EVALUATION OF LIFT-OFF EFFECT ON SURFACE DEFECT METAL WITH NON-CONDUCTIVE COATING BY USING EDDY CURRENT TESTING TECHNIQUE

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

FACULTY OF SCIENCE AND NATURAL RESOURCES
UNIVERSITI MALAYSIA SABAH
2023

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DEGREE : **MASTER OF SCIENCE**

FIELD : **PHYSICS WITH ELECTRONIC**

VIVA DATE : **17 NOVEMBER 2022**

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ACKNOWLEDGEMENT

First foremost, I want to express my gratitude to God. He has provided me strength and encouragement during the tough process of finishing this master's thesis. I am truly grateful for His unconditional and endless love, mercy, and grace.

I would like to express my sincere gratitude to my research supervisor, Prof. Madya. Dr. Fauziah Sulaiman. She has enlightened me with thoughtful comments on my research that have been a huge help in this endeavour. I could not have finished my dissertation without her assistance and unwavering support. I would like to thank you very much for your support and understanding over these past two years. It has been a great pleasure and honor to have her as my supervisor.

I would also like to express my deepest appreciation to all the individuals who have contributed to help my research and made it easier for me to write my thesis: Siti Syahirah, Astri M Fadzli, Nuraziana Fatina, Aiman Nabila, and Nasra Amsyellacibah. Thank you also to my colleague at Kolej Kediaman Tun Ahmad Raffae who provided me an accommodation at the residential college which would make it easier to attend my lab for my research experiment. Thank you to all of them who have offered invaluable advice that will benefit me throughout my MSc. Journey.

Finally, but most importantly, none of this could have happened without the support of my family. I would like to give special thanks to them for their continuous support and understanding when I decided to pursue my studies for my master's degree.

Syafiqa Putri Adlina binti Harun
17 November 2022

ABSTRACT

Eddy Current Testing (ECT) technique is a Non-Destructive Testing (NDT) method widely used in industries. The advantages of using the Eddy Current Testing technique are highly capable of detecting surface defects, determining material properties, e.g., conductivity and electrical permeability, measuring the thickness of materials, and performing nonconductive coatings on metal testing. However, the main obstacle of ECT is difficulty in detecting deeper defects and the undesirable lift-off distance between the sample and the sensor. Moreover, when applying the eddy current testing approach, nonmagnetic coating thickness variation frequently impedes flaw detection in metal testing. This research aims to develop the eddy current testing probe that generates eddy current signals when a coil is placed above each metal testing, i.e., copper 101, aluminium 6061, and stainless steel 304, with and without nonconductive coating and the presence of lift-off height, i.e., 0 mm, 2.5 mm, 5.0mm, 7.5 mm, and 10.0 mm. In addition, each metal test has a variety of thicknesses, i.e., 1.5 mm, 3.0 mm, and 5.0 mm, and an artificial surface defect, i.e., 10 mm, 20 mm, and 30 mm, engraved on each metal testing. The coil probe is a rod-shaped solenoid coil designed with an iron core with 65 mm length, 5 mm area, and 200 N turns. It demonstrates how the rod-shaped solenoid coil may be used to detect various surface defects in copper 101 (C101), aluminium 6061 (Al6061), and stainless steel 304 (SS304). The optimal frequencies for C101 were 7.850 MHz, aluminium Al6061was 7.383 MHz, and SS304 metal was 7.956 MHz. In conclusion, the output voltage signals for larger surface defect sizes increase but decrease as the thickness becomes thicker. Furthermore, as the lift-off height increases, the output voltage for both coated and non-coated metal decreases accordingly. Therefore, besides comparing the output voltage for coated and non-coated metals, there are minor differences which shows that the ECT technique in this research can still detect surface defects appropriately.

ABSTRAK

PENILAIAN KESAN JARAK ANGKAT TERHADAP LOGAM BERKECACATAN BAWAH PERMUKAAN DENGAN LAPISAN TIDAK BERKONDUKTIF MENGGUNAKAN TEKNIK UJIAN ARUS PUSAR

Teknik ujian arus pusar merupakan salah satu kaedah ujian tanpa musnah yang digunakan secara meluas dalam industri. Kelebihan menggunakan teknik ujian arus pusar (ECT) adalah keupayaan untuk mengesan kecacatan diatas dan dibawah permukaan, menentukan sifat bahan contohnya konduktor dan kebolehtelapan elektrik, mengukur ketebalan bahan, dan pada logam yang dilapisi menggunakan lapisan tidak berkonduktif. Walau bagaimanapun, halangan utama ECT ialah kesukaran mengesan kecacatan yang lebih mendalam dan jarak angkat yang tidak diingini antara sampel dan sensor. Selain itu, apabila menggunakan pendekatan ujian arus pusar, variasi ketebalan lapisan bukan konduktif akan menghalang pengesanan kecacatan dalam setiap logam. Penyelidikan ini bertujuan untuk menambah baik gegelung yang menghasilkan ujian arus pusar yang menjana isyarat arus pusar apabila gegelung diletakkan di atas setiap ujian logam, iaitu, tembaga101, aluminium 6061, dan keluli tahan karat 304, dengan dan tanpa lapisan bukan konduktif dari ketinggian jarak angkat, iaitu, 0 mm, 2.5 mm, 5.0mm, 7.5 mm, and 10.0 mm. Di samping itu, setiap logam mempunyai pelbagai ketebalan, iaitu, 1.5 mm, 3.0 mm, dan 5.0 mm, dan kecacatan bawah permukaan buatan, iaitu, 10 mm, 20 mm, dan 30 mm, terukir pada setiap logam. Kuar gegelung solenoid berbentuk batang yang direka dengan teras besi dengan panjang 65 mm, luas 5 mm, dan lilitan 200 N. Ia menunjukkan bagaimana gegelung solenoid tersebut boleh digunakan untuk mengesan pelbagai kecacatan bawah permukaan pada setiap logam yang dipilih. Frekuensi optimum untuk C101 ialah 7.850 MHz, aluminium Al6061 ialah 7.383 MHz, dan logam SS304 ialah 7.956 MHz. Kesimpulannya, isyarat voltan keluaran meningkat untuk saiz kecacatan bawah permukaan yang lebih besar tetapi berkurang apabila ketebalan meningkat. Tambahan pula, apabila ketinggian angkat bertambah, nilai voltan keluaran untuk logam dengan lapisan dan tanpa lapisan menunjukkan perbezaan yang tidak terlalu jauh. Oleh itu, kajian ini menunjukkan teknik ECT dalam penyelidikan ini boleh mengesan kecacatan bagi setiap parameter dengan perbezaan yang ketara.

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LIST OF SYMBOLS

% - Percent
± - Plus minus
$\Delta\Phi_B$ - Magnetic Flux
µm - micrometer
A - Cross-sectional area
B - Magnetic field
C - Capacitance
cm - Centimeter
D - Diametre
dB/dt - Rate of change of magnetic flux
f - Frequency
h - Height
H - Henries
Hz - hertz
I - Electric Current
kHz - Kilohertz
kOe - Kilo-oersted
l - Coil length
L - Inductance
MHz - Megahertz
mm - Millimeter
N - Number of turns
r - Radius
R - Resistance
V - Volt
XL - Inductive Reactance
Z - Impedance
δ - Standard depth of penetration
ε - Electromotive force
θ - Angle
µr - Relative Permeability
ξ - Efficiency Coefficient
ρ - Electrical Conductivity
σ - Conductivity
Φ - Phase angle
ω - Angular frequency
Ωm - Ohm metre

LIST OF ABBREVIATIONS

AC	-	Alternating Current
ACFM	-	Alternating Current Field Measurement
Al6061	-	Aluminium 6061
AMR	-	Anisotropy Magneto Resistance
C101	-	Copper 101
CCD	-	Composed Central Design
DC	-	Direct Current
ECS	-	Eddy Current Sensor
ECT	-	Eddy Current Testing
EDM	-	Electrical Discharge Machine
EMF		Electromotive Force
GMR	-	Giant Magneto Resistance
HAZ	-	Heat-Affected Zone
IC	-	Integrated Circuit
LII	-	Lift-Off Invariant Inductance
LO	-	Lift-Off
LOC	-	Lift-Off Curve
LOI	-	Lift-Off Point of Intersection
MEC	-	Magnetic Eddy Current
MPI	-	Magnetic Particle Inspection
MR	-	Magnetoresistance
MRI	-	Magnetic Response Imaging
NDT	-	Non-Destructive Testing
PEC	-	Pulsed Eddy Current
RSM	-	Response Surface Methodology
SMR	-	Spin Hall Magnetoresistance
SPEC	-	Swept-Frequency Eddy Current
SQUIDs	-	Superconducting Quantum Interference Devices
SS304	-	Stainless Steel 304

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter outlines an introduction to the non-destructive testing (NDT) related to the study of evaluating the lift-off effect on surface defect metal with non-conductive coating using eddy current testing techniques. Additionally, a summary of the work's execution is also discussed. Furthermore, this chapter addressed the existing problems and explained the aims, objectives, scope of research, and operational meaning frequently used in this research. Finally, the thesis content structure is also discussed.

1.2 Research Background

In today's rapidly evolving development and technology, we often see some failures in construction development. One of the failures can be referred to on July 19th, 1989, the DC-10 (registered as N1819U) serving the route crashed-landed in Sioux City, Iowa, due to a catastrophic failure of the tail-mounted engine, which resulted in the loss of several flight controls. This happened because of a defect that went undetected in an engine disk (Ranter, 2022). Based on this incidence, we may conclude that non-destructive testing (NDT) is critical in detecting flaws in any equipment or materials. For instance, we can say that the slightest hazardous defect can lead to significant failure or accident.

Non-destructive testing is a medium to test and evaluate material, equipment, or any construction without affecting the material's utility. It is necessary to do non-destructive testing and evaluation regularly on high-risk machinery. As a result, one of several NDT techniques used in this study is eddy current testing, widely used in various industries to detect surface and subsurface defects (Angani et al., 2015). Furthermore, eddy current testing (ECT) is well-known for its multiple benefits, which are high detectability (AbdAlla et al., 2018), non-contact testing (Burkhardt, 2019), and high-speed inspection. According to García-Martín (2011), in severe working circumstances, the current eddy test can check at high speeds up to 150m/s when other techniques cannot. However, ECT still faced difficulty detecting deeper defects (Kasai et al., 2013). This problem is quite popular among researchers as they try to enhance the sensitivity of detecting the subsurface defect.

Because of the skin effect associated with alternating currents, high frequencies keep the eddy currents circulating near the surface (García-Martín et al., 2011a). Hence, due to the skin effect, when the probe moves near the test material, the Current flow is greater at the surface and decreases as the probe moves away from the material's surface (Zeng et al., 2019). Jiao (2017) thoroughly investigated the skin effect in eddy current with a pancake coil, showing two factors leading to discrepancies: Cancellation/diffusion effect. The diffusion effect spreads eddy current energy with depth, and the cancellation/diffusion effect increases eddy current cancellation with depth. Therefore, when detecting surface defects and measuring test material, it is necessary to have prior knowledge of skin depth.

The essential part of the eddy current testing setup is sensitivity, and the linearity range of the detection coil has a high impact on its performance (Zhou et al., 2015). Besides, the coil's dimensions and excitation frequency also impact the eddy current signal (Zhou et al., 2015). The ECT equipment's frequency range and output impedance must be compatible with the coil or probe. Zhou also claims that by varying the coil size and excitation frequency, ECT finite element models may identify a subsurface flaw in ferromagnetic and non-ferromagnetic materials.

Rosado (2013) stated that the coil's shape and geometrical parameters should be quantified to enhance its performance. Like Misron (2011), who has investigated the efficacy of various designs of inductive coils with varying turn numbers. Thus, each type of shape resulting its advantages and disadvantages.

Crack detection beneath plating and coating in metal is related to surface defect identification. Eddy current testing can be less expensive than other approaches since it does not need stripping and polishing surface coatings (Abdalla et al., 2018; Meng et al., 2021). However, as the distance between the probe coil and the test material increases, a lift-off effect can occur on curved surfaces and with non-conductive coatings. In a conventional ECT system, some researchers studied that developing an ECT probe can be utilized to assess deeper defects. This reason can be seen in Rifai et al. (2016) growing weld probe with different diameter sizes i.e., 9mm and 16mm, and an optimum frequency as a reference signal. Saari et al. (2019) studied using a magnetic sensor such as anisotropy magnetoresistance (AMR) can detect sub-millimeter surface defects. In addition, Nardoni et al. (2014) developed a double differential ECT probe with 5mm and 6mm diameters for surface and sub-surface blade inspection.

Generally, the inspection system, the qualities of the material, and the test conditions all play a significant role in identifying eddy currents. Therefore, this study was carried out to overcome one of the drawbacks of the eddy current testing approach: the lift-off effect when detecting defects in metal testing. According to Rao (2020), successful testing requires selecting proper instruments and probes, optimizing test frequency, and using reference calibration standards. So, by establishing a coil probe (receiver and excitation coil) with an established amplifier instrument, the output voltage signals achieved with an optimum distance of LO height are used to detect the test materials.

1.3 Problem Statement

Eddy Current Testing technique is highly capable of detecting surface and subsurface defects (Rifai et al., 2016), determining material properties, i.e., conductivity and electrical permeability (Du et al., 2020), and determining the thickness of materials (Huang et al., 2020), conductive coatings and non-conductive coatings on metal testing (Burkhardt, 2019). However, many researchers agreed that ECT still faced difficulty detecting deeper defects because ECT is poorly sensitive to the low frequency used to inspect subsurface defects and the high frequency for surface defects (Sophian et al., 2001). Kasai (2008) studied that it's hard to identify defects on the backside of an oil-storage tank's bottom plates because the measurement of the plate's thickness cannot be carried out over its entirety. Then, he discovered that to find backside defects in ferromagnetic plates, remote field eddy current testing was designed for his research experiment. Hence, the problem in detecting deeper defect can be overcome by selecting an optimum frequency based on the test material and the depth of defect (Sophian et al., 2001)

The lift-off (LO) effect is well-known among NDT practitioners, described in terms of how far the probe is from the surface of the material always happens during an inspection. For instance, the lift-off effect also became the main problem for over a decade. Moreover, it is widely known that the undesirable lift-off effect has usually been a concern for accurate enhancement in eddy current non-destructive testing (Tian & Sophian, 2005b). Moreover, we can't eliminate the LO effect instead of finding a way to reduce it and maintain a consistent lift-off (Abdallah et al., 2018). Therefore, some researchers have proposed a beneficial method to overcome the lift-off problem. Methods that most researchers used in reducing the lift-off effect are the lift-off point of intersection (LOI) (Wen et al., 2018; Meng et al., 2021), dual excitation frequency (Yin & Peyton, 2007), Normalization technique (Tian et al., 2009), Dodd and Deeds method (Lu et al., 2018). These techniques have also been applied to measuring coating and thickness and identifying defects in metal testing.

Coatings degrade over time while a product is in use; therefore, measuring its coating thickness and conductivity is crucial (Xu et al., 2020). Furthermore, most aerospace, power plant, piping, and oil & gas industries use coating technology to prevent corrosion and maintain isolation at high temperatures (Hardwicke & Lau, 2013). Even though the coating acts as an anti-corrosive, it will mask the defect in the substrate while inspecting by using eddy current testing (Meng et al., 2021). However, Non-magnetic coating thickness on ferromagnetic or non-ferromagnetic substrates can be measured with eddy current testing, although this technique is affected by the lift-off distance between the sample and the sensor (Tian et al., 2005). Therefore, many researchers developed a way to overcome the LO effect on the coating thickness measurement. Several EC techniques are using dual EC sensors (Yu et al., 2017), swept-frequency eddy current (SPEC) (Tai, 2000), Pulsed eddy current (PEC) method (Zhang et al., 2015), multi-frequency (Lu et al., 2019) and more.

Hence, it is vital to determine an appropriate parameter for the eddy current testing signal: the optimum frequency, the probe sensor design, and the magnetic and electrical properties of the material to increase the sensitivity of the ECT. This research is developing a cost-effective eddy current instrument that can contribute to high sensitivity toward detecting surface defects on coated metals and non-coated metals.

1.4 Research Objectives

The objectives of this research are listed as follows:

1. To develop an ECT instrument setup to generate an eddy current signal on an artificial defect of each metal testing.
2. To investigate the optimal frequency between 5 MHz – 10 MHz for each test metal by using the ECT technique.
3. To Evaluate output testing signals imperfection for the varying thickness of test metals with different artificial defects size, different lift-off heights, and non-conductive layers on the test material.

1.5 Research Scope

In this research, there are several things to consider establishing the eddy current testing (ECT) equipment with high sensitivity, especially for surface defects. Firstly, the eddy current testing (ECT) coil probe was developed by experimenting with several turns (N), i.e., 50, 100, 150, and 200 turns of the coil, until the coil probe obtained a stable ECT signal. Secondly, an optimum frequency for each metal testing (copper 101, aluminium 6061, and stainless steel 304) was accepted as a reference signal to induce eddy current on the metal testing and measure the thickness, electrical conductivity, and magnetic permeability of metal testing. Another highlight of this research is applying various lift-off heights from (0 mm, 2.5 mm, 5.0 mm, 7.5mm, and 10.0 mm) ± 0.5 mm to this experiment to evaluate the lift-off effect on surface defect and the impact on ECT signals when coating (paint) was used on the surface of metal testing. Finally, as references from a previous researcher on ECT techniques, the results were analyzed and compared to this research field.

1.6 Operational Definition

Several terminologies with definitions as it is often used in this research:

i. Non-destructive Testing (NDT): A technique for testing the quality of a product or a part without affecting or damaging its strength and durability.

ii. Eddy Current Testing (ECT): Eddy current inspection is a non-destructive method in which eddy current flow is induced on the surface defect of test material by using electronic probes.

iii. Lift-Off (LO): The distance between the face of a surface probe and the surface under inspection.

iv. Probe/Sensor: An arrangement with a tiny coil or coils for eddy current inspection and an electromagnet for magnetic inspection.