{\frac{3}{2}}}$$
(3.25)

Thus,  $B_z$  is the only non-vanishing component of the magnetic field along the symmetric axis.

Another derivation from the Biot-Savart Law, which is of interest to this research, is that of solenoids, discussed further in chapter 4. The magnetic field along the centre axis of an infinitely long solenoid can be considered to be approximately uniform within the central part of the solenoid. However, for practical solenoids of finite length, the magnetic field rarely achieves true uniformity which is shown in Figure 3.5. The figure also shows the flow of a steady current *I* through a solenoid and the resultant magnetic field.



Figure 3.5: Magnetic field lines of a solenoid [73].

If the length of the solenoid is finite, the magnetic field can be regarded as consisting of that caused by the superposition of the fields from large number of circular loops.



Figure 3.6: Magnetic field for a solenoid of finite length [73].

Figure 3.6 shows the geometry for a solenoid of finite length, one cross-section of adjacently packed loops positioned at z' with a thickness of dz'. The thickness of the cross-section is proportional to the current through the solenoid, the current dI can be written as:

$$d\mathbf{I} = I(n\,d\mathbf{z}') = I(N/l)\,d\mathbf{z}' \tag{3.26}$$

where n = N/l is the number of turns per unit length.

Using the result of Equations (3.25) and (3.26), the magnetic field at position *P* which contributed by the cross section is

$$d\boldsymbol{B}_{\boldsymbol{z}} = \frac{\mu_0 R^2}{2((z-z')^2 + R^2)^{\frac{3}{2}}} dI = \frac{\mu_0 R^2}{2((z-z')^2 + R^2)^{\frac{3}{2}}} (nI \, d\boldsymbol{z}')$$
(3.27)

Therefore, the magnetic field over the solenoid can be integrated over the whole length.

$$B_{z} = \frac{\mu_{0} n I R^{2}}{2} \int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{d\mathbf{z}'}{((z-z')^{2} + R^{2})^{\frac{3}{2}}} = \frac{\mu_{0} n I R^{2}}{2} \frac{z'-z}{R^{2} \sqrt{(z-z')^{2} + R^{2}}} \Big|_{-\frac{l}{2}}^{\frac{l}{2}}$$
$$= \frac{\mu_{0} n I}{2} \left[ \frac{\left(\frac{l}{2}\right) - z}{\sqrt{\left(z-\frac{l}{2}\right)^{2} + R^{2}}} \frac{\left(\frac{l}{2}\right) + z}{\sqrt{\left(z-\frac{l}{2}\right)^{2} + R^{2}}} \right]$$
(3.28)

### **3.3 Magnetic Dipole Moment**

An essential theory for representing the response of a small metal object is the magnetic dipole moment which can be described as a plane current loop. Assume a plane loop C of arbitrary shape with a current *I* flowing through; then the magnetic dipole moment can be written as [74]:

$$\boldsymbol{m} = \boldsymbol{S} \boldsymbol{I} \tag{3.29}$$

where S is the vector area enclosed by the loop.

Equation (3.29) only represents the current loop lying in a plane, and the extended equation (3.30) can be applied to any loop.

$$\boldsymbol{m} = \frac{1}{2} \int_{S} \ \boldsymbol{\bar{\mathbf{r}}} \times \boldsymbol{\bar{\mathbf{j}}} d\boldsymbol{\bar{\mathbf{S}}}$$
(3.30)

where  $\bar{r}$  is the position vector,  $\bar{j}$  is the current density, and  $d\bar{S}$  is the area element. The origin of  $\bar{r}$  can be anywhere.

A vector potential  $\overline{\mathbf{A}}$  is generated due to the magnetic dipole, and can be written as:

$$\overline{\mathbf{A}} = \frac{\mu_0}{4\pi} \frac{m \times \hat{\mathbf{r}}}{r^2} \tag{3.31}$$

The magnetic flux density  $\overline{\mathbf{B}}$  can be described by the vector potential  $\overline{\mathbf{A}}$ , as shown:

$$\overline{\mathbf{B}} = \nabla \times \overline{\mathbf{A}} \tag{3.32}$$

Combining this with Faraday's Law as expressed in Equation (3.10), the induced voltage, generated in the receiver coil of a metal detector, can be derived as:

$$V_{ind} = \oint_{\mathbf{C}} \bar{\mathbf{E}} \cdot d\bar{\mathbf{L}} = -\oint_{\mathbf{C}} \frac{\partial \bar{\mathbf{A}}}{\partial t} \cdot d\bar{\mathbf{L}}$$
(3.33)

The vector potential  $\overline{\mathbf{A}}$  will become a varying vector if the magnetic dipole moment is timevarying. The dipole moment is being used to describe the magnetic field created as a result of eddy current flowing in the metal objects of the secondary field. Therefore, Equation (3.33) can be rewritten as following based on a time-varying dipole moment:

$$V_{ind} = -\oint_{C} j\omega \overline{\mathbf{A}} \cdot d\overline{\mathbf{L}}$$
(3.34)

By applying Equation (3.31) to Equation (3.34), the induced voltage can be written as:

$$V_{ind} = -j\omega \oint_{\mathcal{C}} \frac{\mu_0}{4\pi} \frac{m \times \hat{\mathbf{r}}}{r^2} \cdot d\bar{\mathbf{L}}$$
(3.35)

At last, combining Equations (3.12) and (3.35),

$$V_{ind} = -j\omega \frac{\mu_0}{I_R} \boldsymbol{m} \cdot \overline{\mathbf{H}}_R$$
(3.36)

The terms  $\overline{\mathbf{H}}_R$  is the incident magnetic field generated on the receiver coil, the value at the observation points can be measured via numeric methods, by treating the receiver coil as a transmitter coil carrying unit current  $I_R$  by an exciting current in landmine detectors. The assumption for the magnetic dipole moment expressions is  $a^3 \ll r^3$  where *a* is the longest dimension of the loop [74].

The section above derived the formula of the induced voltage of a receiver coil in terms of the magnetic dipole moment. In addition, the magnetic dipole moment is used to reflect the response of the object to the induced magnetic field. Therefore, the tensor derivation will now be introduced based on the dipole moment model and this is discussed further in next section.

## 3.4 Magnetic Polarizability Tensor

The magnetic dipole moment m represents the unique response of the object which is tested within an incident magnetic field. The relationship between the tensor and the moment can be described as [75]:

$$\boldsymbol{m} = \boldsymbol{\bar{\mathsf{M}}} \cdot \boldsymbol{\bar{\mathsf{H}}}_T \tag{3.37}$$

where  $\overline{\mathbf{M}}$  is the magnetic polarizability tensor and  $\overline{\mathbf{H}}_T$  is the incident field. The incident field is usually produced by a transmitter coil.

By applying Equation (3.37) to Equation (3.36), the induced voltage can be rewritten as:

$$V_{ind} = j\omega \frac{\mu_0}{I_R} \quad (\mathbf{\bar{M}} \cdot \mathbf{\bar{H}}_T) \cdot \mathbf{\bar{H}}_R \tag{3.38}$$

Equation (3.38) is a key equation for metal detection as it presents the induced voltage on a receiver coil because of the existence of an object within the incident field. It can be seen from Equation (3.38) that  $\overline{\mathbf{M}}$  is the only unknown parameter with known coil geometries and the electrical parameters of the measurement system. So after re-arranging Equation (3.38), the tensor  $\overline{\mathbf{M}}$  can be described as:

$$\overline{\mathbf{M}} = \frac{V_{ind}I_R}{j\omega\mu_0} (\overline{\mathbf{H}}_T \cdot \overline{\mathbf{H}}_R)^{-1}$$
(3.39)

The transformation from Equation (3.38) to Equation (3.39) is the main computation milestone for this research, and they are typical forward and inverse problems respectively. The tensor measurement system can be described using Equation (3.38). Firstly, the transmitter coil, which carries an arbitrary current, produces a varying magnetic field. Then an induced field is generated due to the varying primary field named as the secondary field. Lastly, an induced voltage on the receiver coil can be measured because of the object within the secondary field. Equation (3.39) mainly describes the object's characteristics via the analysis of the tensor.

Three assumptions in Equation (3.39) are made to make sure the magnetic dipole moment can be applied to calculate an object's tensor. Firstly, the longest dimension of the object, a, is assumed to be much smaller than the distance between the object and the coils, r, to meet the requirement  $a^3 \ll r^3$ . Secondly, the magnetic field at the object's location is assumed to be uniform, in effect this is linked to the first assumption because if  $r \gg a$  then the coil is sufficiently far away for the magnetic field to be near constant in the vicinity of the object. Finally, filamentary wires are assumed to be used for transmitter and receiver coils, therefore, the derived form of the Biot-Savart Law, Equation (3.14), can be applied to calculate the magnetic field strength.

### 3.4.1 Tensor Composition

At this point, it is necessary to make a fuller explanation of the tensor  $\overline{\mathbf{M}}$ . A particular tensor  $\overline{\mathbf{M}}$  for each metal object located in the magnetic field is used to illustrate the signature of the object. According to the reciprocal rule between transmitter and receiver, there are six unique complex values in the symmetric, frequency dependent matrix. Therefore,  $\overline{\mathbf{M}}$  can be expressed in the following format:

$$\overline{\mathbf{M}} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{bmatrix}$$
(3.40)

In Equation (3.40), the six components  $M_{11}$  to  $M_{33}$  are defined as different characteristics of the objects in XX, XY, XZ, YY, YZ, and ZZ directions, respectively. Each of them is a complex value, the real part reflects the in-phase (reactive) induced voltage and the imaginary part shows the quadrature (resistive) component, which represents the magnetic and conductive properties respectively for different objects in addition to information about orientation [76]. The shape also affects the tensor as shown in Figure 3.7.



Figure 3.7: Various tensors for different objects where  $k_1, k_2, k_3$  and  $k_4$  is a complex scalar [76].

The tensor components are the same in all three directions, i.e. x, y, and z-direction, for a sphere or other uniform symmetrical objects (*e.g.* cubes) due to the equal responses at different orientations. In addition, the tensor is not sensitive to the rotation of the object. For a magnetic rod, the tensor is concentrated in one direction and has no response to the other two directions. In the case of the thin non-magnetic disc, the magnetic field would be focused in the x- and z-directions instead of the y-direction. At last, eddy currents would be induced in a thin conducting disc, a secondary field would be generated in the y-direction, and the corresponding tensor is shown in Figure 3.7. The scalar  $k_4$  is complex due to the existence of the secondary field.

Figure 3.8 shows the design of a circular coil with different materials, such as different magnetic, conductivity, or operating frequencies. A cross section through a circular rod and in the middle of a long rectangular coil that is producing the background field is shown in the design, and the long

dimension of the coil is perpendicular to the page. The thin side is 10 cm and current flows out for the upper side and in for the lower sides as shown in the Figure 3.8.



Figure 3.8: Layout of a circular coil with various materials [77].

The different responses for a magnetic, non-conducting rod are shown in Figure 3.9, as the magnetic permeability is increased. The field lines are concentrated through the sphere with an increase in material magnetic permeability. This results in a positive real tensor at lower frequencies, a negative value at higher frequencies, and approaching to an asymptote at the end for the magnetic cases. For example, ferrous objects approach their asymptotes at very high frequencies which are out of the scope of common practice.



Figure 3.9: The effect of increasing conductivity on magnetic field lines [78].

Additionally, the tensor  $\overline{\mathbf{M}}$  is dependent on the operating frequencies, and the effects of eddy currents through a conductive, non-magnetic sphere at different frequencies are shown in Figure 3.10.



Figure 3.10: The effects to eddy current generated by a conductive, non-magnetic sphere with increasing operating frequencies [78].

At low frequencies, such as 100 Hz, there is a relatively weak secondary field produced by the eddy current. The real component of the tensor is nearly zero as the field lines can flow unimpeded through the object at low frequencies. As the frequency increases, the eddy currents become more resistive to the applied field which is shown by the field lines which are pushed to the edges of the object from Figure 3.10. In addition, the paths of the eddy currents and the field lines around the object are increasing determined by the shape of the object as frequency increases.

# 3.5 Calculation of Tensor $\overline{\mathbf{M}}$

This section describes the formulation and calculation of the tensor  $\overline{\mathbf{M}}$  and this includes a description of the forward and inverse models. The limitations and assumptions of the forward model have been discussed, and the inverse method has been applied to the tensor measurement system.

#### 3.5.1 The Forward Model

Based on Equation (3.38), the sensitivity can be defined by the dot product of the received magnetic field with M times the transmitted magnetic field. This can be expressed as follows:

$$\begin{pmatrix} \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{bmatrix} \begin{bmatrix} H_{Tx_{x}} \\ H_{Tx_{y}} \\ H_{Tx_{z}} \end{bmatrix} ) \cdot \begin{bmatrix} H_{Rx_{x}} \\ H_{Rx_{x}} \\ H_{Rx_{z}} \\ H_{Rx_{z}} \end{bmatrix} = V$$
(3.41)

The result of the calculation is a scalar value of V. The above equation can be expanded in terms of the x, y, z components of the transmitter and receiver field strengths as:

$$(M_{11}H_{Tx_x} + M_{12}H_{Tx_y} + M_{13}H_{Tx_z})H_{Rx_x} + (M_{12}H_{Tx_x} + M_{22}H_{Tx_y} + M_{23}H_{Tx_z})H_{Rx_y} + (M_{13}H_{Tx_x} + M_{23}H_{Tx_y} + M_{33}H_{Tx_z})H_{Rx_z} = V$$

$$(3.42)$$

Furthermore, the above equation can be expanded further and rearranged into tensor components.

$$M_{11}(H_{Tx\_x}H_{Rx\_x}) + M_{12}(H_{Tx\_y}H_{Rx\_x} + H_{Tx\_x}H_{Rx\_y}) + M_{13}(H_{Tx\_z}H_{Rx\_x} + H_{Tx\_x}H_{Rx\_z}) + M_{22}(H_{Tx\_x}H_{Rx\_y}) + M_{23}(H_{Tx\_z}H_{Rx\_y} + H_{Tx\_y}H_{Rx\_z}) + M_{33}(H_{Tx\_z}H_{Rx\_z}) = V$$
(3.43)

Here, we define  $\alpha = H_{Tx_x}H_{Rx_x}$ ,  $\beta = H_{Tx_y}H_{Rx_x} + H_{Tx_x}H_{Rx_y}$ ,  $\gamma = H_{Tx_z}H_{Rx_x} + H_{Tx_x}H_{Rx_z}$ ,

$$\delta = H_{Tx\_x}H_{Rx\_y}, \varepsilon = H_{Tx\_z}H_{Rx\_y} + H_{Tx\_y}H_{Rx\_z}, \zeta = H_{Tx\_z}H_{Rx\_z}.$$

Then the Equation (3.43) can be written as:

$$\begin{bmatrix} V_1 \\ V_2 \\ \cdots \\ V_4 \end{bmatrix} = \begin{bmatrix} \alpha_1 & \beta_1 & \gamma_1 & \delta_1 & \varepsilon_1 & \zeta_1 \\ \alpha_2 & \beta_2 & \gamma_2 & \delta_2 & \varepsilon_2 & \zeta_2 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \alpha_i & \beta_i & \gamma_i & \delta_i & \varepsilon_i & \zeta_i \end{bmatrix} \begin{bmatrix} M_{11} \\ M_{12} \\ M_{13} \\ M_{22} \\ M_{23} \\ M_{33} \end{bmatrix}$$
(3.44)  
$$\overline{\mathbf{V}} = \mathbf{R} \cdot \overline{\mathbf{M}}$$

The expanded method shows that the tensor only needs to be multiplied once by the field components to obtain the induced voltage. This reduces the computation time and is more efficient. From Equation (3.44), the system responses marked as a vector  $\overline{\mathbf{V}}$  can be expressed by different locations in the magnetic field **R** multiply by the tensor  $\overline{\mathbf{M}}$ .

The forward model has been used in a number of electromagnetic imaging systems, such as a new version of walk-through metal detector systems [76]. However, it should be pointed out that there are some limitations and assumptions for the forward model. Firstly, the  $\overline{\mathbf{H}}$  fields are not perfectly uniform and any results obtained from this method will be subject to this constraint. Secondly, the forward model assumes that the measured object is only placed at a single position. Finally, the Biot-Savart field data in the walk-through metal detector system is calculated with the resolution of 1 cm voxel. The resolution will be a problem for the positional error over this limit [79].

#### **3.5.2 The Inverse Model**

Recalling Equation (3.43), and writing it in the following format:

$$\overline{\mathbf{V}} = \mathbf{R}\overline{\mathbf{M}} \tag{3.45}$$

Equation (3.45) presents the response of the measurement system described by an object of known properties and a set of parameters. The core concept of the inverse model is finding the inverse of **R**, and then calculating the tensor  $\overline{\mathbf{M}}$  directly. This process is shown in Equation (3.46).

$$\overline{\mathbf{M}} = \mathbf{R}^{-1}\overline{\mathbf{V}} \tag{3.46}$$

For a given matrix, it is invertible only if it can meet two requirements [80]:

- The matrix must have a non-zero determinant.
- The matrix must be square.

In this situation, the **R** matrix cannot be inverted since it is not square. The matrix contains many rows corresponding to the number of measurements, and the columns related to coefficients of the characteristics of the object. From Equation (3.44), it clearly presents six different components of the tensor. In the existing measurement system, there are 25 measurement points due to rotating through a circle in 15-degree increments as shown in Figure 3.11. In this measurement mechanical system, the tested object can be rotated by 15 degree at a time via the connected rubber wire. It means the dimension of **R** matrix is 25 by 6. The easiest way to make the matrix invertible would disregard a large amount of measurement and decrease the matrix size to 6 by 6. But this requires the selected measurement results to be correct entirely, i.e. noise free, or the results will be not correct due to the noise on the measurement data.


Figure 3.11: A tested object, PMA-2 surrogate, settled by a mechnical device within the coils.

There is a more suitable way to apply the Gaussian distribution of error using a large number of measurements which can average to the right solution. The Equation (3.47) should be minimised with the norm operator based on Equation (3.48).

$$\|\mathbf{R}\overline{\mathbf{M}} - \overline{\mathbf{V}}\|^2 \tag{3.47}$$

$$\|X\| = \sqrt{X_1^2 + X_2^2 + \dots + X_n^2}$$
(3.48)

Combining the equations, the function in terms of  $\overline{\mathbf{M}}$  can be written as:

$$f(\overline{\mathbf{M}}) = \|\mathbf{R}\overline{\mathbf{M}} - \overline{\mathbf{V}}\|^2 = (\mathbf{R}\overline{\mathbf{M}} - \overline{\mathbf{V}})^{\mathrm{T}}(\mathbf{R}\overline{\mathbf{M}} - \overline{\mathbf{V}}) = \overline{\mathbf{M}}^{\mathrm{T}}\mathbf{R}^{\mathrm{T}}\mathbf{R}\overline{\mathbf{M}} + \overline{\mathbf{V}}^{\mathrm{T}}\overline{\mathbf{V}} - 2\overline{\mathbf{M}}^{\mathrm{T}}\mathbf{R}^{\mathrm{T}}\overline{\mathbf{V}}$$
(3.49)

By differentiating Equation (3.49) and setting the derivative to zero, we can obtain the minimum value of the function. It can be processed by Equation (3.50) shown below:

$$\nabla f(\overline{\mathbf{M}}) = 2\mathbf{R}^{\mathrm{T}}\mathbf{R}\overline{\mathbf{M}} - 2\mathbf{R}^{\mathrm{T}}\overline{\mathbf{V}} = 0$$
(3.50)

The above equation can be rearranged to Equation (3.51):

$$\mathbf{R}^{\mathrm{T}}\mathbf{R}\overline{\mathbf{M}} = \mathbf{R}^{\mathrm{T}}\overline{\mathbf{V}}$$
(3.51)

 $\mathbf{R}^{T}\mathbf{R}$  is invertible if and only if this matrix has full rank; then multiplying both sides of Equation (3.51) by  $(\mathbf{R}^{T}\mathbf{R})^{-1}$  on the left:

$$(\mathbf{R}^{\mathrm{T}}\mathbf{R})^{-1}\mathbf{R}^{\mathrm{T}}\overline{\mathbf{V}} = (\mathbf{R}^{\mathrm{T}}\mathbf{R})^{-1}\mathbf{R}^{\mathrm{T}}\mathbf{R}\overline{\mathbf{M}} = \mathbf{I}\overline{\mathbf{M}}$$
(3.52)

Tikhonov regularisation is a good approach to deal with the ill-conditioned R matrix, and illconditioning is caused by the small changes of a measurement output which result from a large range of inputs [81]. The regularisation adds another term in Equation (3.47) to try to find the value of tensor  $\overline{\mathbf{M}}$ . It is defined as below [82]:

$$\overline{\mathbf{M}}_{\lambda} = \min_{\mathbf{M}} (\|\mathbf{R}\overline{\mathbf{M}} - \overline{\mathbf{V}}\|^2 + \lambda^2 \|\overline{\mathbf{M}}\|^2)$$
(3.53)

where  $\lambda$  is defined as the parameter of regularisation to determine the size of results and the most proper calculation of the least squares error.

# **3.6 Conclusions**

In this chapter, basic electromagnetic theories have been introduced at first, such as Maxwell's Equations and Biot-Savart Law. In addition, calculating magnetic fields of a finite length of straight wire, a circular loop and solenoids using Biot-Savart Law were analysed, and the discussed result will be applied to design coils of the tensor measurement system. Then, the magnetic dipole moment was presented which directly leads to the introduction of the concept of the magnetic polarizability tensor. Furthermore, the chapter focused on the composition of the tensor and discusses how object shapes, conductivity, and operating frequencies affect the components of the tensor. Finally, the forward and inverse methods, which are used to calculate the tensor, were presented.

# **4.Coil Design**

This chapter describes the development process of the coil arrangement, which is deployed in the tensor measurement system, and the construction of the coil according to the chosen design. Firstly, the ideal coil arrangement is introduced. Then, coil Design A is introduced with the simulation results in Ansys Maxwell, analytical results in MATLAB and the measurement results obtained from an experimental research coil. Afterwards, coil Design B is described with a more refined analytical solution; this design is also compared with Design A. Finally, the chapter highlights the chosen coil with corresponding measurement results. Some limitations of this chosen design are also presented.

# 4.1 Ideal Coil Arrangement

Coil design is one of the most essential steps in the development of the tensor measurement system. The ideal coil arrangement is required to create a uniform electromagnetic field in order to calculate the tensors for various test objects [83-84]. The tensor theory in Chapter 3 also illustrates that the eigenvalues can be obtained if the eigenvector is symmetrical and this can be achieved if the applied magnetic field is both uniform and parallel.

The tested object can fit into the coil array and the measuring procedure is presented in Section 5.3. The information of the object from different orientations can be collected by the measurement system described in Chapter 5 in order to calculate the full tensor matrix using the methodology described in Chapter 3.

# 4.2 Coil Design A - Overview

The first attempt at a coil design consisted of a transmitter and receiver, each of which had been split into four coil sections. The aim of this design was to improve the uniformity of the field over the earlier solenoidal arrangement developed by [85]. In effect this coil geometry was an attempt to approximate the well-known Helmholtz configuration [86], which uses two coils to create a near uniform field. In this case with the gradiometer coil, four sections were needed, with two in each half.

There are different approaches to produce uniform magnetic fields, such as three-coil system, four equi-radial coils and spherical coils. The advantage of using the gradiometer coil lies on its small

dimension and good sensitivity, while the main shortage is massive analytical and simulation processes.

The objective of this first coil design was to produce a magnetic field within the measurement region which is as uniform as possible over a volume sufficiently large so as to study the response of typical AP landmines. The design for both the transmitter and receiver coils was based on a Helmholtz coil arrangement. Design of the coils involved electromagnetic simulations by the Finite Element Method (FEM) using Ansys Maxwell [87]. The simulations determined the optimized coil spacing to provide a near uniform field within the measurement volume of the sensor. The simulation interface is shown in Figure 4.1, and the innermost four modelled parts represent the receiver coils whilst the outermost four modelled parts represent the transmitter coils. The model is axis-symmetrical about the z-axis. After a trial and error approach using different simulations with different length ratios for the transmitter and receiver coils, the length to radius ratios were determined according to the uniformity of the magnetic field. The simulations yielded a coil length ratio for the receiver coil of 8:10:10:8 and for the transmitter coil of 9:7:7:9.



Figure 4.1: Simulation interface for the designed coil in Ansys Maxwell.

Figure 4.2 shows the simulated magnetic flux density along the axis of the sensor. The blue line shows the magnetic flux density for the transmitter coil individually excited and the red line shows the calculated magnetic flux density for the receiver coil, individually excited with unit current. The fields are both relatively flat at the distance 0.025-0.1 m and 0.275-0.35 m. These regions are

intended to be the measurement spaces; the test object is intended to be positioned in the centre of one of these regions.



Figure 4.2: Magnetic flux density for transmitter and receiver coils on the axis of the sensor.

Figures 4.3 – 4.4 show the basic dimensions of the coils in a solid modelling computer-aided design (CAD) and computer-aided engineering (CAE) computer program, Solidworks. The overall height of the solenoid for the transmitter coil is 405.16 mm and for the receiver coil is 405.17 mm. The transmitter outer diameter is 199.32 mm with a wall thickness of 5 mm whilst the inner receiver diameter is 180 mm with a wall thickness of 4 mm. The thickness of the designed coil supporting formers is 5 mm for the receiver tube and 10 mm for the transmitter tube. The widths of the four segments of the receiver tube from top to bottom are 17.20 mm, 21.50 mm, 21.50 mm and 17.20 mm respectively. The width ratio is 8:10:10:8 which corresponds to the simulated result. Similarly, the widths of the four segments of the transmitter tube are 19.35 mm, 15.05 mm, 15.05 mm and 19.35 mm respectively. The width ratio is 9:7:7:9, which corresponds to the simulated result. The design was implemented using two acrylic tubes with the described coil formers manufactured in-house via 3D printing. Further dimensional details of the 3D printed supports are given in Appendix I.

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Figure 4.3: Design A showing transmitter and receiver supports in Solidworks.



#### (a) Transmitter and Receiver Coils

Figure 4.4: Design A in Solidworks with 3D view.

(b) Transmitter and Receiver Coils 3D View

# (a) Transmitter Coil

(**b**) Receiver Coil

### 4.2.1 Comparison between plastic and enamelled wire

The resonant frequencies of the coils determine the operational characteristics of the complete front-end electronic circuitry, and consequently, fix the upper frequency at which the system can usefully be used for experimental data capture. Therefore, some basic tests were performed in order to explore the effects of insulation on the resonant frequency of a coil winding and hence determine the best wire to use. The objective of the tests was to determine whether the resonance frequency of enamelled wire is less than that of plastic-coated wire. Figure 4.5 shows two 10-turn coils, one coil is wound using plastic-coated wire and another is wound from the enamelled wire. The core diameters of these two wires are same. The resonance frequencies of these two coils were measured by a commercial Impedance Analyser (Solatron SI 1260).



Figure 4.5: A 10-turn coil with wound using (a) plastic wire and (b) enamelled wire.



Figure 4.6: Impedance plot showing the resonance frequencies for 10-turn coils of (a) PVC plastic insulated wire and (b) enamelled coated wire.

Figure 4.6 shows the resonance frequencies for the plastic-coated and enamelled coil windings measured by the Impedance Analyser at 9.6 MHz and 6.32 MHz respectively. Both resonance

frequencies are well-beyond the intended linear operating region of the new system. The experimental data aids in the selection of the most appropriate wire and the number of turns for the transmitter and receiver coils. Although the resonance frequency for the enamelled wire is smaller than the plastic-coated wire, the reduced overall diameter of the enamelled wire enables sufficiently many turns to be wound in a smaller available surface area. For this reason, enamelled wire was selected to wind the transmitter coil.

# 4.2.2 Preliminary Transmitter Coil

Figure 4.7 shows the constructed preliminary transmitter coil based on coil Design A. Four segments were wound using 2 mm diameter insulated enamelled wire. The segments from top to bottom were wound with 18, 14, 14 and 18 turns respectively giving a total of 64 turns.



Figure 4.7: The constructed transmitter coil.

An impedance plot was measured for the complete transmitter coil and Figure 4.8 shows the resonance frequency of the transmitter coil is now 281.8 kHz. The impedance magnitude between 1 kHz to 100 kHz is linear, which is characteristic of a substantially inductive response and meets the requirements of the measurement system. As can be seen from the figure, the impedance fluctuates at frequencies higher than the resonant frequency. This is likely to be a consequence of higher order dynamics, with mutual coupling between the coil sections. However, this impedance fluctuation is far beyond the useful linear range of the coil winding. Additionally, the impedance

of the coil winding is 6  $\Omega$  at the frequency of 2 kHz, which determines the power requirements of the drive stage.



Figure 4.8: Impedance plot for the complete transmitter coil, showing a principal resonant frequency of 282 kHz.

# 4.2.3 Preliminary Receiver Coil

Figure 4.9 shows the construction of the receiver coil based on coil Design A. Four segments were wound using 0.6 mm diameter insulated plastic wire. The segments from top to bottom were wound with 52, 65, 65 and 51 turns respectively giving a total of 233 turns. During the winding process, it was not possible to completely fit 52 turns on the lowest support segment. However, as only a preliminary coil arrangement, the adoption of 51 turns here was not regarded as significantly affecting the operating characteristics of the receiver coil.



Figure 4.9: The constructed receiver coil.

Figure 4.10 shows the impedance plot of the complete receiver coil, indicating that the resonance frequency for this coil is 283.9 kHz. The impedance magnitude between 800 Hz and 100 kHz is linear and satisfies the measurement system's requirements.



Figure 4.10: Impedance plot for the complete receiver coil showing that the resonance frequency of the receiver coil is 284 kHz.

## 4.3 Analytical Approach to Optimising the Coil Geometry

In order to verify the FEM simulation results from the Ansys Maxwell simulation package, an analytical solution of the coil arrangement has been formulated. The analytical solution considers that the transmitter and receiver coils can be decomposed into a number of concentric circular loops. The calculations of the magnetic field in one circular loop and over a finite length solenoid are discussed in section 3.2 of the thesis. In particular, Equation (3.28) has been implemented by the creation of a bespoke MATLAB code given in Appendix II. In practice, the coil arrangement of Design A uses four symmetrical segments for both coils. Therefore, using the same method of solenoid calculation, the magnetic flux density for the transmitter and receiver coils can be accumulated using four different segments. The Figures 4.11-4.12 show the output of the MATLAB code given in Appendix II.



Figure 4.11: Comparison of the solenoid, FEM simulated and analytically calculated magnetic flux density of the transmitter coil along the central axis.



Figure 4.12: Comparison of the solenoid, FEM simulated and analytically calculated magnetic flux density of the receiver coil along the central axis.

Figures 4.11 and 4.12 show the comparisons between a solenoid, FEM simulated and analytically calculated magnetic flux densities of the transmitter and receiver coils. It can be seen that the FEM simulated and analytical data are in a good agreement. In fact, the disagreement for the transmitter coil is less than 2% whilst the difference for the receiver coil is less than 1%. These small differences are a consequence of the analytical solution only approximating the receiver and transmitter coils to a summation of one-turn circular loops. However, the FEM simulation gives a more accurate representation of the physical reality of the coil windings. The figures also show that the magnetic flux density of the solenoid arrangement does not provide a uniformly flat region of sufficient size suitable for measuring large objects.

The induced voltages along the centre axis of the transmitter and receiver coils have been measured experimentally using a search coil. The diameter of the search coil was 9 mm wound with a total of 60 turns. As previously described, the overall height of the coil arrangement (Design A) is 405.16 mm. A marking system of 21 evenly spaced marks from z=8mm to 408 mm in 20 mm increments enabled the manual positioning of the search coil with sufficient accuracy. Tests were performed at an operating frequency of 100 kHz.

The search coil setup was used to carry out a series of simple repeatability tests, which involved data acquisition on three different days separated by at least 48 hours. Figures 3.16-3.17 show the measured induced voltage for the transmitter and receiver coil on the three separate days. It is clear that the measurement setup yields good repeatability (better than 95%) since there are no significant differences during the three different data acquisitions with the same currents.



Figure 4.13: The induced voltage of the transmitter coil for three tests.



Figure 4.14: The induced voltage of the receiver coil for three tests.

Figures 4.13-4.14 show the measured search coil results for the induced voltage in the search coil, which is proportional to flux density, for both the transmitter and receiver coils which is normalised to a unit current in the coil. The results are compared to FEM simulated and calculated (theoretical) data. For the transmitter coil data, Figure 4.15 shows the characteristic four distinct broad peaks due to the four coil segments. Some disagreement between the search coil based data and the theoretical and simulated data exists. Firstly, the experimental results are smaller than the simulated results when the height is less than 68 mm. Secondly, the experimental results are higher than the simulated results when the height is between 150 mm and 200 mm. Thirdly, the experimental results are smaller than the simulated results when the height agreement exists thereby giving further confidence in the original FEM and theoretically calculated data. The finite volume of the search coil can account for the difference of the results.

The receiver coil data are shown in Figure 4.16. It can be clearly seen that the experimental search coil based data agree well with the simulated data. For the first half of the receiver coil, the magnetic flux density is negative. The flux density becomes positive in sign for the second half of the receiver coil. This is due to the coil-wiring direction being oppositely wound between the first two coil windings and the next coil windings. Thereby, the geometry generates opposite magnetic flux densities for the upper and lower coil winding segments.



Figure 4.15: Comparison among simulated, analytically calculated and measured magnetic flux density of the transmitter coil.



Figure 4.16: Comparison among simulated, analytically calculated and measured magnetic flux density of the receiver coil.

Figure 4.16 shows that the ideal measurement region is approximately 60 mm in axial length and lies between 288 mm and 348 mm. Within this region, FEM simulated, analytical solution and measurement data show a relatively flat region of magnetic flux density which is anticipated to be suitable for obtaining accurate tensor measurements for larger objects. The statistical analysis of this region is given in Table 4.1.

	Mean value (10 <sup>-6</sup> T)	Maximum Value (10 <sup>-6</sup> T)	Minimum Value (10 <sup>-6</sup> T)	Maximum variation (%)	Minimum variation (%)
Transmitter Coil	7.0475	7.233	6.92	2.63	1.81
Receiver Coil	6.575	6.762	6.442	2.84	2.02

Table 4.1: Value analysis for the height between 288 mm and 348 mm.

Table 4.1 shows the mean value, maximum variation and minimum variation values at the height between 288 mm and 348 mm. As can be seen from the table, the greatest variation is 2.84% and smallest variation is 1.81%. The variation can be reduced to near zero theoretically.

In order to analyse the magnetic flux densities of the transmitter and receiver coils more precisely, the tube, with a length of 405 mm, was divided into 2000 elemental loops. The current flow through each elemental loop could be varied independently. Based on Equations (3.25) and (3.28), the magnetic flux density for each position along the centre axis is contributed by the 2000 subsets.

$$\overrightarrow{\mathbf{B}(\mathbf{z})} = \mathbf{K}(\mathbf{z}) \cdot \overrightarrow{\mathbf{I}(\mathbf{z})}$$
(4.1)

where K(z) =  $\frac{\mu_0 R^2}{2(R^2 + z^2)^{\frac{3}{2}}}$ .

$$\begin{bmatrix} B(z_1) \\ B(z_2) \\ \vdots \\ B(z_{2000}) \end{bmatrix} = \begin{bmatrix} K_1(z_1) & K_2(z_1) & K_3(z_1) & K_4(z_1) & \dots & K_{2000}(z_1) \\ K_1(z_2) & K_2(z_2) & K_3(z_2) & K_4(z_2) & \dots & K_{2000}(z_2) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ K_1(z_{2000}) & K_2(z_{2000}) & K_3(z_{2000}) & K_4(z_{2000}) & \dots & K_{2000}(z_{2000}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ \vdots \\ I_{2000} \end{bmatrix}$$

(4.2)

The individual matrix elements  $K_i(z_i)$  of the  $i^{th}$  row is

$$K_{i}(z_{j}) = \frac{\mu_{0}R^{2}}{2\left(R^{2} + (z_{j} - \frac{d}{2} - (i-1)*d)^{2}\right)^{\frac{3}{2}}}$$
(4.3)

where d is the diameter of the coil wire.

Due to the characteristic of the perfectly flat magnetic field,  $B(z_1) = B(z_2) = \cdots = B(z_{2000}) =$ 1T, currents can be solved with the 2000 different equations.  $K_i(z_j)$  is a square, non-singular matrix, hence the  $\overrightarrow{I(z)}$  matrix can be inverted directly by:



$$\overrightarrow{\mathbf{I}(\mathbf{z})} = \mathbf{K}^{-1} \overline{\mathbf{B}(\mathbf{z})}$$
(4.4)

Figure 4.17: Calculated current density required to achieve a constant flux density along the axis of the transmitter coil.



Figure 4.18: Calculated current density required to achieve a constant flux density along the axis of the receiver coil.

Figures 4.17-4.18 show the current solutions of the transmitter and receiver coils for perfectly flat magnetic flux density. As expected, the results are symmetric along the x-axis, but there are two problems with this current distribution. First, it requires very large currents for both transmitter and receiver coils to achieve a constant flux density, and the currents are unachievable in practice. Second, it would be required a complex turns distribution that would be difficult to fabricate. Therefore, the solution is only valid in theory and cannot be applied in practice.

# 4.4 Coil Design B - Overview

The above section shows the first attempt of the coil design for the measurement system, Design A. However, the magnetic flux density for transmitter and receiver coils of Design A is not perfectly flat and this can be improved by adding more coil segments. According to the theoretical analysis of magnetic flux density, the more sections of the coils, the flatter of the magnetic flux density. A new design, Design B, with more coil sections for the transmitter and receiver coils has been introduced in this section. The total coil sections of the transmitter and receiver coils of Design B are 7 and 6, whilst there are only 4 coil sections for both the transmitter

and receiver coils of Design A. Figure 4.19 shows the theoretically calculated magnetic flux density for the transmitter coils for Design A and Design B. Similarly, Figure 4.20 shows the magnetic flux density for the receiver coils for both designs. It is clear from the figures that the magnetic flux density of Design B is flatter than Design A. This is as a direct consequence of the inclusion of more receiver and transmitter coil segments. The Figures 4.19-4.20 have been plotted automatically by the developed MATLAB code given in Appendix III.



Figure 4.19: Comparison magnetic flux density for the transmitter coil between two designs.



Figure 4.20: Comparison magnetic flux density for the receiver coil between two designs.

In practice, the actual coils of Design B are supported by physical formers. Figure 4.21-4.22 show the completed former arrangement mounted on the transparent acrylic tubing. An engineering drawing of coil Design B can be found in Appendix IV.



Figure 4.21: Design B showing the transmitter and receiver supports from a side projection.

- (a) Transmitter and Receiver Supports
- (b) Transmitter and Receiver Supports

#### in 3D View



Figure 4.22: Complete coil assembly from side projection and with a 3D view.

## 4.4.1 Transmitter Coil

Figure 4.23 shows the constructed transmitter coil based on coil Design B. The coil is wound by enamel insulated copper wire of 2.1 mm diameter and glued by the epoxy adhesive (Araldite<sup>TM</sup>) to the acrylic tube. The segments from top to bottom were wound with 12, 6, 7, 6, 7, 6, and 12 turns respectively giving a total of 56 turns with the maintained wound direction.



Figure 4.23: Constructed transmitter coil.

The spectral response of the transmitter coil was measured using the impedance analyser (Solatron 1260) over a frequency range from 800 Hz to 2 MHz. Figure 4.24 shows that the resonance frequency of the transmitter coil is 1.507 MHz. The magnitude of the impedance between 800 Hz and 100 kHz is linear and satisfies the measurement system's requirements.



Figure 4.24: Spectral response of the transmitter coil over the frequency range from 800 Hz to 2 MHz.

# 4.4.2 Receiver Coil

Figure 4.25 shows the constructed receiver coil based on coil Design B. Six segments were wound using 1.2 mm diameter insulated plastic wire. The segments from top to bottom were wound with 42, 21, 51, 51, 21 and 42 turns respectively giving a total of 228 turns.



Figure 4.25: Constructed receiver coil.

The spectral response of the receiver coil was measured using the impedance analyser (Solatron 1260) over a frequency range from 500 Hz to 800 kHz. Figure 4.26 shows that the resonance frequency of the receiver coil is 376.6 kHz. The magnitude of the impedance between 800 Hz and 100 kHz is linear and satisfies the measurement system's requirement for an inductive response.



Figure 4.26: Spectral response of the receiver coil over the frequency range from 500 Hz to 800 kHz.

## 4.4.3 Final Coil Assembly

Once the transmitter and receiver coils were wound, the transmitter coil was slid over the outside of the receiver coil, and two coils were fixed onto a flat platform as a base. The base is a woody paperboard with the length of 45 cm, the width of 30 cm and the height of 15 cm. The completed coil assembly is shown in Figure 4.27.



Figure 4.27: Fully assembled coil array.

A final set of resonance frequency tests were conducted on the fully assembled coil array in order to determine the full coil characteristics. The test results are beneficial to understand the combined behaviour of the transmitter and receiver coils.



Figure 4.28: Resonance frequency of the transmitter coil of the full coil array.



Figure 4.29: Resonance frequency of the receiver coil of the full coil array.

Figures 4.28-4.29 show the impedance measurement of the transmitter and receiver coils of the full coil array. The results present significant interaction and coupling between the transmitter and

receiver coils. The resonance frequency of the transmitter coil shifts to 445.6 kHz from 1.507 MHz, while the value for the receiver coil changes slightly to 343.9 kHz from 376.6 kHz.

The main dimensional details of the coil geometry are given in Table 4.2.

Features	Size / mm		
Transmitter coil			
Overall height	405.0		
Inner diameter	99.8		
Outer diameter	219.3		
Supporter width	9.9		
Wire diameter	2.1		
Winding area(From top to bottom)	25.2, 12.6, 14.7, 12.6, 14.7, 12.6, 25.2		
Receiver coil			
Overall height	405.0		
Inner diameter	89.8		
Outer diameter	94.4		
Supporter width	4.6		
Wire Diameter	1.2		
Winding area (From top to bottom)	16.8, 8.4, 20.4, 20.4, 8.4, 16.8		

Table 4.2: Main dimensional details of the transmitter and receiver coils.

# 4.4.4 Measurement Results of the Coils

The induced voltages along the centre axis of the transmitter and receiver coils have been measured experimentally using the same search coil which was introduced in section 4.2. As previously described, the overall height of the coil arrangement (Design B) is 405.2 mm. A marking system of 18 evenly spaced marks from z=22 mm to 379 mm in 21 mm increments with another two measurement positions at 8 mm and 398 mm enabled the accurate manual positioning of the search coil. Tests were performed at an operating frequency of 100 kHz.

The search coil setup was used to conduct similar repeatability tests to Design A, which involved data acquisition on three different days separated by at least 48 hours. Figures 4.30-4.31 show the measured induced voltages for the transmitter and the receiver coil on the three days. Again, the results show a good repeatability since there are no significant differences during the three different data acquisitions.



Figure 4.30: The induced voltage of the transmitter coil for separate data acquisitions.



Figure 4.31: The induced voltage of the receiver coil for separate data acquisitions.

Figures 4.32-4.33 show the measured search coil results of the magnetic flux density for the transmitter and receiver coils which is normalised by the induced voltage. The results are compared to calculated (theoretical) data. For the transmitter coil data, Figure 4.32 shows good agreement between the analytical and the experimental results of the magnetic flux density at the

centre of the transmitter coil. It can be easily found that the flat magnetic flux density region is between 80 mm and 330 mm. The value of the magnetic flux density in this region is 7.43 mT for a coil current of 1 A.

The receiver coil data are shown in Figure 4.33. It can be seen that the experimental search coil based data agree well with the analytical data. As with Design A, the receiver coil generates opposite magnetic flux densities for the upper and lower coil winding segments due to the opposite coil-winding directions. Figure 4.33 also shows two flat magnetic flux density regions along the centre of the receiver coil. The first flat region is located between 43 mm and 106 mm with the value of -7.31 mT, and the second flat region is located between 280 mm and 360 mm with the value of 7.16 mT for a coil current of 1 A.



Figure 4.32: Comparison between analytically calculated and measured magnetic flux density of the transmitter coil.



Figure 4.33: Comparison between analytically calculated and measured magnetic flux density of the receiver coil.

Although the data obtained by the search coil for the transmitter and receiver coils are generally in accord with the analytical data, some disagreements still exist which can be found in the Figures 4.32 and 4.33. Firstly, the experimental results are slightly smaller than the analytical results for the region between 150 mm and 200 mm for the transmitter coil. Secondly, the experimental results are slightly higher than the analytical results for the region between 280 mm and 310 mm for the transmitter coil. Thirdly, the experimental results are lower than the analytical results for the region between 50 mm and 100 mm for the receiver coil. These differences between the experimentally obtained measurements and the analytical data can be attributed to the physical differences in the coils compared with the simulation model in MATLAB. In particular:

- The build tolerances of the assembled transmitter and receiver coils gives rise to a small difference in geometrical dimensions between the simulation model and the actual coils.
- The coils were wound manually which introduced a small amount of asymmetry not represented in the simulation model.
- The finite size of the search coil used to measure the field, therefore the measured field is not a point value, but averaged over a volume equivalent to that occupied by the search coil.

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Additionally, the simulation model does not consider any effects due to wire insulation. However, this is anticipated to be virtually negligible at the studied frequencies. Finally, experimental positional errors when conducting the measurements will give rise to differences between experimental measurements and simulation.

However, despite the differences described above, it can be seen that an ideal measurement region of approximately 60 mm exists and lies between 290 mm and 350 mm. Within this region, analytical solution and measurement data both show a relatively flat region of magnetic flux density which is anticipated to be suitable for obtaining an accurate tensor measurement for larger objects.

# **4.5 Conclusions**

This chapter has described the process of designing and determining the coil geometry, along with the manufacturing procedures. It contains a number of analytical means which were employed to choose the optimal coil design. The transmitter and receiver coils were manufactured and assembled as a full coil array, and the impedance measurements were also carried out. The chosen coil geometry was verified as a better choice compared to the initial design via measurement of a search coil and the repeatability test. However, the final tests of the assembled coil still presented a number of differences between the analytical solution and the real measurement results. A machine wound coil array may deal with this issue.

# 5. Tensor Measurement System

This chapter gives an overview of the tensor measurement system including the methodology, electronics, and integration of the data acquisition system. The chapter begins with a description of the apparatus and the methodology applied. Afterwards, the front-end electronics are described with their specifications. The chapter follows with a description of the integrated data acquisition system using a Red Pitaya data acquisition and signal generation platform [88]. Noise calculation, experimental procedure, potential signal drifting issues of the system and the measurement system specifications are also discussed.

## **5.1 Measurement Apparatus**

An open source and reconfigurable measurement and signal generation platform, the Red Pitaya [88], was used in the tensor measurement system. The Red Pitaya generates excitation signals, which are further amplified to the transmitter coil. The excitation signals are generated at a set of discrete fixed frequencies, over a sufficiently wide range (1 kHz to 100 kHz) to characterise the whole spectroscopic response of the target measurements. The Red Pitaya also contains to ADC channels to digitise the received signal, as well as on chip (SoC), which can be programmed to with the necessary functionality to demodulate and filter the acquired signals.

A schematic of the measurement arrangement is shown in Figure 5.1. The full system comprises the Red Pitaya board, a bespoke coil for field generation (as described in Chapter 4) and measurement, transmitter (Tx) and receiver (Rx) amplifiers, a one-turn wire for field measurement with corresponding amplifier (AD8429), and a data acquisition PC. The range of the excitation signal is between 1 kHz and 100 kHz in 29 steps logarithmically. The Tx amplifier (LT1210) enables the delivery of a suitable driving current to the transmitter coil and Rx amplifier (AD524) enlarges the induced voltage from the receiver coil. The whole measurement system is controlled by bespoke software embedded in the Red Pitaya, the software was largely developed by team member for use on metal detectors, but was adapted in the PhD for the purpose of the tensor measurement system. The software collected measurement results from the system, which was further processed by a MATLAB program. This program performs data inversion and tensor calculation, and this program was developed by team member and adapted to the research project.

Figure 5.2 shows the experiment apparatus including the data acquisition board, Red Pitaya, frontend electronics, and the sensing coils.



Figure 5.1: System schematic showing signal flow along with measurements to and from Red Pitaya, front-end amplifiers, and the sensing coils.



Figure 5.2: The measurement system shows Red Pitaya, front-end amplifiers, and the sensing coils.

### 5.1.1 Transmitter Amplifier

The transmitter coil requires amplified drive signals. The developed design uses ten transmitter amplifiers (LT1210) placed in parallel to drive the voltage for the transmitter coil. Each transmitter amplifier can drive a current of 1.1 A [89]. Therefore, the arranged parallel amplifiers can provide a combined drive current of approximately 11 A. The voltages applied across the amplifiers are  $\pm 17.5$  V. Figure 5.3 shows the schematic diagram of one pair of the Tx amplifiers and the full circuit design can be found in Appendix V. An input signal, generated by the Red Pitaya, is applied into the Tx amplifiers, and two outputs are produced which noted as non-inverting output, Vo-non, and inverting output, Vo-inv. The transmitter amplifier was originally developed by Dr Michael O'Toole for the purpose of food inspection, but was repurposed for this project.



Figure 5.3: Schematic diagram for one pair of the Tx amplifiers.

Figure 5.4 shows the completed PCB mounted on two large heatsinks. The power connections, inputs connections, and regulators are also shown in the picture.



Figure 5.4: The completed amplifier PCB with external heatsinks.

The constructed circuit comprises ten pairs of the LT1210 power amplifiers, which generates ten pairs of inverting outputs and non-inverting outputs accordingly. The ten outputs on each side are connected in a parallel. The values of  $R_1$ ,  $R_2$  and  $R_3$  are 909  $\Omega$ , 681  $\Omega$  and 226  $\Omega$  respectively. Therefore, the gain of the non-inverting amplifier is:

$$G_{non-inv} = 1 + \frac{R_2}{R_3} = 1 + \frac{681}{226} = 4.013$$

And the gain of inverting amplifer is:

$$G_{inv} = -\frac{R_1}{R_3} = -\frac{909}{226} = -4.022$$

Preliminary testing of the amplifier arrangement has been carried out and a typical test data is presented in this section. The measurement data were aquired using a digital oscilloscope, Agilent infinitum 54832D MSO. Figure 5.5 shows the input and output signals for one pair of the amplifiers. The yellow data trace shows the original input signal, the purple trace shows the inverting output signal and the green trace shows the non-inverting output signal. The peak to peak mean values of the output signal are 25.64 V and 24.94 V respectively. Due to the gains of inverting and non-inverting amplifiers are -4.02 and 4.01, the input voltages should be 6.37 V and 6.22 V. There is a pre-circuit composed by two voltage regulators and a differential receiver amplifier AD8130. The result of the circuit is a phase shift of 90 degrees with an amplification gain of 2.4. Figure 5.5 shows the original input signal with the value of 2.62 V, so the input signal for inverting amplifier is  $\left|\frac{6.37-6.29}{6.37} \times 100\%\right| = 1.26\%$ . The error for the non-inverting amplifier is  $\left|\frac{6.22-6.29}{6.22} \times 100\%\right| = 1.13\%$ . All ten pairs of the amplifiers were tested and the error for each pair is less than 1.5%.



Figure 5.5: The input and two outputs signals for one pair of the Tx amplifiers.

In addition, the amplifier gain can be modified via changing the value of the potentiometer.

### 5.1.2 Receiver Amplifier

The transmitter coil is driven by the transmitter bank, and a receiver amplifier, AD524, is connected to the receiver coil. The full description of the transmitter and receiver coils is presented in Chapter 4.

Figure 5.6 shows the main schematic diagram of the circuit design and built on a two-sided prototyping board (colander ground plane 0.1 mm matrix pads). The power applied to the amplifier is  $\pm 12$  V. The amplifier AD524 guarantees low offset voltage, low offset drift, and low noise for precision high gain application. In addition, the amplifier can perform well with a gain bandwidth product of 25 MHz.

(a) (b)

Figure 5.6: The circuit design of the receiver amplifier in (a) schematic diagram and (b) built on a prototyping board.

Inputs

Some preliminary testing of the amplifier has been conducted, and a typical test is presented in this section. In common with the transmitter amplifier tests, the digital oscilloscope, Agilent infiniium 54832D MSO has been used again. Figure 5.7 shows the input and output signals of the circuit, and yellow trace represents the input signal generated from a function generator, TG330 3 MHz Analogue Function Generator with Dual Display; and the frequency of 10 kHz has been used for testing the amplifier. The purple trace represents the inverting output signal, and the green trace represents the non-inverting output signal of the circuit.


Figure 5.7: The waveforms of the input and output signals of the receiver amplifier circuit.

In Figure 5.7, the peak to peak value of the input signal is 213 mV, and the value of the output signals is 9.67 V, so the amplifier gain for the receiver amplifier circuit is:

$$G_{Receiver} = \frac{9.67 \times 1000 \text{ mV}}{213 \text{ mV}} = 45.4$$

In addition, potentiometer A shown in Figure 5.6, can be modified where necessary in order to change the amplifier gain of the circuit.

#### 5.1.3 Data Acquisition System - Red Pitaya

The data acquisition system of the measurement system uses the Red Pitaya, which is closedsource hardware that includes basic functions of a signal generator, LCR meter, spectrum analyser, and the bandwidth of 50 MHz 2x2 multiple inputs multiple outputs (MIMO) proportional-integralderivative PID controller [88]. The Red Pitaya also includes two 14 bit analogue to digital and digital to analogue converters, and the sample rate is 125 Msps. A significant advantage of the device is that it can be programmed by the user via the on-board field programmable gate arrays (FPGA). Figure 5.8 shows the layout of the Red Pitaya along the main function ports, i.e., two fast analogue inputs, two analogue outputs, power, micro SD card, console, universal serial bus (USB) connection, and gigabit Ethernet.



Figure 5.8: The layout of the Red Pitaya with main function ports [88].

The tensor measurement system uses one analogue output and two analogue inputs of the Red Pitaya. Sinusoidal signals of user defined frequencies are generated by the Red Pitaya and are sent to the transmitter coil after being enlarged by the transmitter amplifier. The frequencies from 1 kHz to 100 kHz have been produced with an interval 100 ms before the next frequency. The signal produced by the receiver coil is sent back to the Red Pitaya after the receiver amplifier, and the magnetic field measurement result are also performed by the Red Pitaya. Then the data was analysed within Red Pitaya initially and further analysed in MATLAB. A be spoken operating interface of the Red Pitaya after completing all configurations has been provided in Appendix VI.

# **5.2 Noise Calculation**

It is important to quantify the noise level of the measurement system. It is assumed that the main contribution to noise is due to the electronic components of the front end amplification stages. The instrumentation noise of these stages has been calculated and is presented in this section. Additional potential noise sources within the systems are as a consequence of mutual coil coupling and any noise introduced by the Red Pitaya acquisition system. These sources of noise are difficult quantify analytically. For this reason, the actual total noise present within the system is likely to be higher than that presented in this section.

The noise characteristics of operational amplifiers have been analysed by different manufacturers. In particular, a Texas Instruments noise model has been used to determine the typical noise performance of the amplifiers within the measurement system.



Figure 5.9: Adopted noise calculations; (a) Op-amp noise model introduced by Texas Instruments adapted from [90] and (b) schematic diagram of AD8429 used for field measurement.

This is shown schematically by the Texas instruments model and shown in Figure 5.9 (a). The internally generated noises can be broken down into two parts. The first part can be represented by a voltage source, **en**, connected to the positive input of a noiseless operational amplifier; and the second part can be represented by two current sources, **inn** and **inp**, connected to ground and the negative input of the noiseless operational amplifier. In this noise calculation, noise is referred to the input (RTI). The field measurement amplifier AD8429 has been analysed. The total voltage noise for AD8429 amplifier compromise of the input noise, output noise, and the gain resistor noise of the amplifier, and it is calculated as follows [91]:

Voltage Noise = 
$$\sqrt{(Output Noise/G)^2 + (Input Noise)^2 + (Noise of R_G)^2}$$
 (5.1)

where *G* is the gain of the amplifier, and  $R_G$  is the gain resistor of the amplifier. The relationship between two parameters can be calculated by the following gain equation [91]:

$$R_G = \frac{6 \,\mathrm{k}\Omega}{G-1} \tag{5.2}$$

In Figure 5.9 (b), the gain resistor was 60.4  $\Omega$ , so the gain of the amplifier is 100.3. According to the datasheet of the AD8429, the input noise is 1 nV/ $\sqrt{\text{Hz}}$  and the output voltage noise is 45 nV/ $\sqrt{\text{Hz}}$  at the gain of 100.3. Therefore, the voltage noise of the amplifier can be calculated as:

Voltage Noise = 
$$\sqrt{(45 \times 10^{-9}/100.3)^2 + (1 \times 10^{-9})^2 + (\sqrt{4kTR_G})^2}$$

where  $\sqrt{4kTR_G}$  is a formula to calculate thermal noise density of resistors. In addition, k is Boltzmann's constant, T is the temperature of the resistor in Kelvin, and R<sub>G</sub> is the value of the gain resistor. The voltage noise is calculated at 300 °K, so it can be further calculated as follows:

Voltage Noise

$$= \sqrt{(45 \times 10^{-9}/100.3)^2 + (1 \times 10^{-9})^2 + (\sqrt{4 \times 1.38 \times 10^{-23} \times 300 \times 60.4})^2}$$
  
=1.42 nV/ $\sqrt{\text{Hz}}$ 

Due to the inputs of the amplifier is just one-turn wire, the input resistor can be neglected. Therefore, there is not current noise of the instrumentation amplifier, and the total noise density for AD8429 is the voltage noise,  $1.42 \text{ nV}/\sqrt{\text{Hz}}$ .

Figure 5.10 shows the result of a noise test for the amplifiers of two amplifiers, the receiver amplifier (AD524) and the loop measurement amplifier (AD8429), with the amplifier gains of 98 and 100 respectively; the noise level is around 1.9 nV/ $\sqrt{\text{Hz}}$  at the operating frequency between 1 kHz and 60 kHz, and the noise gradually decreases to 0 nV/ $\sqrt{\text{Hz}}$  at the frequency of around 1 MHz. A signal produced by the function generator, TG 330, was applied to AD524 and AD8429, and the results were generated by the digital oscilloscope, Agilent infinitium 54832D MSO which installed a pre-designed noise test MATLAB program. Therefore, the voltage noise of AD524 at the frequency between 1 kHz and 60 kHz is about  $\sqrt{1.9^2 - 1.42^2} = 1.26 \text{ nV}/\sqrt{\text{Hz}}$ .



Figure 5.10: The noise test for the amplifiers of AD524 and AD8429 with the total amplifier gain of 9800.

## **5.3 Experimental Procedure**

A bespoke mechanical arrangement enabled the rotation of test objects within the coils. The mechanical devices comprised of two separate upper and lower pulley wheels of 1:1 ratio which connected by a rubber band. The rotation device was designed and constructed by a previous student. The test object was rotated within the coils by the lower pulley wheel via the manual movement of the upper pulley wheel which was conducted from outside of the coil arrangement. The test object was attached to the lower pulley wheel shown in Figure 5.11.



Figure 5.11: The rotation mechanism mounted with a test object.

The fixing arrangement was used for providing rotation about the X axis in full-circle 15° increments. This resulted in 24 orientated positions for each measurement. At each angular rotation a full frequency sweep produced by Red Pitaya was performed from 1 kHz to 100 kHz in approximately logarithmic increments giving rise to 29 measured frequencies.

## **5.4 Measurement System Stability**

A preliminary stability test was carried out after the completion of the measurement system. A significant drifting issue was observed on the received data from Red Pitaya, as shown in Figure 5.12. This shows that the receiver response is increasing from 377.5 mV to 380.6 mV gradually within 130 mins.



Figure 5.12: Preliminary measurement showing receiver response over a two hour time period.

Identification of the exact cause of the drift would aid in potentially developing methods to minimise the effect on the measurement results. Therefore, further tests were carried out to identify the source of the observed drifting issue. Primarily, two stability tests were carried out; one to the receiver amplifier, AD524, and one to the loop measurement amplifier, AD8429. A signal with the operating frequency of 10 kHz generated by the Red Pitaya applied to the amplifiers separately, and the output signals of the amplifiers have been measured by the oscilloscope.

Figure 5.13 shows that the data after the receiver amplifier is becoming stable after 20 mins, and the value is around 624.1 mV. In addition, the initial 20 mins can be regarded as the warm up period of this amplifier.



Figure 5.13: The drifting test for the receiver amplifier, AD524.

Figure 5.14 shows that the drifting test result of the loop measurement amplifier, which becomes stable around 25 mins, settling to a mean value of approximately 316.36 mV. Therefore, the initial 25 mins can be regarded as an appropriate warm up period for this amplifier.



Figure 5.14: The drifting test for the loop measurement amplifier, AD8429.

According to the results of the drifting tests for the two amplifiers, they show that the amplifiers are not the sources of the drifting issue of the measurement results shown in Figure 5.12. Afterwards, another stability test was conducted to check whether the temperature of the coil affects the measurement result or not. Initially, the sensor coil was warmed by a temperature chamber for twenty minutes until the temperature reached to 35 °C, and the drifting test of the measurement system was conducted afterwards. The chamber can fit the transmitter and receiver coils.

Figure 5.15 shows the corresponding drifting results of the temperature stability test. From the figure it can be clearly seen that the response initially decreases from 492.3 mV to 490.5 mV at the first half hour because the coil was cooling down out of the temperature chamber; the response result of the measurement system was stabilised around 490.4 mV for the next half hour, and then the response climbs gradually.



Figure 5.15: Temperature stability testing of the measurement system.

Figure 5.15 strongly indicates that the most significant drifting issue associated with the measurement system relates to temperature. The temperature differences cause physical expansion and contraction of the coil geometry, and the impedance of the coils will also be changed. However, the drifting amplitude of the measurement results is less than 0.4%, and the required measurement accuracy is less than 5%, so the measurement is recommended to be carried out when the testing room is cool and quiet, and decreasing the operating time as much as possible after enough warm up period to minimise the drifting effect.

## 5.5 Measurement System Specifications

There are three specifications of the measurement system should be pointed out. First of all, the magnetic field generated by the coils should be as flat as possible for the measurement region, the suggested flatness is more than 90% in order to obtain solid measurement results. The flatness of the coils employed in this measurement system is better than 95%, and it guarantees that the measurement results are accurate. Secondly, the ideal measurement region of around 60 mm exists and locates between 290 mm and 350 mm, and the volume of this region can fit tested pieces described in this thesis also for majority landmines. Lastly, the operating frequency of the measurement system is between 100 Hz and 100 kHz. From Section 4.4.3, the resonance frequencies of the transmitter and receiver coils of the full coil array are 445.6 kHz and 343.9 kHz, respectively, it ensures that the maximum operating frequency is lower than the 343.9 kHz.

## **5.6 Conclusions**

This chapter has described the measurement apparatus including the front-end electronics and the Red Pitaya as the data acquisition system. The noise has been calculated and the experiment procedure has also been discussed. The drifting issue of the measurement system has been raised and the potential reason has been investigated. The effect of the drift can cause less than 0.4% difference which can be omitted, and the measurement is recommended to be performed within a cool and quiet environment. Finally, three measurement system specifications have been presented in order to ensure the measurement results are accurate.

# 6. Measurement Results of US coinage

In order to provide measurement from a set of metal objects that are widely available and have tensor spectra over an equivalent range of frequencies to landmines and small items of metallic clutter that may be found in demining operations, US coinage was chosen. Coinage was chosen because this can be used by other groups to compare measurements.

The United States Mint produces legal tender coinage within the USA and there are six circulating coin denominations, i.e. dollar, half dollar, quarter dollar, dime, nickel, and penny. This chapter presents the experimental trans-impedance data of US coinage, simulations and the experimental eigenvalues of the same-sized copper disks, and the tensors of the US coinage via the simulation and the experiment.

The work reported in this chapter is a combination of contributions from a team of researchers involved in research on detectors for humanitarian demining and the elements were drawn together to form a common theme for this thesis. The contribution of others is highlighted as appropriate throughout the chapter.

## 6.1 Trans-impedance data of US coinage

This part gives details of experimentally acquired trans-impedance data of US coins as shown in Figure 6.1. Table 6.1 shows the specifications of the tested US coinage, and it shows that the US penny is plated and the US nickel is monolithic. The remaining denominations use a cladding construction intended to provide more consistent electromagnetic characteristics in order to deter counterfeiting. The edge design is plain for US penny and nickel, with lettering for the dollar, and with reeds for the dime, quarter dollar and half dollar.



Figure 6.1: Measured US coins, (1) US Dollar, (2) US Nickel, (3) US Penny, (4) US Quarter, (5) US Dime, and (6) US Half-Dollar.

	US Dollar	US Nickel	US Penny	US Quarter	US Dime	US Half- Dollar
Standard	8.100	5.000	2.500	5.670	2.268	11.340
Weight	grams	grams	grams	grams	grams	grams
Standard Diameter	26.49 mm	21.2 mm	19.1 mm	24.26 mm	17.91 mm	30.61 mm
Thickness	2.00 mm	1.55 mm	1.50 mm	1.75 mm	1.35 mm	2.15 mm
Bulk Compositio n <sup>^</sup> (weight percent[%])	Clad Manganese Brass (88.5%Cu- 6%Zn- 3.5%Mn- 2%Ni)	Monolithic Cupronickel (75%Cu- 25%Ni)	Copper- Plated Zinc (97.5%Zn- 2.5%Cu)	Cupronickel -Clad Copper (91.67% Cu- 8.33%Ni)	Cupronic kel-Clad Copper (91.67% Cu- 8.33%Ni)	Cupronic kel-Clad Copper (91.67%C u- 8.33%Ni)
Surface*	0.413 mm Cu-12Zn- 7Mn-4Ni	N/A	8 micron plaed Cu	0.226 mm 75Cu-25Ni	0.175 mm 75Cu- 25Ni	0.289 mm 75Cu- 25Ni
Edge Design	Edge Lettering	Plain	Plain	Reeds	Reeds	Reeds

Table 6.1: Specifications of tested US coinage adapted from [92],[93].

Cu = copper; Mn =manganese; Ni = nickel; Zn = zinc

\*mm = millimeter; N/A = not applicable



Figure 6.2: Trans-impedance measurements along angles and frequencies for US dollar.



Figure 6.3: Trans-impedance measurements along angles and frequencies for US nickel.



Figure 6.4: Trans-impedance measurements along angles and frequencies for US penny.



Figure 6.5: Trans-impedance measurements along angles and frequencies for US quarter.



Figure 6.6: Trans-impedance measurements along angles and frequencies for US dime.



Figure 6.7: Trans-impedance measurements along angles and frequencies for US half-dollar.

Figures 6.2-6.7 show the trans-impedance measurements' results for different US coinages. The results along angles are smooth and symmetric, because the coins themselves are symmetric. The results indicate that there are different peak values for each coin. It can be understood by the

compositions, weight and dimensions of various materials. From Table 6.1, it can be easily found that US dollar is made by 6% Zinc, 3.5% Manganese, 2% Nickel and Balance Copper; US Nickel is based on 25% Nickel and Balance Copper; US penny is composed by 2.5% Copper and Balance Zinc; US quarter dollar, US dime and US half-dollar are consisted of 8.33% Nickel and Balanced Copper. In the measurement results along frequencies, there are 7 groups of lines with 25 measured angles. The reason is the measured coins are symmetric and measured results for some angles are similar. For example, the measured results of 15°, 165°, 195° and 345° are similar and shown in one group.

US Coinage	Peak Frequencies (Hz)
Dollar	1200-1400
Nickel	18000
Penny	5000
Quarter	1400
Dime	2400
Half-Dollar	<1000

Table 6.2: Peak frequencies for the US coinage.

Table 6.2 shows the peak frequencies of the US coinages according to the information provided between Figure 6.2 and Figure 6.6. It shows that the peak frequencies for the US dollar and quarter dollar are similar and relatively low because of low content of Nickel and relatively larger physical size; the US penny and US dime exhibit similar peak frequencies, although the Dime's is lower than penny's, and these frequencies are significantly higher than those associated with the US dollar and US quarter. Figure 6.3 represents the coin with the highest frequency is the US nickel which has by far the highest Nickel content which is 25% Nickel. Figure 6.7 suggests the lowest frequency is for the half dollar (determination of the actual peak value is limited by the lowest frequency provided by the measurement system) which is due to the physical size of the coin. The conductivity of Nickel and Copper alloy is changed with different content of Nickel, and the conductivity of alloy is also related to peak frequency.

## 6.2 Simulations

In order to study the electromagnetic characteristics of the US coinage fully, a set of same-sized copper disks were manufactured used for tensor measurements as shown in Figure 6.8 [94].



Figure 6.8: US coins and corresponding same-sized copper disks. Scale in mm. Bottom row presents the same-sized copper disks of the penny, nickel, quarter dollar and half dollar.

The Ansys Maxwell v 16 was used to perform the simulations, and this work was performed in partnership with Dr John Davidson. A series of simulations involved geometrical rotations of the test object about its centre in  $15^{\circ}$  increments from  $0^{\circ}$  to  $345^{\circ}$ , and the operation frequencies are from 10 Hz to 100 MHz in tem logarithmic increments per decade change resulting in 71 frequencies. The conductivity of the pure copper set at  $5.8 \times 10^7$  S/m for copper test disk models. Figure 6.9 shows the magnetic field distributions of a US dime-sized copper disk within the coil for a 100 kHz excitation current at  $0^{\circ}$ ,  $45^{\circ}$  and  $90^{\circ}$  to the z-axis.



Figure 6.9: The magnetic field distribution of a US dime-sized copper disk at (a)  $0^{\circ}$ , (b)  $45^{\circ}$  and (c)  $90^{\circ}$  to the z-axis.

All coins were modelled to the dimensions as shown in Table 6.1. Skin depth refinement was applied to the coins to increase the mesh density at the surface of the disks and correctly model the skin effects at high frequencies. The electrical conductivity of the metal and alloy content of the coins used values detailed in Table 6.3 [95].

The one-cent and nickel coins were modelled as simplistic solid monolithic disks. Two models of each of the one-cent and nickel coins were produced. The one-cent coin was modelled using the electrical conductivity of pure zinc and corresponding to 95% electrical conductivity of pure zinc.

The nickel coin was initially modelled using electrical conductivity of 75-25 Cupro-Nickel (CuNi) alloy and then, modelled corresponding to the electrical conductivity of 70-30 CuNi alloy.

The dime, quarter and half dollar coins were each modelled as disks with and without a top and bottom clad layer sandwiching a solid core. The clad layer respected the outermost dimensions of each coin type as described in Table 6.1. The electrical conductivity of 99-1 CuNi alloy was assigned to the cores of the dime, quarter and half dollar coins. The clad layer was assigned corresponding to the electrical conductivity of 75-25 CuNi alloy.

Finally, the one dollar was modelled by 6 models. An electrical conductivity corresponding to the electrical conductivity of 99-1 CuNi alloy was used of an inner core for all models. Five models comprised of top and bottom clad layers sandwiching the core using electrical conductivity corresponding to 20% to 60% conductivity of pure copper in 10% incremental steps. The sixth model comprised of a complete wrap-around clad layer of the top, bottom and sides of the central core. An electrical conductivity corresponding to 30% conductivity of the pure copper was assigned to the clad layer.

Coin	Model Details
One Cent	Model 1: modelled as pure Zinc ( $\sigma = 16.7 \times 10^6$ )
	Model 2: modelled as 95% conductivity of Zinc ( $\sigma = 15.9 \times 10^6$ )
Nickel	Model 1: modelled as 75%-25% CuNi alloy ( $\sigma = 3.19 \times 10^6$ )
	Model 2: modelled as 70%-30% CuNi alloy ( $\sigma = 2.72 \times 10^6$ )
Dime and	Model 1: modelled as 99%-1% CuNi alloy ( $\sigma = 35.1 \times 10^6$ )
Quarter	Model 2: modelled as 99%-1% CuNi alloy core with 0.2 mm cladding
	of 75%-25% CuNi alloy ( $\sigma = 3.19 \times 10^6$ )
Half Dollar	Model 1: modelled as 99%-1% CuNi alloy ( $\sigma = 35.1 \times 10^6$ )
	Model 2: modelled as 99%-1% CuNi alloy core with 0.3 mm cladding
	of 75%-25% CuNi alloy ( $\sigma = 3.19 \times 10^6$ )
One Dollar	Models 1 to 5: modelled as 99%-1% CuNi alloy core with 0.4 mm cladding
	of 20%-60% Cu conductivity in 10% steps.
	(Conductivity of pure copper is $\sigma = 5.8 \times 10^7$ )
	Model 6: modelled as 99%-1% CuNi alloy core with 0.4 mm wrap-around cladding
	of 30% Cu conductivity ( $\sigma = 17.4 \text{ x} 10^6$ )

Table 6.3: The model details of the coin and the set electrical conductivities ( $\sigma$ ) in S/m.

## 6.3 Assessment of Simulation

The normalized RMS error, NRMSE was used to evaluate the level of agreement between the simulated and experimentally derived data across the frequency range used for the experimentally acquired data. In this case, normalization refers to the mean of the simulated data interpolated to the 29 experimental frequencies, *n*. The NRMSE was calculated by bespoke MATLAB code using the formulae:

NRMSE = 
$$\frac{\sqrt{\frac{\sum_{i=1}^{n} (\text{Expt}_{i} - \text{Sim}_{i})^{2}}{n}}}{\frac{1}{\text{Sim}}}$$
(6.1)

where  $\text{Expt}_i$  and  $\text{Sim}_i$  refer to the experimental and simulated data at the ith frequency and  $\overline{\text{Sim}}$  is the average of the simulated data for the experimental frequency range. In this way, NRMSE values tending towards zero represent a high level of agreement between the experimental data and the tested simulated data.

## **6.4 Copper Disks Results**

A set of copper disks manufactured to the same size of the US coinage shown in Figure 6.8, and the US nickel same-sized copper disk was employed to check the system's repeatability. The data was collected for ten separate acquisitions, and the acquisitions were performed within a period of 4 days. The longest period between two consecutive data acquisitions was 14 hours, and the time scale of the acquisition gaps was deemed to check the short and long term instrumentation stability. In addition, the tests shown the potential rotational errors introduced by the adopted manual coin rotation mechanism which is used for acquisition of actual coin tensors. Figure 6.10 shows the derived eigenvalues for the 10 consecutive acquisitions related to the US nickel-sized copper disk. The derived eigenvalues for the 10 consecutive data acquisitions associated with the US nickelsized copper disk. The solid line is the mean of all acquisitions at each one of the acquired 29 spectroscopic frequencies. The vertical bars with horizontal end-caps show the maximum and minimum values of the eigenvalues across the 10 consecutive acquisitions at a given frequency. The results shows that the real components (Re) of the eigenvalues,  $\Lambda_1$  and  $\Lambda_3$ , are negative which suggests a conductive object. In addition, an order of magnitude difference exists between  $\Lambda_1$  and  $\Lambda_3$  as a result of the  $\Lambda_1$  associated with the large cross-sectional obverse and reverse face area associated with the diameter of the disk and the  $\Lambda_3$  being indicative of the smaller cross-sectional area associated with the thickness of the disk.



Figure 6.10: Experimental real and imaginary eigenvalues of the derived magnetic polarizability tensor of the US nickel-sized copper disk. Plots are for real (Re) and imaginary (Im) components of eigenvalue,  $\Lambda_1$ , in (a) and (b), whilst (c) and (d) show eigenvalue,  $\Lambda_3$ .

Table 6.4: Range of the magnitude of standard deviations related to the data shown in Figure 6.11.

	Real $(\Lambda_1)$	Im $(\Lambda_1)$	Real $(\Lambda_3)$	Im $(\Lambda_3)$
Standard deviations range (x $10^{-8}$ m <sup>3</sup> )	1.77-3.15	0.25 - 1.86	1.42 - 2.19	0.14 - 1.57

The range of the magnitude of standard deviations associated with the data in Figure 6.10 is presented in Table 6.4. The table shows the minimum and maximum values of the magnitude of standard deviations calculated at each of the 29 frequencies for the 10 measurement sets. It shows that the standard deviations of the imaginary part of  $\Lambda_1$  and  $\Lambda_3$  are smaller than corresponding real parts. The deviations can be explained by the manual rotation on the copper disk of the measurement system, although plenty of care was taken during the data collection.

Figure 6.11 shows the data of derived tensor eigenvalues for the four copper disks that shown in Figure 6.8. All the simulations used the value of the IACS resistivity of copper as 17.241 n $\Omega$  m. The eigenvalues associated with the disks show good agreement between simulated and experimental data. For example, the dime-sized copper disk shown in Figure 6.11 (a) shows

agreement between experimental and simulated peak magnitudes for the imaginary  $\Lambda_1$  component better than 1.5 kHz. The corresponding agreement at peak magnitudes for the imaginary  $\Lambda_3$ component is approaching 5%. This corresponds to the data of a 12 kHz.

Generally, for all disks, the eigenvalues of the tensors match closely. This is particularly true for imaginary eigenvalue  $\Lambda_1$  at frequencies up to about 30 kHz beyond this the deviation between simulated and experimental data becomes more apparent. This deviation at higher frequencies is likely because of the induced eddy currents in the object being pushed to the outermost peripheral surface of the disk and hence at these frequencies the precise shape has more influence on the eddy current distribution, and the skin depth and ultimately the imaginary component  $\Lambda_1$ . Table 6.5 shows the NRSME values as described by Equation (6.1) for the copper disks. It can be seen from the table that the difference between the simulated and experimental data for the copper disks. Typically, the largest deviation occurs for the eigenvalue  $\Lambda_3$  irrespective of  $\Lambda_3$  being real or imaginary, the overall data shows the strong agreement between the simulated and experimental data.



Figure 6.11: Simulated and experimental real and imaginary eigenvalues of the derived magnetic polarizability tensors for copper disks machined to the US coin sizes of (a) dime, (b) nickel, (c) quarter dollar and (d) half dollar. Experimental data plotted as points, and simulated data shown as lines.

	Real $(\Lambda_1)$	Im $(\Lambda_1)$	Real $(\Lambda_3)$	$\operatorname{Im}(\Lambda_3)$
Cu Dime	0.010	0.010	0.226	0.118
Cu Nickel	0.014	0.038	0.172	0.131
Cu Quarter-Dollar	0.019	0.043	0.061	0.059
Cu Half-Dollar	0.023	0.079	0.335	0.209

 Table 6.5: NRMSE of the differences between simulated and experimental values for the copper disk data in Figure 6.11.

Due to the US coinages were measured in different rotations and the eigenvalue matrices,  $\Lambda$ , were calculated to derive corresponding tensors. The eigenvalue matrix is independent of the orientation of the coin but gives an absolute measure of the tensor's frequency response characteristics.

$$\overline{\mathbf{M}} = \mathbf{R} \cdot \mathbf{\Lambda} \cdot \mathbf{R}_{\mathrm{T}} \tag{6.1}$$

where  $\Lambda$  is the diagonal matrix:

$$\mathbf{\Lambda}(\mathbf{f}) = \begin{bmatrix} \mathbf{\Lambda}'_{\mathbf{xx}} + \mathbf{j}\mathbf{\Lambda}''_{\mathbf{xx}} & 0 & 0\\ 0 & \mathbf{\Lambda}'_{\mathbf{yy}} + \mathbf{j}\mathbf{\Lambda}''_{\mathbf{yy}} & 0\\ 0 & 0 & \mathbf{\Lambda}'_{\mathbf{zz}} + \mathbf{j}\mathbf{\Lambda}''_{\mathbf{zz}} \end{bmatrix}$$
(6.2)

The spectroscopic and complex nature of tensor implicitly describes the phase shift exhibited between the applied primary field and the induced dipole or secondary field. This depends on the electromagnetic properties of the object. Therefore, the tensor can yield information about the object's material and size.  $\Lambda_1$ ,  $\Lambda_2$ ,  $\Lambda_3$  represent eigenvalues from x-direction, y-direction, and zdirection. Due to the US coinage and similar-sized copper disks are symmetric, and there is insignificant response at y-direction, therefore the value of  $\Lambda_2$  is nearly zero while the value of  $\Lambda_1$ and  $\Lambda_3$  are non-zero.

#### **6.5 Tensors of US Coins**

This part presents eigenvalues of the derived tensors for the US coins. In terms of the copper disk data, experimental eigenvalues are plotted as 29 discrete solid-filled markers over the frequency range of 1 kHz to 100 kHz whilst overlaid simulated eigenvalues are plotted over the frequency range from 10 Hz to 100 MHz. For all data, simulated eigenvalues  $\Lambda_1$  and  $\Lambda_3$  are shown as solid and broken lines respectively.

Figure 6.12 shows the one cent experimental data compared with monolithic disk simulations set to conductivities of pure zinc and 95% conductivity of pure zinc. From Table 6.6, it can be seen that the better modelling agreement is for the model using 95% conductivity of pure zinc. This is particularly evident in the imaginary and real components of the larger eigenvalue,  $\Lambda_1$ , which suggests an overall improved fitting with the experimental data for the model using the lower conductivity of 15.9 x 10<sup>6</sup> S m<sup>-1</sup> compared with the simulated data from the model considering pure zinc. In reality, the one cent comprises of a thin 8 micron copper plate layer over a solid zinc core. Such a thin layer is difficult to model using FEM with practicable computational time requirements. Despite this, the simplified monolithic tested models give reasonable agreements with experimental data considering the trade-off between absolute accuracy and computational effort.



Figure 6.12: US cent modelled as (a) pure Zinc and (b) 95% Zinc conductivity.

 Table 6.6: NRMSE of the differences between simulated and experimental values for the US cent data in Figure 6.12.

	Real $(\Lambda_1)$	$\operatorname{Im}(\Lambda_1)$	Real $(\Lambda_3)$	Im $(\Lambda_3)$
US cent modelled by pure Zinc	0.060	0.102	0.548	0.263
US cent modelled by 95% Zinc	0.044	0.078	0.518	0.245

Figure 6.13 shows eigenvalue tensor data for the US nickel. From the experimental data, the peak frequency for the imaginary eigenvalue,  $\Lambda_1$ , is approximately 18 kHz. The position of this peak is dependent on the coil's size and composition; for equal shape and sizes, the lower the conductivity the higher the peak frequency. The value is significantly higher than the corresponding value of the US cent, 5 kHz. This is consistent with the significantly lower conductivity of the monolithic nickel coin compared with the higher conductivity one-cent coin which is primary based on zinc.

The simulated results for the US nickel agree with experimentally derived eigenvalues and this is quantified in Table 6.7. This is consistent with the significantly lower conductivity of the monolithic CuNi nickel coin compared with the higher conductivity one-cent coin which is primarily based on zinc. In Table 6.6, it can be seen that the simulated data for the US nickel gives reasonable agreement with the experimentally derived eigenvalues. The NRMSE values shows that the best fit between simulated and experimental data is for the dis modelled to a conductivity set to  $2.72 \times 10^6$  S M<sup>-1</sup> corresponding to 70-30 CuNi binary alloy. This is particularly evident in the visually indiscernible differences between the experimental data points and simulated solid lines corresponding to the imaginary eigenvalue,  $\Lambda_1$ , as shown in Figure 6.13(b).



Figure 6.13: US nickel modelled as (a) 75-25 CuNi and (b) 70-30 CuNi.

 Table 6.7: NRMSE of the differences between simulated and experimental values for the US nickel data

 in Figure 6.13.

	Real $(\Lambda_1)$	$\operatorname{Im}(\Lambda_1)$	Real $(\Lambda_3)$	$\operatorname{Im}(\Lambda_3)$
US nickel modelled by 75-25 CuNi	0.142	0.106	1.494	0.565
US nickel modelled by 70-30 CuNi	0.038	0.035	1.330	0.444

Figure 6.14 shows that the measured and simulated derived eigenvalues of the spectroscopic tensor for the US coins dime, quarter and half dollar. As described previously, all these coins comprise of a roll-clad layer. The first left-hand side column of the figure compares experimental data with simulated results derived from simple models without using any cladding material, whilst the second column shows simulations using top and bottom cladding. Modelling using solely top and bottom cladding for these coins was deemed a good representation of reality since even on newly circulated coins such as the quarter dollar the copper core is clearly visible along the edges of the coin. The eigenvalues for coins using cladding layers differ significantly compared with non-clad coins. For example, considering experimental measurements, and despite the limited number of data points at higher frequencies, such coins do not present a truly symmetrical peak in the imaginary eigenvalues,  $\Lambda_3$ . This is due to the intrinsic nature of having a physical structure of different metals and alloys possessing different electromagnetic properties forming sandwich layers. Generally, the eigenvalues of Figure 6.14 show better agreement for simulated data from models considering the cladding layers. This is particularly evident when looking at the shape, height and peak position of imaginary eigenvalues,  $\Lambda_3$ . For all cases of the US dime, US quarter and US half dollar, the visual fit between experimental based eigenvalues and simulations from clad-type models is far better than for non-clad models. This is can be verified by lower NRMSE values shown in Table 6.8.





Figure 6.14: US coins dime, quarter and half dollar all modelled with a core of 99-1 CuNi (35.1 x  $10^6$  S/m) without and with top and bottom cladding layers of 75-25 CuNi (3.19 x  $10^6$  S/m); (a)-(b) dime without and with 0.2 mm cladding, (c)-(d) quarter without and with 0.2 mm cladding, (e)-(f) half dollar without and with 0.3 mm cladding.

Table 6.8: NRMSE of the differences between simulated and experimental values for the US dime, quarter dollar (QD) and half-dollar (HD) coins data of Figure 6.14.

	Real $(\Lambda_1)$	$\operatorname{Im}(\Lambda_1)$	Real $(\Lambda_3)$	$\operatorname{Im}(\Lambda_3)$
US Dime (without cladding)	0.127	0.103	1.028	0.667
US Dime (0.2 mm cladding)	0.068	0.083	0.251	0.261
US QD (without cladding)	0.083	0.067	0.793	0.568
US QD (0.2 mm cladding)	0.034	0.065	0.083	0.197
US HD (without cladding)	0.042	0.091	0.492	0.397
US HD (0.3 mm cladding)	0.026	0.111	0.261	0.275

Figure 6.15 shows that the associated eigenvalue tensor data for the US dollar. In this case, experimental data is compared with models comprising of top and bottom cladding, finally to a model using total wrap-around cladding which encompasses the edge of the coin. In reality, the cladding of the dollar itself is of manganese brass alloy as described in Table 6.1. In common with all brass alloys, the conductivity of the cladding is likely to be highly dependent on material composition since alloying of a pure metal significantly affects the electrical conductivity of the host metal [95]. For this reason, the conductivity of the cladding was treated as unknown and initial top and bottom clad models set conductivities in the range of 20% to 60% of IACS conductivity. The simulations of Figure 6.15 (a-e) failed to give good agreement with experimental data for both real and imaginary components of eigenvalues,  $\Lambda_1$  and  $\Lambda_3$ . However, the total wrap-

around model using conductivity set to 30% of IACS conductivity yielded a better agreement between experimental and simulated data. The comparison results of the imaginary data in Figure 6.15 (f) particularly show the improvement. Although, the agreement for real eigenvalue,  $\Lambda_3$  is still relatively poor, the overall fit across all data using this model is much improved compared with the models using only top and bottom cladding. The NRSME values can be found in the Table 6.9.



Figure 6.15: US dollar all modelled with a core of 99-1 CuNi (35.1 x 10<sup>6</sup> S/m); (a)-(e) with 0.4 mm top and bottom cladding layers of 20% to 60% Cu conductivity in 10% incremental steps and (f); total wrap-around cladding with 30% Cu conductivity (17.4 x 10<sup>6</sup> S/m).

	Real $(\Lambda_1)$	Im $(\Lambda_1)$	Real $(\Lambda_3)$	Im $(\Lambda_3)$
20% Cu	0.039	0.078	0.657	0.480
30% Cu	0.047	0.045	0.737	0.535
40% Cu	0.065	0.034	0.779	0.583
50% Cu	0.081	0.039	0.803	0.621
60% Cu	0.094	0.058	0.818	0.653
30% Cu (total cladding)	0.030	0.070	0.734	0.533

Table 6.9: NRMSE of the differences between simulated and experimental values for the US dollar coinsdata of Figure 6.15.

Considering all the coin data, it shows a strong correlation between the magnitude of the eigenvalues and the size of the coins. In particular, smaller coins have smaller eigenvalues compared with larger coins which have larger eigenvalues. In addition, the differences in magnitude between eigenvalues  $\Lambda_1$  and  $\Lambda_3$  clearly show the relative size differences between the axial and traverse responses of the experimentally derived and simulated tensors. Namely, the diameter of the coins are substantially greater that of the thickness of the coins. However, the data also suggests that the ratios of  $\Lambda_1$  and  $\Lambda_3$  do not directly correlate with the ratios of coin diameters to thicknesses. This can be explained that the tensor information is not just related to the dimension of the objects, but also composition. This is also can be explained to the peak frequencies in eigenvalue data shown in Table 6.10, the difference of the peak frequencies are dependent on both composition and dimension of the coins. For example, the bulk composition of the US dime, US quarter and US half dollar are same according to Table 6.1. However, the sizes of the these coins are significantly different, increasing in size from the dime to quarter to half dollar with the half dollar being almost twice the diameter of the dime and five times its mass. As expected, the measured and simulated peak frequencies of the dime, quarter and half dollar decrease with increasing coin size. For the case of one cent, its composition is significantly different as it is a Zn based coin, and its peak frequency in Table 6.9 suggests that the overall conductivity of the cent is higher than nickel but less than the dime. This is consistent with Zn being more conductive than Ni and the relatively higher 25% Ni composition of the CuNi based nickel coin results in the nickel having an overall lower conductivity compared with the cent. In addition, the composition of the dollar by weight is lower compared to that of the clad coins of the dime, quarter dollar and half dollar. All else being equal, this would suggest a lower peak frequency of the eigenvalues. However, the dollar is larger than in size and weight compared with dime and quarter but smaller than half dollar. Therefore, the peak frequency for dollar is lower than dime and similar to quarter. As a whole, the differentiating factor is the larger eigenvalue tensor magnitudes, suggesting an object of greater size and lower conductivity.

	Peak frequency of	Peak frequency of	Peak frequency of	Peak frequency of
	imaginary	imaginary	imaginary	imaginary
	experimental	experimental	simulated	simulated
	eigenvalues for $\Lambda_1$	eigenvalues for $\Lambda_3$	eigenvalues for $\Lambda_1$	eigenvalues for $\Lambda_3$
One Cent	5.0	50.0	4.0	39.8
Nickel	18.0	Above upper limit	15.8	158.5
Dime	2.4	50.0	2.5	63
Quarter	1.4	30.0	1.3	31.6
Half Dollar	1.0	18.0	1.0	19.9
Dollar	1.2	30.0	1.3	20.0

Table 6.10: Peak frequencies of derived eigenvalues of US coins, all the units are kHz.

## **6.6 Conclusions**

This chapter has presented the tensor measurement system with the tensor calculation of the US coins. It contains the measurement apparatus including transmitter and receiver amplifiers, and data acquisition system. Noise calculation and the experimental procedure were also provided. Finally, the results of the trans-impedances and tensors of the US coins have been discussed, and the data between the experimental and simulated data is reasonable. However, the results clearly bring out the limitations of comparing experimental tensor data with simplistic FEM models which cannot adequately describe the spectroscopic nature of the tested coins. In addition, the drifting issue of the system has also contributed to the imperfection of the measurement data, whilst reasonable recommendations to reduce the effect of drifting have been discussed.

# 7. Modelling

This chapter presents both time and frequency domain methods for modelling metal detector applications. The chapter starts by first considering pulsed eddy current metal detection systems, beginning with a literature review of pulsed eddy current testing and its applications. Afterwards, an example of a pulsed metal detection system is presented with simulated results using a commercial field solver and employing two solution methods. Firstly, using a frequency domain eddy current solver and, secondly, a transient solver approach. Finally, the chapter shows that the simulation results in the time domain are consistent with the results in the frequency domain as would be expected from the theory of Fourier transforms.

# 7.1 The Pulsed Eddy Current Testing

Pulsed eddy current testing technology has developed significantly over the past two decades and is now a well-established type of eddy current testing technology. The technique is based on the principle of electromagnetic induction and has been used in both NDT area [96] and metal detection applications [97-98]. Different to conventional eddy current testing, where a single frequency sinusoidal excitation field is applied, the pulsed eddy current approach uses pulsed excitation, which contains information over a range of different frequencies [99].

Witting *et al.* proposed the concept of the pulsed eddy current method, where an exciting coil is fed with a rectangle pulse, and the voltage pulse received by the receiving coil is then analysed in the time domain [100]. Eddy currents are induced in the nearby target because of the step changes in the applied excitation signals. The technology has been used for detecting defects in conductive materials based on the analysis of the excitation frequencies and the eddy current penetration depth [101].

The transient analysis of the magnetic field, which is produced by the eddy current signal and sensed by the receiving coil, has been conducted for pulsed eddy current testing, and defects have been studied via the peak value and the time instant of the peak in the induced voltage by the magnetic field. The lower the peak value of the induced voltage, the weaker the magnetic field produced by the eddy current, and hence, the smaller in size or the greater the depth of the defect. Naturally, the peak value of the induced voltage becomes higher with a more significant defect at the same depth. However, deeper defects typically have a longer time to peak value.

The advantages of pulsed eddy current testing compared to conventional single frequency eddy current testing may be summarised in four regards. Firstly, more frequency components are included in the pulsed eddy current testing system, so a sample can be tested in one pass without having to change the excitation frequency to detect different types of defects (*e.g.* surface versus sub-surface). Secondly, the electronics are relatively simple to implement. Thirdly, the techniques can have better suppression of certain types of noise; for instance, the directly coupled excitation signal from the transmitter coil to the receiver coil is inherently suppressed because of the timegating action used to extract the transient signal in the receiver circuitry [102-103]. Lastly, the traditional frequency domain solver takes too long for complex geometries while the pulsed eddy current solver is much quicker. However, pulsed eddy current systems also have disadvantages, most notably that they operate over a wider bandwidth and are therefore more prone to electromagnetic interference from the nearby environment.

In this research, the main objective of using pulsed eddy current is to study the magnetic characteristics of the tested objects by analysing their induce voltages in the magnetic field. In addition, the method is also verified by the simulation results in the frequency domain using a fast Fourier transform (FFT).

#### 7.1.1 The Penetrating Depth and the Skin Effect

Electromagnetic induction is the theoretical basis for pulsed eddy current testing, and Maxwell's equations have been introduced in section 3.1.

Conventional sinusoidal excitation can be described as follows:

$$H = H_{\rm m} e^{j\omega t} \tag{7.1}$$

where  $H_m$  is the maximum value of the sinusoidal signal, and according to Equations (3.1)-(3.4), the  $\nabla^2 H$  can be expressed as:

$$\nabla^2 \mathbf{H} = \mathbf{j} \omega \sigma \mu \mathbf{H} - \omega^2 \mu \varepsilon \mathbf{H} \tag{7.2}$$

Assuming  $k^2 = j\omega\sigma\mu - \omega^2\mu\epsilon$ , then,

$$\nabla^2 \mathbf{H} - \mathbf{k}^2 \mathbf{H} = \mathbf{0} \tag{7.3}$$

During operation, the coil is placed on or near the surface of the tested object or the ground in the case of mine detection. The z-axis is defined as the axial direction of the coil, and two tangents of the coils which are perpendicular to the z-axis are noted as x-axis and y-axis. Due to the magnetic

field strength of at the directions of y-axis and z-axis is not decaying, so the Equation (7.3) can be transformed as follows:

$$\frac{d^2 H_z}{dx^2} - k^2 H_z = 0 ag{7.4}$$

The solution of above equation is:

$$H_z = c_1 e^{-k_1 x} + c_2 e^{k_2 x}$$
(7.5)

where  $c_1$ ,  $c_2$  are constants of the boundary restriction coefficients.

 $H_z$  will not be restricted in the x-axis if the area of the tested object under the coil is assumed to be infinite, and then  $c_2 = 0$ ,  $H_z = c_1 e^{-k_1 x}$ , where  $k_1 = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)}$ . In addition, generally, the conductivity ( $\sigma$ ) of the coil is much bigger than  $\omega\epsilon$ , i.e.  $\omega\epsilon \ll \sigma$ . For example, the conductivity of the copper is 5.96 x 10<sup>7</sup> S/m, and the  $\omega\epsilon = 2 \times \pi \times 1000 \times 1 = 6.283 \times 10^3$  Hz at the frequency of 1000 Hz. It is clear to see that  $\omega\epsilon \ll \sigma$ . Therefore, Equation (7.5) can be written as follows:

$$H_z = c_1 e^{-x(1+j)\sqrt{\omega\mu\sigma/2}}$$
 (7.6)

When x = 0,  $H_z = H_{z0}$ , hence  $c_1 = H_{z0}$ , so Equation (7.6) can be derived further as follows:

$$H_z = H_{z0} e^{-x(1+j)\sqrt{\omega\mu\sigma/2}}$$
 (7.7)

The eddy current density,  $J_x = -dH_z/dx$ , can be derived as follows:

$$J_{x} = (1+j)\sqrt{\omega\mu\sigma/2}H_{z0}e^{-x(1+j)\sqrt{\omega\mu\sigma/2}}$$
(7.8)

From Equation (7.8), it shows that the eddy current density of the tested object decreases exponentially with the increasing distance from the coil. However, the phase difference of the eddy current increases proportionally with the increasing depth. Equation (7.8) can be written as follows:

$$J_x = J_0 e^{-x\sqrt{\pi f \sigma \mu}} \tag{7.9}$$

where f is the frequency of the excitation eddy current, x is the distance to the defect surface,  $J_0$  is the eddy current at the surface of the tested object, and  $J_x$  is the eddy current density at the depth of x of the tested object. This is called the skin depth effect. The standard penetration depth,  $\delta$ , is the depth when the eddy current is 1/e times of surface eddy current. In addition, when the tested object is located at the depth of  $\delta$ , the phase of the eddy current lags 1 rad.

$$\frac{J_x}{J_0} = e^{-x\sqrt{\pi f \sigma \mu}} = 1/e$$
 (7.10)

Therefore  $\delta = 1/\sqrt{\pi f \sigma \mu}$ . Normally, the standard penetrate depth calculated by the excitation frequency, electric conductivity, and magnetic permeability values should be larger than 1/3 of the testing depth in order to achieve effective performance. The frequency of the excitation signal and the diameter of the probe determine the testing depth of the eddy current. The larger is the diameter of the probe, the deeper is the testing depth, the larger is the range of the distribution of the eddy current, and the lower is the sensitivity of the probe. Therefore, probe design is very important for the performance of the eddy current testing.

#### 7.1.2 Principle of Probe Design

In eddy current testing, the sizes and shapes of the coils, which are normally employed as the probes, play important roles in the sensitivity of the probes and testing ranges. High sensitivity and larger testing range are usually desirable for an ideal eddy current testing system. To achieve a high sensitivity, the axial magnetic field of the coil should change faster, and to gain a larger testing range, the radius of the coil should be larger. The Biot-Savart Law (See section 3.2) shows that the coil excited by the same current with a larger radius will produce a smaller magnetic induction strength near the coil and vice versa. However, the magnetic field changes faster for the coil with a larger radius, i.e. low sensitivity. A coil can be regarded as accumulated by a number of single-turn coils, so the magnetic field can be calculated by the sum of the magnetic fields of the single-turn coils.

Based on the above consideration, the optimum coil design is related to the depth of the axis, the radius of the coil, number of turns, resistance, inductance, wire radius and the frequencies of the excitation signal. Additionally, the characteristics of the tested objects, such as shape, geometry, magnetic permeability, and electrical conductivity need to be considered. Although it is hard to evaluate the effect of the pulsed eddy current signal to the probe design as it contains multiple frequencies, the method of conventional eddy current probe designing with single frequencies still can be applied.

#### 7.1.3 Field Theory of the Pulsed Eddy Current Testing

For pulsed eddy current testing systems, according to the Fourier transform, a pulse can be regarded as an accumulation of an infinite number of harmonic components via performing the Fourier transform of the spectrum of the time function. Assuming  $\Phi_n(x)$  is the family of standard orthogonal functions, and then

$$C_n = \int_a^b f(x)\Phi_n(x)dx \quad (n = 1, 2, 3, ...)$$
 (7.11)

A pulse excitation signal, f(t), can be expressed as the generalised Fourier series of the standard orthogonal functions  $\Phi_k(t)$ ,

$$f(t) = \sum_{n=1}^{\infty} C_k \Phi_k(t)$$
(7.12)

where  $C_k$  can be formularised as follows:

$$C_{k} = \int_{0}^{\infty} f(t)\Phi_{k}(t)dt$$
(7.13)

Therefore, a pulse can be expressed by an infinite number of harmonic components. The coil impedance is analysed to evaluate the tested objects in traditional eddy current testing, while the transient response of the induced voltage is investigated in pulsed eddy current testing.

Figure 7.1 shows a typical transient response when a probe is scanned over a crack of a tested object, and the crack is generated by the metal loss [104]. It shows that the defects have more impacts on the first half of the transient response comparing to the second half section. Peak amplitude, time to peak amplitude (TPA), and time to zero crossing (TZC) of the transient signal are often employed to quantify the defects [105-106]. The peak value of the transient signal is related to the position and the size of the defect. For example, larger defects give rise to greater peak amplitudes compared with smaller defects. The TPA is related to the location of the flaws, and this value is not linear with the distance of propagation. Nonetheless, the larger is the value of TPA, the deeper is the defect position. Finally, the TZC indicates the defect position and the condition of the tested object [107].


Figure 7.1: A typical transient response of the pulsed eddy current testing adapted from [104].

Figure 7.2 shows the transient responses of the probe corresponding to same defects with different depths. It shows that the peak amplitude and the value of TPA and TZC of the response signals are decreasing with increasing of the defect depth.



Figure 7.2: The transient responses for same defects with different depths adapted from [102].

The traditional eddy current testing is often employed to detect surface flaws due to the effect of the skin effect, while pulsed eddy current testing can be used to detect deeper defects because of low-frequency components contained in the excitation signals. In addition, the method also is more capable of anti-inference. In practice, the pulsed eddy current testing technology has been used to quantify the location of the defects in multi-layer structures, such as turbine blades, wing sections of aircraft components [108-109].

## 7.2 Modelling Methods

This section focuses on the modelling methods used for metal detection in this research. A typical simulation geometry has been assumed comprising of a circular sensor coil and a spherical test object. An axi-symmetrical geometry has been selected to minimise the computational burden. Initially, the problem is analysed in the frequency domain and the simulation results are presented. Afterwards, time domain analysis is introduced and the system is simulated using a transient solver. Finally, the simulation results of the system of two solvers are discussed.

## 7.2.1 Modelling using Eddy Current Solver

Figure 7.3 shows the 2D model built in the Ansys Maxwell software for analysing mutual inductance using frequency domain simulations based on the eddy current solver. This is an axissymmetrical geometry and the 3D model can be generated by rotating the 2D plane by 360° around the z-axis. The grey half circle represents the spherical test object with a radius of 2 cm whilst the red circle describes for a one-turn copper excitation coil of radius 9 cm, with coil radius of 1 mm. The distance between the coil and the central line of the tested object is 5 cm. The larger half circle, which covers the tested object, and the circle, which surrounds the sensor coil are designed as additional dummy vacuum spaces to increase the number of the meshes of the tested object and the coil in order to increase the simulation accuracy. Additionally, the vacuum space is 200 mm x 200 mm. This test set-up was chosen to be representative of the metal detection application although a metal sphere is relatively large compared to the size of metal targets in APM's in humanitarian demining operations. Conversely, the sphere would be small compared to the size of Unexploded Ordnance (UXO) such as with cluster munitions.



Figure 7.3: The asymmetrical 2D model built in Ansys Maxwell for analysing mutual inductance using the eddy current solver.

The coil of the model was excited by sinusoidal currents of different frequencies with the same amplitude of 1 A. The frequency range covered 100 Hz to 10 MHz with the frequencies approximately equally spread over a log scale with 15 frequencies per decade, giving a total of 91 stimulated frequencies. The material of the excitation coil was assigned as copper, and the target object was assigned with stainless steel. In order to obtain the real simulation results, another model was built with exactly same design and mesh, but with the target object assigned as vacuum. After the excitation signals were applied to the coil, the excitation coil itself can sense the induced voltage due to the target object, and the mutual inductance can also be calculated. The change in mutual inductance due to the target can be determined by using the result with the assigned materials and subtracting the vacuum case.

The quantity of the mesh plays an important role in the accuracy of the simulation results. Generally, the larger the number of triangular elements in the mesh, the more accurate is the calculated results in Ansys Maxwell, but this gives rise to longer is simulation times. In this model, the maximum length of mesh elements was set as 2  $\mu$ m. Figure 7.4 shows the mesh distribution of the triangular elements in the mesh, with the elements most densely distributed in the region of

the excite coil and the target, and Table 7.1 shows the total number of the meshes is 1294177 after four iterations.



Figure 7.4: Example 2D model in Ansys Maxwell showing mesh distribution.

Pass	Triangles	Total	Energy Error	Delta Energy	Loss (W)	Delta Loss (%)
		Energy (J)	(%)	(%)		
1	588382	1.3013e-007	211.1	N/A	0.00155	N/A
2	765783	1.3649e-007	2.0608	4.8937	0.00155	7.368e-006
3	995520	1.3654e-007	0.31361	0.034528	0.00155	3.907e-007
4	1294177	1.3655e-007	0.064432	0.0051888	0.00155	4.2378e-008

Table 7.1: The simulation results of convergence of the model in Ansys Maxwell.

Figure 7.5 shows the block diagram of the frequency domain method as used by Ansys Maxwell. As can be seen in the figure this is an iterative process which uses an adaptive solution method. The calculation of field solution will be stopped until the solution gets converged, and corresponding parameters will also be calculated, and the whole process will start again for next frequency if necessary.



Figure 7.5: Block diagram of the eddy current solution process in Ansys Maxwell [111].

## 7.2.2 Simulation Results from the Frequency Domain Solver

Figures 7.6-7.7 show the simulated results of real and imaginary parts of the mutual inductance in the model system. The simulation results are obtained by the subtraction between simulation results of the stainless steel model and the results of the vacuum model. The data generated by Ansys Maxwell was further processed by a bespoke MATLAB program.

In Figure 7.6, the values of the real components of the mutual inductance are negative as the target object is a paramagnetic material, i.e. stainless steel. The graph shows the basic trend, that values at low frequencies are close to 0 H and decrease gradually until the value reaches about  $-9 \times 10^{-10}$  H. In addition, the mutual inductance changes fastest at frequency of about 10 kHz. However, the results are not perfectly smooth at very low and very high frequencies. A potential

reason for this can be the size of the mesh is still not enough to provide a sufficiently appropriate level in accuracy of the simulation results. This issue can be dealt with a finer model but this would be at the expense of computational runtime.



Figure 7.6: Real part of the mutual inductance.

Figure 7.7 shows the imarginary part of the mutual inductance is around 0 H at low frequencies, climing to the peak value  $3.123 \times 10^{-10}$  H at 3.415 kHz, and gradually decresing to  $1 \times 10^{-11}$  H at high frequencies. The graph is smooth except at low frequencies, below  $10^3$  Hz, and the solution drops to zero below 300 Hz, which is incorrect. As discussed previously, higher density mesh model would probably reduce this error, but at the cost of a longer simulation time.



Figure 6.7: Imarginary part of the mutual inductance.

## 7.2.3 Modelling using Transient Solver

In the previous section, a model, which was built in Ansys Maxwell using the frequency domain eddy current solver, was analysed. An excitation sinusoidal signal with different frequencies were simulated and analysed, the results of the mutual inductance were also discussed. In order to verify if the results can be obtained from time domain after a process of the Fourier transforms, a pulsed eddy current testing system was modelled, and the transient response of the system has been investigated.

Figure 7.8 shows the 2D model of the system input to the Ansys Maxwell simulation software. The geometry of the system is same as the one built for analysing mutual inductance in the frequency domain as described in section 3.6.1. The excitation coil, which assigned with the properties of copper, is represented by a red circle and the diameter of the coil wire is 2 mm; the tested object, a stainless steel sphere, is again represented by a half-circle with a radius of 2 cm; the distance between the centre of the coil and x-axis is 5 cm and the radius of the excitation coil is 9 cm. An extra rectangle area, which settled for calculating transient signal produced by tested object in a magnetic field, is noted as the transient setup region.



Figure 7.8: The asymmetrical 2D model built in Ansys Maxwell for analysing mutual inductance in the time domain.

The output from the time transient solver needs to have a Fourier transform applied in order to gain the information of the frequency domain, and therefore the induced voltage should be able to apply Fourier transforms which requires its waveform to be continuous. Different excitation current signals have been tested to analyse their transient responses in the modelled system. Figure 7.9 shows a pulsed excitation current with a 0.02 s window period, and corresponding transient signal shows two spikes at 0.01 s and 0.03 s respectively.



Figure 7.9: A pulsed excitation current and corresponding transient response.

Figure 7.10 show a triangle-shaped excitation current signal where the ramp area is between 0.008 s and 0.01 s, and the decreasing area is between 0.01 s and 0.012 s. The corresponding transient response indicates an instant change at 0.008 s, 0.01 s, and 0.012 s.



Figure 7.10: A triangle-shaped excitation current and corresponding transient response.

Figure 7.11 shows a ramp-shaped excitation current with the starting ramp point of 0.001 s and the finishing point of 0.02 s. The corresponding transient signal presents an instant change at 0.001 s and gradually increasing to 0 at the completing point.

Additionally, the period of the window areas for the excitation pulses, the triangle-shaped and the ramp-shaped excitations are not important as long as there are saltations from 0 A to nonzero ampers.



Figure 7.11: A ramp-shaped excitation current and corresponding transient response.

The square pulse, triangular and ramp-shaped excitation currents all give rise to "spike-like" behaviour in the transient response. This can be described by Gibbs phenomenon where the Fourier series of a piecewise continuously differentiable periodic function behaves at a jump discontinuity; and there are large oscillations near the jump [112]. Either spikes or instant changes

occurred in the transient responses of the above three excitation current signals, which will cause significant Gibbs phenomenon and thus the responses are not suitable for performing the Fourier transform. For this reason, a Gaussian pulse has also been tested as an excitation current for the modelled system.

Figure 7.12 shows the Gaussian pulsed current applied to the model system and Figures 7.13-7.14 gives the simulation induced voltages of the stainless steel sphere and vacuum models respectively.



Figure 7.12: Gaussian pulsed current with mean of 250 ns.



Figure 7.13: The induced voltage of stainless steel sphere with the Gaussian pulsed current.



Figure 7.14: The induced voltage of the vacuum model with the Gaussian pulsed current.

Figure 7.15 shows the transient response caused by just the presence of the stainless steel sphere with the Gaussian pulsed current, and was generated by the subtraction between induced voltage of the object shown in Figure 7.13 and the vacuum model shown in Figure 7.14. The response has central symmetry and it begins at 0 V until around 190 ns where the voltage starts to decrease, the lowest value of -0.53 mV happens at 234 ns and starts to increase and crosses zero line at 250 ns corresponding to the peak point of the Gaussian pulsed excitation current. The response continues to climb and the maximum value of 0.55 mV which occurs at 265 ns, after which the values start to decrease again and reaches 0 V after 308 ns.



Figure 7.15: The transient response of the simulation model with the Gaussian pulsed current.

The continuous Fourier transform of a function f(t) and corresponding inverse form are given in [110], and the Gaussian excitation current signal can be expressed as follow:

$$f(t) = \frac{1}{2\pi} e^{-\frac{\delta^2}{2}t^2}$$
(7.14)

where  $\delta$  is the standard deviation, and  $\delta^2$  is the variance.

Therefore, the integral of the Gaussian signal is calculated as follows:

$$F(\omega) = \int_{-\infty}^{+\infty} \frac{1}{2\pi} e^{-\frac{\delta^2}{2}t^2} e^{-i\omega t} dt$$
$$= \frac{1}{\sqrt{2\pi\delta}} e^{-\frac{\omega^2}{2\delta^2}}$$
(7.15)

From Equations (7.14) and (7.15), show that the Fourier transform of a Gaussian is another scaled and stretched Gaussian. Figure 7.16 shows the Gaussian distributions and corresponding Fourier transform waveforms with the standard devirations of 0.5, 1, and 2 based on the Equations (7.14) and (7.15). The larger is the value of the standard deviration, the lower is peak amplitude of the Fourier transform result, and the larger is the bandwidth of the Fourier transform waveform.



Figure 7.16: The Gaussian distributions and corresponding Fourier transform results with the standard deviations of 0.5, 1, and 2.

The model, which was described in Section 7.2.1 shows the range of the simulted frequencies are between 100 Hz and 10 MHz, and the results are shown in Figures 7.6 – 7.7. In order to cover the whole frequency range, the coil was excited by five different Gaussian pulsed excitation currents. Table 7.2 gives the parameters describing the tested Gaussian excitation signals, and  $f_1$ ,  $f_2$ ,  $f_3$ ,  $f_4$ , and  $f_5$  refer to five simulated bandwidth.

$\frac{1}{2\pi}e^{-\frac{\delta^2}{2}t^2}$	$\frac{1}{\sqrt{2\pi}\delta}e^{-\frac{\omega^2}{2\delta^2}}(\omega=2\pi f)$
$\delta_1 = 5k \times 2\pi$	$f_1 = 5 \text{ kHz}$
$\delta_2 = 50k \times 2\pi$	$f_2 = 50 \text{ kHz}$
$\delta_3 = 100 k \times 2\pi$	$f_3 = 100 \text{ kHz}$
$\delta_4 = 1M \times 2\pi$	$f_4 = 1 MHz$
$\delta_5 = 10M \times 2\pi$	$f_5 = 10 \text{ MHz}$

 

 Table 7.2: The relationship between the standard deviation of the Gaussian pulsed excitation signals and the corresponding bandwidth after performing Fourier transform.

Figure 7.17 shows the general block diagram of the transient solution in Ansys Maxwell, and Ansys Maxwell will take over and step through stages of the solution process after the model has been built. The conduction solution will be firstly caluated, then the field solution will be caculated by the concurrent with external cicuit solution for one time step. The solutions for next time steps will be automatically calculated when necessary.



Figure 7.17: Block diagram of the transient solution process in Ansys Maxwell [111].

## 7.2.4 Comparison of the Simulation Results

Figures 7.18 - 7.19 show the comparison of the simulation results using both the frequency domain eddy current solver and the time transient solver in Ansys Maxwell of the mutual inductance. The red line represents for the simulation results using eddy current solver, and other five lines combine the whole frequency range simulated using the transient solver. The cyan line represents the simulation result with the  $\sigma$  of 5k × 2 $\pi$ , the green line represents the simulation result with the  $\sigma$  of 50k × 2 $\pi$ , the blue line represents the simulation result with the  $\sigma$  of 100k × 2 $\pi$ , the black line represents the simulation result with the  $\sigma$  of 10M × 2 $\pi$ .

Figure 7.18 shows the comparison result of the real part of the mutual inductance using the two different solvers. The two results agree very well between the frequency of 500 Hz and 30 kHz, and the difference occurs when the frequency is less than 500 Hz due to the simulation limitation of the eddy current solver. The difference of two solvers at the frequency of 100 kHz is  $\left|\frac{-7.958e(-10)-(-8.231e(-10))}{-7.958e(-10)}\right| \times 100\% = 3\%$ , and when the frequency is over 30 kHz, the disagreements of the results of the two solvers come from the insufficient samples when performing the Fourier transform of the transient response and the imperfect result of the eddy current solver.



Figure 7.18: Comparision of the simulation results using eddy current solver and transient solver in Ansys Maxwell of the real part of the mutual inductance.

Figure 7.19 shows the comparison result of the imaginary part of the mutual inductance using two different solvers. The comparison results agree very well between the frequency of 500 Hz and 40 kHz. However, differences occur when the frequency is less than 500 Hz due to the simulation limitation of the eddy current solver. The difference between the two solvers at the frequency of 73.5 kHz is  $\left|\frac{1.093e(-10)-8.9671e(-11)}{1.093e(-10)}\right| \times 100\% = 18\%$ , and when the frequency is over 40 kHz, the disagreements of the results of the two solvers come from the insufficient samples when performing the Fourier transform of the transient response.



Figure 7.19: Comparision of the simulation results using eddy current solver and transient solver in Ansys Maxwell of the imaginary part of the mutual inductance.

Although the simulation data obtained by the eddy current slover agrees well with the transient solver, some disagreements still exsit which has been described above. However, the results could be further improved from as follows:

- Increase the mesh quantity in the eddy current solver.
- Excite more Guassian pulsed currents in the transient solver.
- Refine the sampling method of the Fourier transforms for the transient signals.

The present simulation results are sufficient to suggest that the transient solver can be used in place of the eddy current solver to produce the mutual inductance of the tested object in the measurement system. The main advantage of the transient solver is that it is much faster than the eddy current solver, and it can be applied readily applied to simulate the real landmines in the future. It took over 23 hours to simulate via the eddy current solver, whilst it took less than 40 minutes to complete the same simulation via the transient solver using the same machine.

## 7.3 Conclusions

This chapter introduced the modelling methods of eddy current solver and transient solver in Ansys Maxwell. The concept of the pulsed eddy current testing and corresponding magnetic theory and applications have also been described. The simulation results of the transient solver, which used excitations by different Gaussian pulsed currents, agrees with the simulation results of the eddy current solver. Therefore, the transient solver can be used in place of the eddy current solver for simulating the landmine measurement system. This has the advantage of being much more computationally efficient.

# 8. Conclusions and Future Work

This final chapter summarises the research work presented in this thesis. This chapter goes on describing the future work to progress the research in order to achieve better performance of humanitarian demining.

## **8.1 Conclusions**

Throughout this thesis it is clear that some elements of the initial objectives of the research have been completed successfully with positive results whilst other areas have progressed considerably. In particular, a tensor measurement system has been successfully developed which comprised of front-end electronics, sensing coil, and the integration of a data acquisition system. The sensing coil has been designed from first principles along with utilising FEM simulations for uniform field optimisation and is presented used in the tensor measurement system. The system can accurately determine the tensors of various objects. In particular, the measurement system has provided unique tensors of US coins, various clutter items and AP mines, typically to an accuracy of around 5% between simulated and experimental data where available. In addition, the simulations of metal objects in the time and frequency domains have been studied, and the positive results can boot the research of AP / UXO detection via time domain techniques.

The main objectives of this research, defined in section 1.1, are repeated again here in order to evaluate the work presented in this thesis officially. The corresponding sections, supporting the claims, are referred to and the accomplishments achieved.

• To design and construct a sensor coil array, which is appropriately sized to measure the tensor spectra of typical anti-personnel mines.

Through Chapter 4, the thesis described an ideal sensor coil array which can produce a uniform electromagnetic field in order to help the measurement system to determine the tensor spectra of various objects. Two iterated coil designs were attempted with corresponding simulations in Ansys Maxwell, search coil verifications, and analytic calculations. The optimal design according to analytical calculation was provided along with a discussion of practical build considerations. Two coil designs were constructed and resonance frequencies were also tested. The magnetic flux densities of the transmitter and receiver coils, generated by two designs, were compared, and lastly the coil Design B was chosen to form the basis of the measurement system. In Design B, the

transmitter coil is composed by seven sub-segments and the receiver coil is composed by six subsegments. Afterwards, the chapter compared the calculated and measured magnetic flux densities of the transmitter and receiver coils of Design B, and the results were encouraging which are uniform and parallel enough to measure test objects. Finally, the possible reasons for differences between experimentally obtained measurements and the analytical data were presented. Therefore, based on these statements the sensor coil array has been successfully designed and constructed and is appropriately sized to measure certain landmines.

• To design and implement front-end amplifiers which can amplify the detector signal to a sensible level with suitable SNR.

The front-end amplifiers of the measurement system were presented in Chapter 5. The chapter initially described the measurement apparatus and the transmitter amplifiers, which are capable of driving current of over 10 A, was introduced. Afterwards, one pair of the Tx amplifiers was tested and the amplifier gain was determined. Similarly, the receiver amplifier was introduced with the testing of the amplifier gain. The chapter also presented the data acquisition system, and the noise calculation of the electronics. All the testing results showed that the front-end amplifiers can enlarge the signal with a good SNR.

#### • To use the system to determine the tensor spectra for a range of metallic objects of interest.

The spectroscopic measurement results of the US coinage and the corresponding tensor calculation have been shown in Chapter 6. Throughout this section, trans-impedance data of the US coinage was presented, and followed by the discussion of the simulation results of the same-sized copper disks compared to US coinage. Afterwards, different simulation models were introduced and the simulation and experimental results of the copper disks were compared. Finally, the tensor calculation of the US coinage according to simulation and experimental results was presented and discussed. The system has been validated by measuring copper disks and US coinage. These results were highly encouraging and resulted in publication. Additionally, metal objects including different AP landmines were measured using the developed tensor system.

• To simulate the response of metal objects in time domain and frequency domain in Ansys Maxwell, which is a commercial finite element electromagnetic field solver, in order to match these two responses via Fourier transform of the pulse system.

The modelling of a simple metal object in both the time and frequency domains along with simulation results were presented in Chapter 7. The chapter introduced the background and the

basic theory of the pulsed eddy current testing. Afterwards, a 2D model was built in Ansys Maxwell, and the simulation results in the frequency domain of the mutual inductance of the test object were presented. Then a transient solver with Gaussian pulsed current was discussed. Finally, the simulation results of the mutual inductance of the test object using both the frequency domain eddy current solver and the time transient solver were compared. The comparison results show that two solvers agree very well between the frequency of 500 Hz and 30 kHz for both real and imaginary parts of the mutual inductance of the test object. This was sufficient to indicate that the transient solver can be used in place of the eddy current solver which is computationally time-consuming. The method can be applied to simulate the real landmines which can increase the efficiency significantly. Therefore, according to the evidence provided in Chapter 6, simulations for the metal object in time domain and frequency domain have been completed with the discussions and suggestions of the comparison results.

## 8.2 Future Work

Two main parts throughout this thesis have been presented; one concentrates on the tensor measurement system and another one emphasises the simulation using the transient solver to obtain important information of a test object which can be applied to the humanitarian demining. According to these two areas, this section will recommend the potential future work in each area.

The potential improvements of the measurement system will now be addressed. Additionally, future work will consider the further use of the transient solver of Ansys Maxwell applied to humanitarian demining. In particular, the following areas of future work are suggested:

- (1) For the design and construction of the sensing coil array, as shown in Chapter 4, the measurement results obtained by the search coil still yield difference with the analytical solution. It will be worth investigating this further in two ways. Firstly, it will be useful to improve the construction process of the coil assembly as the coil was wound by hand instead of using professional engineering coil winding machine which would provide greater accuracy in laying down individual coil turns. Secondly, the search coil, employed as a tool to measure the magnetic flux density of the transmitter and receiver coils, can be refined by increasing the turns with narrower width to improve the measurement accuracy.
- (2) For the ability to measure larger objects or typical landmines, a new coil geometry should be designed using the presented analytical method. Before constructing the coil, the

geometry should also be simulated using FEM and the simulation results be compared to analytical calculation. Then front-end electronics should be modified accordingly.

- (3) For the drifting issue of the measurement system, as shown in section 5.4, it is worth conducting future measurement in a constant temperature environment. In addition, the data acquisition system can be refined to minimise the experimenting duration without causing problem of generating or receiving signals.
- (4) For the simulations using transient solver and eddy current solver, as shown in Chapter 7, only one sphere object with the radius of 4 mm was simulated in the 2D model. It will be advantageous to ensure further test the transient solver is in place of eddy current solver using more test objects. Firstly, simulating objects with various shapes, such as spheres with smaller and larger radii, or objects with different materials would be beneficial. Secondly, just five Gaussian pulsed excitation signals have been discussed in section 6.2.3, and were applied in the transient solver, so it will be helpful to choose more excitation signals to refine the simulation results, especially for lower and higher frequencies.
- (5) For the potential application of transient solver in humanitarian demining, as introduced in Chapter 7, it is worthwhile to refine simulation model in Ansys Maxwell to match different metal detectors and to verify the capability of the transient solver further, such as the portable metal detector developed within the Sir Bobby Charlton Research Institute, University of Manchester. Afterwards, different AP / UXO can be simulated using the model.

This thesis has presented several innovative aspects of research, although there are still much further work that need to be addressed. The coil design process and the manufactured transmitter and receiver coils generate a uniform electromagnetic field within the coil, and this geometry provides an ideal solution for inversion purposes, and this leads to the experimental results of the tensor measurement system with an improved accuracy. This thesis also introduced a novel modelling of a pulsed system magnetic detection system in a commercial electromagnetic simulation package. The solver has been verified by frequency domain simulation and can be applied to other metal detection systems in the future.

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# **Appendices**

# **Appendix I: Engineering Drawing of the Coil Design A**



# Appendix II: MATLAB Code for Magnetic Field of the Solenoid

```
%------ B-field for solenoid in one equation------ B-field for solenoid in one equation------
%-----%
8-----% PH 29/03/2016-----%
clc
close all
clear all
%-----%
R= 0.1795/2; % the radius of receiver is 0.1795/2 m
I1=0.1;
d=0.001; % the diameter of transmitter/receiver wire 1.2 mm
N=1; %simulated number of turns is 1 turn each round
pi=3.141592654;
u0=4*pi*(10.^(-7)); % Vacuum permeability N/A(2);
index = 1;
for h=0:0.001:0.405
   a=(h-0.405)/(((h-0.405).^2)+(R.^2)).^{(0.5)};
  b=(h-0.2025) / (((h-0.2025).^2) + (R.^2)).^{(0.5)};
  c=h/(((h.^2)+(R.^2)).^{(0.5)});
  Bsolenoidrec(index) = ((u0*I1*N)/2)*(-c+2*b-a);
index = index+1;
end
§______$
%------ B-field for solenoid in one equation------ B-field for solenoid in one equation------
%-----%
8-----%
clc
close all
clear all
%-----%
R= 0.1996/2; % the radius of receiver is 0.1795/2m, transmitter is 0.1996/2m
I1=0.1;
d=0.00215; % the diameter of transmitter/receiver wire 2.15mm
N=1; %simulated number of turns is 1 turn each round
pi=3.141592654;
u0=4*pi*(10.^(-7)); % Vacuum permeability N/A(2);
index = 1;
for h=0:0.001:0.405
```

a=(h-0.405)/(((h-0.405).^2)+(R.^2)).^(0.5); c=h/(((h.^2)+(R.^2)).^(0.5)); Bsolenoidtrans(index) = ((u0\*I1\*N)/2)\*(a-c);

index = index+1;
end

plot(0:0.001:0.405,Bsolenoidrec);

# Appendix III: MATLAB Codes for Magnetic Field of the Coil Design B

```
%------ B-field for solenoid in one equation------ B-field for solenoid in one equation------
%-----receiver------%
8-----% PH 29/03/2016-----%
clc
close all
clear all
load 'B rec.mat';
%-----%
R= 0.1795/2; % the radius of receiver is 0.1795/2 m
I1=0.1;
d=0.0012; % the diameter of receiver wire 1.2 mm
d1=14*d;
d2=17*d;
d3=4*d;
N=1; %simulated number of turns is 1 turn each round
pi=3.141592654;
u0=4*pi*(10.^(-7)); % Vacuum permeability N/A(2);
index = 1;
for
h=0:0.001:0.405
        a=((h-0.01608-d1)/(((h-0.01608-d1).^2)+(R.^2)).^{(0.5)})-((h-0.01608)/(((h-0.01608))))
0.01608).^{2} + (R.^{2})).^{(0.5)};
        0.13001).^{2} + (R.^{2})).^{(0.5)};
         c = ((h-0.3865) / (((h-0.3865).^2) + (R.^2)).^{(0.5)} - ((h-0.3865+d1) / (((h-0.3865+d1)))) - ((h-0.3865+d1)) - ((h-0.3865+d1)))
0.3865+d1).^{2}+(R.^{2}).^{(0.5)};
        d=((h-0.27257)/(((h-0.27257).^{2})+(R.^{2})).^{(0.5)})-((h-0.27257+d2)/(((h-0.27257+d2)))))
0.27257+d2).^{2}+(R.^{2}).^{(0.5)};
        e = ((h - (0.081645 - d3/2) - d3) / (((h - (0.081645 - d3/2) - d3) .^2) + (R.^2)) .^{(0.5)}) - (0.5)) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5) - (0.5
((h-(0.081645-d3/2))/(((h-(0.081645-d3/2)).^2)+(R.^2)).^{(0.5)});
        g = ((h - (0.320955 - d3/2) - d3) / (((h - (0.320955 - d3/2) - d3) .^2) + (R.^2)) .^{(0.5)}) - (0.5) - (0.5)
((h-(0.320955-d3/2))/(((h-(0.320955-d3/2)).^2)+(R.^2)).^(0.5));
        Bsolenoidrec(index) = -((u0*I1*N)/2)*(a+b-c-d-g+e);
index = index+1;
end
K equa=pinv(Bsolenoidrec.')*(Brec.');
Bsolenoidrec2 = Bsolenoidrec.*K equa;
plot(0:0.001:0.405,Bsolenoidrec2,'r','linewidth',2);
hold on;
plot(0:0.001:0.405,Brec,'linewidth',2);
                                                                                                     Receiver Coil', 'fontsize',
                   ('Magnetic
                                               Flux
                                                                Density
                                                                                        for
title
18, 'fontweight', 'bold');
xlabel('Distance [m]','fontsize',16,'fontweight','bold');
```

#### **ELECTROMAGNETIC METHODS FOR LANDMINE DETECTION**

```
ylabel('Magnetic Flux Density (T)', 'fontsize',16,'fontweight','bold');
legend('Present Design', 'Previous Design');
grid on;
ç_____ç
%----- B-field for new coil in one equation------ 8-field for new coil in one equation-------
%-----%
%-----%
ClC
close all
clear all
load 'B.mat';
%-----% all units are SI -----%
R= 0.1996/2; % the radius of transmitter is 0.1996/2m
I1=0.1:
d=0.0021; % the diameter of transmitter/receiver wire 2.15mm
d1=12*d:
d2=7*d;
d3=6*d;
d4=6*d;
N=1; %simulated number of turns is 1 turn each round
pi=3.141592654;
u0=4*pi*(10.^(-7)); % Vacuum permeability N/A(2);
index = 1;
for h=0:0.001:0.402
         a = ((h-0.015-d1) / (((h-0.015-d1).^2) + (R.^2)).^{(0.5)} - ((h-0.015) / (((h-0.015))) - ((h-0.015)) - ((h-0.015
0.015).^{2} + (R.^{2})).^{(0.5)};
         b = ((h-0.13823-d2) / (((h-0.13823-d2).^2) + (R.^2)).^{(0.5)} - ((h-0.13823) / (((h-0.13823))).^{(0.5)} - ((h-0.13823)) / (((h-0.13823)))).^{(0.5)} - ((h-0.13823)) / (((h-0.13823)))).^{(0.5)} - ((h-0.13823)) / (((h-0.13823))))))
0.13823).^{2} + (R.^{2})).^{(0.5)};
         c = ((h-0.38892) / (((h-0.38892).^2) + (R.^2)).^{(0.5)} - ((h-0.38892+d1) / (((h-0.38892+d1))))
0.38892+d1).^{2}+(R.^{2})).^{(0.5)};
         d=((h-0.26569)/(((h-0.26569).^2)+(R.^2)).^{(0.5)})-((h-0.26569+d2)/(((h-0.26569+d2)))))
0.26569+d2).^{2}+(R.^{2}).^{(0.5)};
         (0.08629-d3/2))/(((h-(0.08629-d3/2)).^2)+(R.^2)).^{(0.5)});
         (0.20197-d4/2))/(((h-(0.20197-d4/2)).^2)+(R.^2)).^{(0.5)});
         (0.31765-d3/2))/(((h-(0.31765-d3/2)).^2)+(R.^2)).^{(0.5)};
         Btransmitter(index) = -((u0*I1*N)/2)*(a+b+c+d+g+e+f);
index = index+1;
end
K equa=pinv(Btransmitter.')*(Btrans.');
Btransmitter2 = Btransmitter.*K equa;
plot(0:0.001:0.402,Btransmitter2,'r','linewidth',2);
hold on;
plot(0:0.001:0.402,Btrans,'linewidth',2);
```
title ('Magnetic Flux Density for Transmitter Coil','fontsize', 18,'fontweight','bold'); xlabel('Distance [m]','fontsize',16,'fontweight','bold'); ylabel('Magnetic Flux Density (T)', 'fontsize',16,'fontweight','bold'); legend('Present Design','Previous Design'); grid on;

## **Appendix IV: Engineering Drawing of the Coil Design B**





## Appendix V: Full Schematic Diagram for the Transmitter Amplifier



## **Appendix VI: An operating interface of the Red Pitaya**

RPTMS - Host Control	
Connection  192.168.128.1  5000  Connect	Saturation Rx Voltage: Not Saturated Tx Current: Not Saturated
Sweep	Statistics
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11,         Interval (ms)         2000           12, 14, 16, 18, 20, 24, 30, 40,         TX Scale         1	Rx Voltage (rms): 0.17 mV Sample rate: 59.34 sps
Start       Display       ADC Samples       Polar       I / Q       Skip Factor:     6	
Logging	
Browse	
Marker: U V	