2010

**Proximity and Thickness Estimation of Aluminum 3003 Alloy Metal Sheets Using Multi-Frequency Eddy Current Sensor**

Sunil S. Kamanalu  
*Wright State University*

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PROXIMITY AND THICKNESS ESTIMATION OF ALUMINUM 3003 ALLOY METAL SHEETS USING MULTI-FREQUENCY EDDY CURRENT SENSOR

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

By

SUNIL SONDEKERE KAMANALU
M.S., Wright State University, 2002
B.E., Bangalore University, 1999

2010
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY SUNIL SONDEKERE KAMANALU ENTITLED PROXIMITY AND THICKNESS ESTIMATION OF ALUMINUM 3003 ALLOY METAL SHEETS USING MULTI-FREQUENCY EDDY CURRENT SENSOR BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

Douglas T. Petkie, Ph.D.  
Thesis Director

Lok C. Lew Yan Voon, Ph.D.  
Department Chair

Committee on Final Examination

Douglas T. Petkie, Ph.D.

Jerry D. Clark, Ph.D.

Jason A. Deibel, Ph.D.

Andrew Toming Hsu, Ph.D.  
Dean, School of Graduate Studies
ABSTRACT

Kamanalu, Sunil Sondekere. M.S., Department of Physics, Wright State University, 2010.
Proximity and Thickness Estimation of Aluminum 3003 Alloy Metal Sheets Using Multi-Frequency Eddy Current Sensor.

The research work is focused on conducting a feasibility study on a new “non-contact” single probe dual coil inductive sensor for sensing the proximity and thickness of Aluminum (Al) 3003 alloy metal sheets, which is a non-magnetic metal. A bulk of the research and development (R&D) work has already been done in the area of non-destructive testing (NDT) using eddy current technology targeted to various applications like corrosion detection, material thickness, material conductivity, etc. The research work presented in this thesis uses the prior R&D work completed in NDT as a platform for conducting this study to estimate proximity and thickness of Aluminum 3003 alloy metal sheets, which is not considered a flaw detection application. Some of the current technologies in the area of eddy current NDT for proximity and thickness estimation, each with its own limitations, include single probe ‘contact’ sensors for magnetic metals, single probe ‘non-contact’ sensors with separation distance of less than 1 mm and dual probe sensors that requires probes on both sides of the metal sheet.

A swept multi-frequency scanning technique is used together with an automated data collection system to measure and collect output voltage and phase difference data over a wide range of frequencies. The skin effect in conductors and its associated property of skin depth is used to extract proximity and thickness information from the data collected, and then correlated with reference values to validate the results. Experimental
results show the output voltage and phase difference of the sensor is dependent on the metal parameters (resistivity ‘\(\rho\)’, permeability ‘\(\mu\)’, thickness ‘\(T\)’) and coil parameters (diameter ‘\(D\)’, frequency ‘\(F\)’, lift-off ‘\(L\)’). Further, proximity is estimated from output voltage difference, and metal thickness (single/double) is estimated from phase difference independent of lift-off, which is a novel approach for thickness detection. The test sensor provides an accurate measure of proximity and thickness of Al 3003 alloy from a single sided measurement with varying lift-off, overcoming the limitations of other sensor configurations.
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ACKNOWLEDGEMENT

I would like to take this opportunity to express my gratitude and appreciation to my thesis advisor Dr. Douglas T. Petkie for his advise, encouragement and support during my entire Master’s program. Further, the ‘Sensors Design’ course offered by Dr. Petkie was the primary source for my interest and motivation in the field of Sensors. Special thanks to Dr. Gust Bambakidis, Professor Emeritus, for giving me the opportunity to pursue my Master’s program.
DEDICATION

I would like to dedicate this thesis in memory of my paternal grandfather Mr. S. K. Hanumantha Reddy and my maternal grandfather Mr. C. P. Narasimhulu. I would also like to thank my wife Shilpa, daughter Saanvi, and my family for all the encouragement and support provided to me in completing my thesis work.
Chapter 1

Introduction

This chapter presents an overview on the theory and underlying principles of eddy current testing, which is the technique employed in this project for sensing the proximity and thickness of metal sheets. The objective of this thesis is to conduct a feasibility study on a new “non-contact” single probe dual coil inductive sensor for sensing the influence of metal proximity and thickness upon the impedance characteristics of the sensor using a swept multi-frequency technique and the concept of skin effect in conductors. The research work presented in this thesis aims to meet the challenges of the metal forming industry by ensuring that only a single sheet of a specific thickness enters the forming machine while making the measurement independent of lift-off distance, as their applications require preserving the integrity of the metal sample and/or space constraint (machines on which the sensors are installed).

The disadvantages of the current eddy current sensors for such an application are as follows:

(1) The single probe contact based sensor must make contact with the metal sheet under test. The probe is used to detect magnetic metals like steel, tinplate, stainless steel (magnetic).

(2) The single probe non-contact based sensor has limited lift-off capability and must be placed at a fixed distance of less than 1 mm from the metal sample.
The dual probe sensor requires probes on both sides of the metal sheet.

Non-destructive testing (NDT) or non-destructive evaluation (NDE) is a technique used for the detection and characterization of surface and sub-surface defects in a material without impairing the intended use of the material. A popular electromagnetic NDT surface technique is Eddy Current Testing (ECT) that is predominantly used wherever metal is being formed in presses and rolling-formers with wide applications in food and beverage, packaging, automotive, appliances, PCB fabrication, nuclear, aerospace, power, petrochemical and other industries. ECT is used to examine metallic sheets/plates, tubes, rods and bars, etc. for detection of metal proximity and thickness, metal type (conductivity and resistivity measurements), cracks, corrosion and other metal deformities during manufacturing as well as in-service. ECT is a simple, high-speed, high-sensitive, versatile and reliable NDT technique.

Many NDE applications in industries today demand an accurate measure of proximity and material thickness. Factors such as corrosion damage and other material defects can jeopardize structural integrity through material thinning and process control considerations often mandate strict limits on material dimensions [19]. Access to the material under test can be limited to a single side and large areas may need to be examined in a small time period. The eddy current sensor developed in this project provides a good measure of proximity and thickness information of Aluminum (Al) 3003 alloy from a single sided measurement. It is straightforward to use and can be easily automated for production line testing. Minimal instrumentation and power requirements for the sensor makes it a good candidate for manufacturing portable units at a substantially lower cost. The eddy current sensor has been used to demonstrate
measurement of proximity and thickness of Aluminum 3003 alloy sheets with a separation (lift-off) distance ranging from 0.0” (probe flush on the metal sheet) to 0.6” in increments of 0.1”, at a frequency range of 500 Hz to 6 KHz in increments of 500 Hz, and for the following standard metal thicknesses (single and double): 0.016”, 0.020”, 0.025”, 0.032”, 0.040”, 0.050”, 0.063”, 0.080”, 0.090”, 0.100”. This research work will explain the output voltage dependence of the sensor as a function of proximity and phase difference as a function of metal thickness independent of lift-off, which is a novel approach for thickness detection, and present experimental results for proximity and thickness gauging. Thickness is defined as a ‘single’, which defines one metal sheet of a given thickness or a ‘double’, which defines two stacked metal sheets of identical thickness.

1.1 Physical Concepts of Eddy Current Testing

![Figure 1. Eddy currents in a conductive material. (Source: NDT Education Resource Center)](image)

Eddy currents are a phenomenon caused by a changing magnetic flux intersecting a conductor or vice-versa (figure 1), which causes a circulating flow (closed loop) of electrons or current within the conductor. Eddy currents are the root cause of the skin effect in conductors carrying alternating current. Eddy currents flow in a plane that is
parallel to the coil winding or material surface and are attenuated and lag in phase with depth. Eddy current inspection works on the principles of electromagnetic induction. In ECT, the coil (also called sensor or probe) is excited with a sinusoidal input voltage source to induce eddy currents in the electrically conducting material under test. Any regions of metal discontinuities or deformities cause an impedance change in the sensing coil, and the resultant differential impedance between the reference and sensing coils is measured and correlated with the corresponding defect. Eddy currents are not uniformly distributed throughout a material being inspected; rather they are densest at the surface immediately beneath the coil and exhibit an exponential decay with increasing distance below the surface.

The following are the principles in ECT listed in sequential order (figure 2), which follow Maxwell’s equations for electromagnetic waves in conductors:

Figure 2. Electromagnetic induction process in a coil.
(Source: NDT Education Resource Center)

(1) Eddy current coil generates primary magnetic field by *Ampere’s law*,

(2) Primary magnetic field induces eddy currents in the electrically conducting material under test by *Faraday’s law*,
Eddy currents generate secondary magnetic field opposing the primary magnetic field by *Lenz’s law*,

Results in a coil impedance change, and

Impedance change is measured, analyzed and correlated with metal proximity and thickness.

The peak-to-peak amplitude and phase of the eddy current signal provides information about the defect severity or proximity and defect location or depth (thickness) respectively. Defects perpendicular to eddy current flow cause maximum coil impedance change categorized by large signal amplitude and high sensitivity compared to defects parallel to eddy current flow that results in minimal change in coil impedance categorized by a small response and low sensitivity.

### 1.2 Operating Variables

The following operating variables play an important role in eddy current inspection:

1. **Coil Impedance** \( Z = R + jX_L \) – It depends on the AC resistance \( R \) of the copper wire and the inductive reactance \( X_L \). Phase is given by: \( \tan \phi = \frac{X_L}{R} \).

The instantaneous voltage across the inductor due to a change in impedance is:

\[ v(t) = \Delta L \frac{di(t)}{dt} \]

The impedance change is the difference in impedance measurement with the coil placed over the metal and the coil over free space (air) i.e., \( \Delta L = L - L_{air} \). For a input sinusoidal AC drive through the inductor, \( i(t) = I_p \sin(2\pi ft) \), the resultant output voltage is, \( v(t) = 2\pi f \Delta LI_p \cos(2\pi ft) \).

Therefore the phase of the current lags that of the voltage by 90°.
(2) **Electrical Conductivity** \( (\sigma) \) – The measurement is based on International Annealed Copper Standard (IACS). In this system, the conductivity of annealed, unalloyed copper is arbitrarily rated at 100%, and the conductivities of other metals and alloys are expressed as percentages of this standard.

(3) **Magnetic Permeability** \( (\mu) \) – It is defined as the ratio of magnetic field strength \( (B) \) and the amount of magnetic flux \( (H) \) within the material, which is a nearly a constant for small changes in field strength. Magnetic permeability strongly influences the eddy-current response. The relative permeability, \( \mu_r \), is the ratio of the permeability \( \left( \text{For Aluminum, } \mu = 1.2566650 \times 10^{-6} \frac{H}{m} \right) \) of a specific material to the permeability of free space \( \left( \mu_0 = 4\pi \times 10^{-7} \frac{N}{A^2} \right) \), and is equal to unity for non-magnetic metals. For Aluminum \( \mu_r \) is 1.000022.

(4) **Electromagnetic Coupling** – The coupling of magnetic field to the material surface is important in eddy current testing. This coupling depends on the type of probes used, which may be surface or encircling probes.

(5) **“Lift-off” Factor** – Relates to surface probes, and is defined as the distance between the probe coil and the material under test, which translates to a change in coil impedance. Uniform and small lift-off is preferred to achieve better sensitivity to defect detection.

(6) **Edge Effect** – The distortion of eddy currents due to the inspection coil approaching the end or edge of a part being inspected. It is difficult to eliminate
edge effects due to practical constraints on coil sizes, as they are application dependent. Scanning in a line parallel to the edge can minimize edge effects.

(7) **Skin Effect** – It is the concentration of eddy currents at the sample material surface. The maximum eddy current density exists at the surface of the material and decreases exponentially with depth. Eddy current inspection works only on the outer “skin” of the material in thicker materials. Inspection sensitivity decreases rapidly with depth and volumetric techniques can be applied only to thin materials.

(8) **Skin Depth or Standard Depth of Penetration** \( \delta = \frac{1}{\sqrt{\pi \mu \sigma f}} \) – The depth at which the density of the eddy current is reduced to 36.8% \((1/e)\) of the density at the surface. The word ‘standard’ denotes the sample material excited with an electromagnetic plane wave, conditions which are very difficult to achieve in reality.

![Figure 3. Skin depth in a good conductor](http://unitmath.com/um/p/Examples/PulsedPower/SkinDepth.html).

(9) **Effective Depth of Penetration** – It is the maximum material depth from which a displayable eddy current signal can be obtained, arbitrarily defined as the depth at
which eddy current density has decreased to 5% of the surface eddy current density.

(10) **Inspection Frequency** \((f)\) – Typically depends on the metal being inspected and can range from 60 Hz to 6 MHz or more. Non-magnetic metals are inspected at a few KHz and lower frequencies are used for magnetic metals due to their low penetration depth with higher frequencies used only to inspect surface conditions. Factors influencing inspection frequency are material thickness, depth of penetration, degree of sensitivity or resolution and purpose of inspection. Often a compromise has to be achieved between these various factors for a given application.

(11) **Inspection Coils** – Coils come in a variety of shapes and sizes that are normally specific to an application. Coil shapes are mainly dependent on external or internal inspection desired and sizes are dependent on the degree of sensitivity desired. A more in-depth discussion on coil design and characterization is presented in Chapter 3 - Coil Design and Characterization.

### 1.3 Principles of Operation

Eddy current inspection in this project is achieved by using an in-house designed automated data acquisition system providing the following functionality:

(1) The inspection coil is excited with a range of frequencies at each lift-off distance using a multi-frequency technique.

(2) The output signal of the inspection coil is modulated by the metal sample being inspected.

(3) Inspection coil output signal is processed prior to amplification.
(4) Amplification of the inspection coil signals using a pre-amplifier.

(5) The amplified signals are digitized using a PCI digitizer followed by amplitude and phase analysis of signals by a computer using an in-house developed data acquisition application written in National Instruments LabVIEW 8.0.

(6) The output signals are displayed, measured and the corresponding data recorded simultaneously into ‘Text’ files.

(7) The raw data is processed using an in-house developed 32-bit Windows dynamic link library (DLL) software application written in Microsoft® Visual Basic 6.0.

(8) The processed data is used in 2D graphical analysis using Microsoft® Excel.

(9) Handling of the metal sample being inspected and support of inspection coil assembly.

1.4 Previous Eddy Current NDT Research Work

According to Dodd and Deeds [15], eddy-current coil problems fall in the intermediate frequency region. They proposed a closed-form theoretical solution of an air-cored coil above a metallic plate using the vector potential as opposed to electric and magnetic fields. The differential equations for the vector potential are derived from Maxwell’s equations, assuming cylindrical symmetry. The derived result for inductance is [16]:

$$
\Delta L(\omega) = K \int_0^\infty \frac{P^2(\alpha)}{\alpha^6} A(\alpha) \phi(\alpha) d\alpha
$$

where

$$
\phi(\alpha) = \frac{(\alpha + \alpha)(\alpha_1 - \alpha) - (\alpha_1 + \alpha)(\alpha_1 - \alpha)e^{2\alpha_1c}}{-(\alpha_1 - \alpha)(\alpha_1 - \alpha) + (\alpha_1 + \alpha)(\alpha_1 - \alpha)e^{2\alpha_1c}}
$$
\[ \alpha_1 = \sqrt{\alpha^2 + j\omega\sigma\mu_0} \]

\[ K = \frac{\pi\mu_0 N^2}{(l_1 - l_2)^2 (r_1 - r_2)^2} \]

\[ P(\alpha) = \int_{\alpha_2}^{\alpha_1} x J_1(x) d\alpha \]

\[ A(\alpha) = (e^{-\alpha_1} - e^{-\alpha_2})^2 \]

where \( \alpha \) is an integration variable, \( \omega \) is the angular frequency of the excitation signal, \( \mu \) and \( \sigma \) are the permeability and conductivity of the metal sample, \( N \) is the number of turns in the coil, \( r_1 \) and \( r_2 \) are inner and outer radii of the coil, \( l_1 \) and \( l_2 \) are the heights of the bottom and top of the coil, \( c \) is the metal sample thickness, \( \mu_0 \) is the permeability of free space, and \( J_1(x) \) is a first-order Bessel function of the first kind. Dodd and Deeds have shown that theoretical and experimental values of impedance are in agreement at higher frequencies as measurements at lower frequencies are difficult to make with poor accuracy.

Yin et al. [16, 17] have employed the technique of using phase signature for thickness detection of non-magnetic metal plates, and shown that phase is independent of lift-off if the pole distance (distance between the excitation and pickup coils) is much larger than the radius of the coils. Their research uses two eddy-current sensors (dual probes) with a single sided measurement. The phase technique is in contrast to using the magnitude of the eddy-current signal which generally decreases with increasing lift-off.

Placko et al. [18] have shown a technique for simultaneous distance and thickness measurements of zinc-aluminum coating on a steel substrate using an eddy-current sensor with a ‘\( H \)’ shaped ferromagnetic core. For distance measurements, they consider a
metallic body placed near the sensor which modifies the path of the magnetic field and changes the reluctance independent of the physical properties of the metal, apart from introducing eddy current losses. The reluctance and eddy current losses are measured separately, from the current in the coil, using a synchronous detection with quadrature or in-phase reference signal with respect to the driving voltage. For non-contact thickness measurements, the two quadrature and in-phase components are coupled to the distance of the plate, and to the thickness of the coating.

Wincheski et al. [19] in an effort to enhance the effectiveness of material thickness measurements developed a flux focusing eddy current probe at NASA Langley Research Center. The flux focusing eddy current probe uses a ferromagnetic material between the drive and pickup coils in order to focus the magnetic flux of the probe. Output voltage dependency as a function of material thickness is used for thickness estimation of conducting materials from a single sided measurement.

1.5 Thesis Layout

This thesis is structured with a theoretical explanation followed by experimental design. Chapter 2 provides the mathematical background, and chapters 3, 4, 5 explain the coil design and characterization, experimental setup and design, and results respectively. Finally, chapter 6 provides a conclusion, summarizes the results of this research study and proposes ideas for future work.
Chapter 2

Mathematical Background

In this chapter, the behavior of electromagnetic waves in conductors is discussed along with the mathematical equations for the physical $E$ and $B$ fields starting from Maxwell’s equations for a linear, homogeneous medium. An important property called skin depth that results out of wave attenuation in conductors is also discussed. The mathematical background presented in this chapter is primarily adopted from “Introduction to Electrodynamics” (3rd Edition) by David J. Griffiths [4].

2.1 Maxwell’s Equations

The general Maxwell’s equations for a linear, homogeneous medium are:

\[
\begin{align*}
(i) \quad \nabla \cdot E &= \frac{1}{\varepsilon} \rho_f, \\
(ii) \quad \nabla \cdot B &= 0, \\
(iii) \quad \nabla \times E &= -\frac{\partial B}{\partial t}, \\
(iv) \quad \nabla \times B &= \mu \varepsilon \frac{\partial E}{\partial t} + \mu \sigma E \\
\end{align*}
\]

Maxwell’s equations for a conducting medium are ($\rho_f = 0$):

\[
\begin{align*}
(i) \quad \nabla \cdot E &= 0, \\
(ii) \quad \nabla \cdot B &= 0, \\
(iii) \quad \nabla \times E &= -\frac{\partial B}{\partial t}, \\
(iv) \quad \nabla \times B &= \mu \varepsilon \frac{\partial E}{\partial t} + \mu \sigma E \\
\end{align*}
\]
2.2 Electric and Magnetic Field Waves in Conductors

The second order wave equations for $E$ and $B$ fields are obtained by applying the curl to Faraday’s and Ampere’s laws in equation (2.2):

$$\frac{\partial^2 E_x}{\partial z^2} = \mu \varepsilon \frac{\partial^2 E_x}{\partial t^2} + \mu \sigma \frac{\partial E_x}{\partial t}, \quad \frac{\partial^2 B_y}{\partial z^2} = \mu \varepsilon \frac{\partial^2 B_y}{\partial t^2} + \mu \sigma \frac{\partial B_y}{\partial t}.$$

These second order wave equations for $E$ and $B$ fields still have monochromatic plane-wave solutions of the form,

$$\tilde{E}(z,t) = E_0 e^{i(\tilde{k}z - \omega t)}, \quad \tilde{B}(z,t) = B_0 e^{i(\tilde{k}z - \omega t)} \quad (2.3)$$

resulting in the modified wave equations:

$$\frac{\partial^2 \tilde{E}_x}{\partial z^2} = [-\mu \varepsilon \omega^2 + i\mu \sigma \omega] \tilde{E}_x, \quad \frac{\partial^2 \tilde{B}_y}{\partial z^2} = [-\mu \varepsilon \omega^2 + i\mu \sigma \omega] \tilde{B}_y,$$

with a complex “wave number” $\tilde{k}$:

$$\tilde{k}^2 = [-\mu \varepsilon \omega^2 + i\mu \sigma \omega] \quad (2.4)$$

or $\tilde{k} = k + i\kappa$,

where,

$\tilde{k}$ - complex wave number;

$k$ - phase constant (radians per unit length); and

$\kappa$ - attenuation constant (nepers per unit length).

Relative values of conduction current density $J = \sigma E$, and displacement current density $\frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t}$ determine whether a given material acts like a good conductor or a good dielectric (Source: Third-year Electromagnetism by Robert D. Watson, School of Mathematics and Physics, University of Tasmania).
The parameter $L$ for forms of $e^{i\omega x}$ is written as:

$$L = \frac{|J|}{\partial D/\partial t} = \frac{\sigma E}{\epsilon_0 \omega E} = \frac{\sigma}{\epsilon_0 \omega}.$$

The parameter $L$ measures the relative values of the conduction and displacement currents. The $\omega$ in $L = \frac{\sigma}{\epsilon_0 \omega}$ means that at low frequencies materials act as conductors and at high frequencies they act as dielectrics, with the transition point depending on the properties of a particular material. The plasma frequency $\omega_p^2 = n e^2/m^*\epsilon_0$, which is the (ultraviolet) frequency at which metals become transparent to electromagnetic radiation due to a positive dielectric constant, is the high frequency limit above the resonant frequency of the dielectric constant $\epsilon(\omega) \approx \epsilon_0(\omega) - \omega_p^2/\omega^2$. Metals reflect with a negative dielectric constant and have a very small skin depth. Plasma frequency of aluminum ($n = 18.1 \times 10^{28} \text{ m}^{-3}$) is $3.82 \times 10^{15} \text{ Hz}$ (wavelength, $\lambda = 78.53 \text{ nm}$). (Source: Robert G. Brown)

Thus the complex wave number $\tilde{k}$ in terms of $L$ can be written as,

$$\tilde{k}^2 = [-\mu \epsilon \omega^2 + i \mu \sigma \omega] = \mu \epsilon \omega^2 [-1 + iL].$$

Therefore the phase and attenuation constants are:

$$k \equiv \omega \sqrt{\frac{\epsilon \mu}{2} \left[1 + L^2 + 1\right]^\frac{1}{2}}, \quad \kappa \equiv \omega \sqrt{\frac{\epsilon \mu}{2} \left[1 + L^2 - 1\right]^\frac{1}{2}}. \quad (2.5)$$

Thus a material behaves as a good dielectric if $L << 1 \Rightarrow k \approx \omega \sqrt{\epsilon \mu} = \omega / \nu$, $\kappa \approx 0$, and as a good conductor if $L >> 1 \Rightarrow k = \kappa = \omega \sqrt{\epsilon \mu / 2} L^{\frac{1}{2}} = \sqrt{\mu \sigma \omega / 2}$. 

14
The complex impedance \( \tilde{Z} \) (if \( \sigma \neq 0 \)) can be determined starting from Faraday’s law:

\[
\nabla \times E = -\frac{\partial B}{\partial t} = -\mu \frac{\partial H}{\partial t}.
\]

If the plane waves are polarized, Faraday’s law reduces to,

\[
\frac{\partial E_x}{\partial z} = -\mu \frac{\partial H_y}{\partial t} \Rightarrow \pm k \tilde{E}_x = -i \mu \omega \tilde{H}_y.
\]

\[
\therefore \tilde{Z} = \frac{\tilde{E}_x}{\tilde{H}_y} = \pm \frac{i \mu \omega}{k},
\]

substituting for \( k \) and after simplification, we get,

\[
\tilde{Z} = \pm \sqrt[4]{\frac{i \mu \omega}{\sigma + i \varepsilon \omega}}; \text{ if } \sigma = 0 \text{ then } Z = \sqrt[4]{\frac{\mu}{\varepsilon}}.
\]

And for good conductors, since \( \sigma >> \varepsilon \omega \), the complex impedance is:

\[
\tilde{Z} \approx \sqrt[4]{\frac{\mu \omega}{\sigma}} (i)^{1/2} = \sqrt[4]{\frac{\mu \omega}{\sigma}} \sqrt{\frac{1 + i}{\sqrt{2}}} = (1 + i) \sqrt{\frac{\mu \omega}{2 \sigma}} = \sqrt{\frac{\mu \omega}{\sigma} e^{i(\phi)}}.
\]

Thus in a good conductor the \( E \) and \( B \) fields are 45° out of phase with each other, with the \( E \) field leading. The real amplitudes of electric and magnetic fields are related similar to the complex amplitudes by:

\[
\frac{B_0}{E_0} = \frac{K}{\omega} = \sqrt{\varepsilon \mu \sqrt{1 + L^2}}, \quad (2.6)
\]

and the real electric and magnetic fields are,

\[
E(z,t) = E_0 e^{-\kappa z} \cos(kz - \omega t + \delta_E) \hat{x}, \quad B(z,t) = B_0 e^{-\kappa z} \cos(kz - \omega t + \delta_B) \hat{y}. \quad (2.7)
\]

### 2.3 Skin Depth

Due to the skin effect, at some distance below the surface of a thick material there will be essentially no currents flowing. The depth of eddy current penetration is an
important parameter for thickness measurements, detection of sub-surface flaws, and nonconductive coating thickness. The distance or depth it takes to reduce the amplitude of the electromagnetic (EM) waves (eddy current density) by a factor of $e^{-1}$ (≈37% of maximum value or density at the surface) is called the skin depth or standard depth of penetration (figure 4):

$$\delta \equiv \frac{1}{\kappa} = \frac{1}{\omega} \sqrt{\frac{2}{\varepsilon \mu}} \left[\sqrt{1+L^2} - 1\right]^{1/2}, \quad (2.8)$$

which is a measure of how far the wave penetrates into the conductor. For a good conductor the general skin depth equation (2.8) reduces to,

$$\delta = \frac{1}{\kappa} = \sqrt{\frac{2}{\mu \sigma \omega}} = \frac{1}{\sqrt{\pi \mu \sigma f}}. \quad (2.9)$$

Figure 4. Depth of penetration. (Source: [NDT Education Resource Center](https://www.ndtei.edu/))

Conductivity and permeability (1 for nonmagnetic metals) are constant for a given material, and therefore skin depth is inversely proportional to the inspection frequency. Thus, high frequencies result in smaller skin depth which can be used to obtain proximity information, and low frequencies result in larger skin depth which can be used to obtain...
thickness information of a given material. Depth of penetration decreases with increases in conductivity, permeability or inspection frequency. Skin depth causes an exponential decay of the electromagnetic field into the material sample as (figure 5),

\[ E_z = E_0 e^{-z/\delta} , \quad B_z = B_0 e^{-z/\delta} \]

An exponential decay of the electromagnetic field for a given thickness \( z \) is therefore expected with the square root of frequency [19].

![Figure 5. Exponential decay of electric and magnetic fields in a conductor.](image)

(Source: “Introduction to Electrodynamics”, by David J. Griffiths, 1999, 3rd Ed., p. 396)

The more popular ASM* standard [6] for skin depth is defined as:

\[ \delta = 1980 \sqrt{\frac{\rho}{\mu f}} , \quad (2.10) \]

where,

* The American Standard for Metals, now known as ASM International.
\(\delta\) - standard depth of penetration (inches);

\(\rho\) - material resistivity (ohm-centimeters);

\(\mu\) - material magnetic permeability (1 for nonmagnetic materials); and

\(f\) - inspection frequency (hertz).

Figure 6 shows a plot of skin depth (in.) versus frequency (Hz) for various types of Al 3003 alloys. The plot was generated using equation (2.10). As can be seen, skin depth decreases exponentially with increase in inspection frequency. Appendix A provides a detailed explanation of the different types of Al 3003 alloys. The shaded box in figure 6 shows the working range for inspection frequency (500 Hz – 6 KHz) and metal thickness (0.016” – 0.100”) used in this project. The red patterned box indicates the potential range of frequencies that can be utilized for thickness (single/double) estimation as long as thickness is less than skin depth at a specific frequency.
Figure 6. Skin Depth (in.) vs. Frequency (Hz) of Various Aluminum 3003 Alloys.
Chapter 3

Coil Design and Characterization

The essential part of any eddy current inspection system is the inspection coil or probe, as it is the probe that dictates the probability of detection and the reliability of characterization. Eddy current probes come in a variety of shapes, cross-sections, sizes and configurations, giving the user flexibility in custom designing a probe for a specific application or inspection. Apart from the component geometry of the eddy current probe, factors such as impedance matching, magnetic field focusing and environmental conditions play a crucial role in its design and development. For precise detection of flaws in the metal under test, it is important for the eddy current flow to be as nearly perpendicular to the flaw as possible. On the other hand, if the eddy current flow is parallel to the flaw, there will be little or no response from the inspection coil as the currents are hardly distorted. In this chapter, a discussion on eddy current sensor components and coil characterization is presented.

3.1 Eddy Current Sensor Components

The eddy current sensor has the following components: physical coil (reference and sensing) specifications, mode of operation, core type, coil configuration, shielding and loading. For a given application, choosing the right coil design is the most important task in any eddy current probe design process. With the target application in this project being the measurement of proximity and thickness of metal sheets, a single probe dual
coil inductive sensor is chosen as shown in figure 7 below. The single probe provides single sided measurement of proximity and thickness of the metal sheet under test.

![Diagram of air-core coils with dimensions and labels](image)

*Figure 7. Geometry and dimensions of the air-core coils used in the experiment.*

### 3.2 Coil Specifications

Four coils designated as models A, B, C, and D are wound separately on coil bobbins using a coil-winding machine (Manufacturer: Ruff, Inc., Kenilworth, NJ) with the specifications given in table 1 on page 21. Using an in-house developed Microsoft® Excel program, given the core diameter, length, wire diameter, resistance and number of turns, parameters such as turns per layer, number of layers, stackup, outside diameter, wire length, total resistance, inductance and quality factor can be computed for any given American Wire Gauge (AWG). The usage of inductive coils has the following advantages [20]: good linearity, small hysteresis, no saturation even at large excitation levels, high flexibility in sensor configuration, and easily adaptable to sensor electronics for signal processing.

Copper or other nonferrous metals are used as wires for winding to avoid magnetic hysteresis effects. The coils are of bobbin form factor with the bobbins made of
NEMA (National Electrical Manufacturers Association) grade XX paper phenolic with natural color. Phenolic sheet is a hard, dense material made by applying heat and pressure to layers of paper or glass cloth impregnated with synthetic resin. These layers of laminations are usually of cellulose paper, cotton fabrics, synthetic yarn fabrics, glass fabrics or unwoven fabrics. When heat and pressure are applied to the layers, a chemical reaction (polymerization) transforms the layers into a high-pressure thermosetting industrial laminated plastic.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>47 mm Dual Coil Probe</td>
</tr>
<tr>
<td>AWG</td>
<td>35 (Copper)</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>1 in.</td>
</tr>
<tr>
<td>Length</td>
<td>0.25 in.</td>
</tr>
<tr>
<td>Wire Diameter</td>
<td>0.0062 in.</td>
</tr>
<tr>
<td>Resistance</td>
<td>327,900 Ohms/1000’</td>
</tr>
<tr>
<td>Number of Turns</td>
<td>1440</td>
</tr>
<tr>
<td>Turns Per Layer</td>
<td>40</td>
</tr>
<tr>
<td>Number of Layers</td>
<td>36</td>
</tr>
<tr>
<td>Stackup</td>
<td>0.2232 in.</td>
</tr>
<tr>
<td>Outside Diameter</td>
<td>1.4464 in.</td>
</tr>
<tr>
<td>Wire Length</td>
<td>419.0633 feet</td>
</tr>
<tr>
<td>Total Resistance</td>
<td>137.410865 Ohms</td>
</tr>
<tr>
<td>Inductance (L)</td>
<td>76.12145205 mH</td>
</tr>
<tr>
<td>Quality Factor (Q = (X_L^{***} / R))</td>
<td>34.806941</td>
</tr>
</tbody>
</table>

Table 1. Coil specifications.

Phenolic sheets have the following properties: excellent dielectric strength, good machinability, lightweight, heat and wear resistant, resists corrosion and chemicals, good mechanical strength and dimensional stability, and low moisture absorption.

*** \(X_L = 2\pi fL\) and assume \(f = 10\) KHz.
Phenolic sheets find applications in terminal boards, switches, gears, bearings, wear strips, gaskets, washers, transformers, machining components, industrial laminates, coil bobbins, etc., to name a few.

3.3 Mode of Operation

The two coils of the eddy current test probe are set up in **reflection mode** (Source: NDT Education Resource Center) i.e., the coil closest to the metal sheet is called the sensing coil and coil farthest from the metal sheet is called the reference coil. Reflection mode probes have a higher gain compared to their differential counterpart when tuned to a specific frequency and are less sensitive to drift problems. They also have a wider frequency range of operation, as the probes do not need to balance the driver and pickup coils, with resolution compromised at certain frequencies being the only drawback. Reflection probes are almost invariably difficult to design and manufacture thereby making them more expensive. Coil windings of the reference and sensing coils are in opposition as in differential mode. The spacing between the two coils is set to 0.25” and this minimum spacing is chosen such that the reference coil is not significantly influenced by the presence of metal at the face of the probe. On the other hand, the maximum spacing is only limited by the desire to keep the probe a reasonable size.

3.4 Core Type

The core of the coils is essentially **air-core**, also called as formers. Core can also be a solid material of hard magnetic or soft magnetic or nonmagnetic type. Both the hard and soft versions of the magnetic material increase the coil inductance whereas the nonmagnetic materials decrease the coil inductance. The hard magnetic materials retain their magnetism after the magnetizing source has been removed effectively turning into
permanent magnets, but the soft magnetic materials lose their magnetism in the absence of the magnetizing source. Sensitivity of eddy current testing also depends on the type of core used in a coil and can swing either up or down depending on magnetic or nonmagnetic respectively.

It is important to maintain the current in the coil as low as possible. As current increases, the inductance increases as the coil expands due to a rise in temperature. Additionally, effects of magnetic hysteresis come into play when magnetic cores are used. Examples of ferrous cores are iron-powder, ferrite, laminated and tuning cores, slugs and toroids where in the core of a coil is adjustable. Similarly cores of nonferrous metals can include brass, copper and silver.

3.5 Coil Configuration

Figure 8. Front and side views of the experimental single probe dual coil test sensor.

The test coils (figure 8) are configured as surface or pancake type (Source: NDT Education Resource Center), with its axis normal to the surface under inspection, and chosen for detecting surface discontinuities either as a single sensing element or an array in both absolute and differential modes. Wider surface coils are needed for scanning large
areas for surface defects and for greater depth of penetration. However, as coil diameter increases, sensitivity decreases.

### 3.6 Probe Shielding and Loading

Shielding an eddy current probe from electromagnetic interference (EMI) is one of the most difficult of challenges that an engineer encounters during the design phase (Source: NDT Education Resource Center). Shielding is a technique used to minimize the interaction of the external forces such as noise and other spurious signals, which are some of the many sources of EMI, from the magnetic field of the eddy current probe within its immediate surroundings. Shielding is also employed to reduce edge effect problems and the effects of magnetic fasteners in the test region. Shielding and loading act together to limit the spread and focus the magnetic field to a narrow area on the test material.

Eddy current probes are manufactured in both shielded and un-shielded versions with shielded versions available in a variety of housings made of magnetic and non-magnetic metals and plastic. Both the necessity and type of shielding are dependent on the end application of the eddy current probe. Area of the flaw to be detected, sensitivity and resolution are some of the main criteria that need to be considered in deciding the necessity and appropriate type of shielding. Probes loaded with ferrite cores tend to be more sensitive and less prone to lift-off and wobble effects compared to its air core counterpart as ferrite cores focus the magnetic field to the center of the probe due to the magnetic flux generated by the coil traveling through the ferrite core rather than air as in air core coils.
3.7 Coil Characterization

Once the design is chosen, the next step is to match and characterize the coil impedance, which is the critical step for coil-based inductor designs. The four coil models $A$, $B$, $C$, and $D$ are characterized in free air using a QuadTech 1910 Inductance Analyzer to verify linearity of operation over multiple frequency ranges. Table 2 on page 26 lists the characterization results for the inductance coil models ‘A’, ‘B’, ‘C’ and ‘D’. The table specifies the number of turns ($N$), direct current resistance (DCR), secondary inductance ($L_S$), secondary (effective AC) resistance ($R_S$), and the quality factor ($Q$).

Each coil is connected to the Inductance Analyzer, scanned through each frequency range and $L_S$, $R_S$, $Q$ are measured using an in-house developed Microsoft® Visual Basic GUI. $L_S$ and $R_S$ are measured at the lower and upper bound of a given frequency range, while $Q$ is measured at the upper bound of the frequency range.

Coil impedances are matched for a given frequency range and if necessary, number of turns of a coil is reduced in small whole turns in order to match the impedance with the other coils. A set of two coils must be matched as close as possible in impedance by maintaining an almost constant inductance value over a wide frequency range. From the above table we can clearly observe that coil models ‘A’ and ‘B’ is most closely matched pair in impedance over all parameters in the 250 Hz to 10 KHz frequency range among the four coil models. This implies that coil models ‘A’ and ‘B’ are the right choice for the dual coil probe and have a linear operating region within the above frequency range. One of the coils (in this case model ‘B’) is used as a reference coil and the other coil (model ‘A’) is used as a sensing coil to measure a change in impedance.
<table>
<thead>
<tr>
<th>Coil Model</th>
<th>Frequency</th>
<th>Ls (mH)</th>
<th>Rs (Ω)</th>
<th>Q</th>
<th>Ls (mH)</th>
<th>Rs (Ω)</th>
<th>Q</th>
<th>Ls (mH)</th>
<th>Rs (Ω)</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(250 – 10K) Hz</td>
<td></td>
<td></td>
<td></td>
<td>(500 – 25K) Hz</td>
<td></td>
<td></td>
<td>(3 – 50) KHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N: 1450</td>
<td>DCR: 159.95 Ω</td>
<td>75.071</td>
<td>160.78</td>
<td>28.7</td>
<td>75.286</td>
<td>160.34</td>
<td>58.08</td>
<td>75.759</td>
<td>162.22</td>
<td>57.03</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N: 1450</td>
<td>DCR: 160.4 Ω</td>
<td>75.524</td>
<td>161.79</td>
<td>28.8</td>
<td>75.725</td>
<td>161.37</td>
<td>58.6</td>
<td>75.759</td>
<td>162.22</td>
<td>58.99</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N: 1450</td>
<td>DCR: 158.23 Ω</td>
<td>75.062</td>
<td>158.72</td>
<td>28.7</td>
<td>75.25</td>
<td>158.61</td>
<td>58.9</td>
<td>75.244</td>
<td>159.78</td>
<td>60.07</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N: 1550</td>
<td>DCR: 161.31 Ω</td>
<td>76.029</td>
<td>162.02</td>
<td>28.7</td>
<td>76.23</td>
<td>161.7</td>
<td>57.8</td>
<td>76.271</td>
<td>162.54</td>
<td>55.07</td>
</tr>
</tbody>
</table>

Table 2. Coil characterization results.

As an example, characterization plots generated by the inductance analyzer are shown below for coil model ‘A’. Figures 9, 10 and 11 below are plots for frequency ranges 0 Hz – 10 KHz, 0 Hz – 25 KHz, 0 Hz – 50 KHz respectively.
Figure 9. Coil model ‘A’ characterization for frequency, F = 0 Hz – 10 KHz.

Figure 10. Coil model ‘A’ characterization for frequency, F = 0 Hz – 25 KHz.
Figure 11. Coil model ‘A’ characterization for frequency, $F = 0 \text{ Hz} - 50 \text{ KHz}$. 
Chapter 4

Experimental Setup and Data Acquisition

This chapter presents a discussion on block diagram (figure 12) of the experimental setup including an explanation of the individual blocks, data acquisition flow chart, mathematical algorithms for processing and analysis of voltage amplitude and phase information.

4.1 Block Diagram

Figure 12. Block diagram of experimental setup.

The sinusoidal waveform generator serves as an input AC voltage source to both the test sensor and the data acquisition card. The test sensor is mounted on positioning slides that are used for precise positioning of the sensor above the metal sample under test.
Raw data obtained from the sensor is passed through a signal conditioning stage before the data acquisition card digitizes both the input and output signals. Amplitude and phase information is extracted from the digitized output signal of the DAQ card and run through algorithms to minimize effects of offset, noise, etc. existing in the data. Finally, relevant data is processed, analyzed and results correlated with proximity and thickness (single/double) of the metal sample under test.

4.1.1 Waveform Generator

The HP 33120A function generator is used as an input sinusoidal AC voltage source for the test setup. Input voltage amplitude is set to 8 VAC (peak-peak) and the frequency is varied from 500 Hz to 6 KHz in increments of 500 Hz. The function generator is automatically programmed to step through the frequencies via an automated data acquisition system designed and implemented in LabVIEW 8.0 with communication established via the RS-232 port and placing the function generator in the “REMOTE” mode of operation.

4.1.2 Positioning Slides

The test sensor is mounted on Velmex UniSlide motorized positioning slides that provide precision movement along the ‘X’ (forward/backward) and ‘Z’ axes (up/down). The travel along the vertical Z axis is from 0.0” (sensor is flush on the metal sample under test) to 0.6” in increments of 0.1”. The slides are controlled using a Velmex VXM stepping motor controller which is user programmed using the data acquisition system in LabVIEW 8.0 and communication is through the RS-232 port of the controller. The X axis slide (MB2506P40-S2.5-0) has a maximum travel of 6” and the Z axis slide (MB2509P40-S2.5-0) has a maximum travel of 9”. Slides have a precision lead screw
with an advance per turn of 0.025”, advance per step of 0.000625”, lead screw error less than 0.0015”/10” and 1 motor revolution is equivalent to 400 steps. UniSlide come with standard limit switches that are internal and adjustable to set the travel limits on the lead screw.

4.1.3 Bridge Circuit

![Wheatstone Bridge Circuit](image)

*Figure 13. Wheatstone bridge circuit and preamplifier.*

The test sensor is implemented as a Wheatstone bridge circuit as shown in figure 13. Sensing and preamplifier circuits are designed into a single printed circuit board. The bridge circuit has two impedance arms $Z_x$ and $Z_s$ which are the impedances of the sensing and reference coils respectively. Coil inductance and its associated DC resistance make up the individual impedance. Variable resistance $R$ is used to balance the bridge circuit to obtain a null output in the absence of a metal sample. With the bridge circuit excited by an AC input source, impedance change results in the sensing coil when brought in close proximity to the metal sample under test. The differential impedance between the sensing
and reference coils results in an output voltage that serves as an input to the signal conditioning stage. Equations below show the output voltage of the bridge circuit is a function of the sensing coil impedance and the input voltage.

\[
V_{A-C} = \frac{(R_B + R)}{(R_B + R + R_X) + j\omega L_X} \times V(t) \\
V_{B-C} = \frac{(R_A + R)}{(R_A + R + R_S) + j\omega L_S} \times V(t)
\]  

Equation (4.1)

Equating (4.1) and (4.2),

\[
V_{A-C} = V_{B-C}
\]

Equation (4.3)

\[
\frac{(R_B + R)}{(R_A + R)} = \frac{(R_B + R + R_X) + j\omega L_X}{(R_A + R + R_S) + j\omega L_S}
\]

Equation (4.4)

Equation (4.5)

Equating (4.4) and (4.5),

\[
V_{A-D} = V_{B-D}
\]

Equation (4.6)

\[
\frac{(R_X + j\omega L_X)}{(R_S + j\omega L_S)} = \frac{(R_B + R + R_X) + j\omega L_X}{(R_A + R + R_S) + j\omega L_S}
\]

Equation (4.4) and (4.5)

The component values of the passive devices used in the bridge circuit are given below:
\[ L_X = L_S \approx 75 \, mH \]
\[ R_X = R_S \approx 165 \, \Omega \]
\[ R_A = R_B \approx 499 \, \Omega \]
\[ R = 10 \, \Omega \]

### 4.1.4 Signal Conditioning

The signal conditioning stage is essentially an op-amp based preamplifier circuit that has a differential amplifier followed by a voltage follower. Output of the bridge circuit serves as the input for the differential amplifier that has a closed loop gain of 9.82 set by the gain resistor \( R_G \). The voltage follower is used to isolate the high input and low output impedances and acts as a buffer amplifier to eliminate loading effects. The gain equation for the differential amplifier is:

\[ G = \frac{49.4 \, K\Omega}{R_G} + 1 \]

### 4.1.5 Data Acquisition Card

AlazarTech’s [ATS460](https://www.alazar.com/products/ats460/) waveform digitizer for PCI bus is used as a data acquisition (DAQ) card. This digitizer has two 14 bit resolution analog input channels, real-time sampling rate of 125 MS/s to 10 KS/s, 8 Million samples of onboard memory, 65 MHz analog input bandwidth, input voltage range of ±20 mV to ±10 V, half length PCI bus card form factor, analog trigger channel with software-selectable level and slope, software-selectable AC/DC coupling and 1M\( \Omega \)/50\( \Omega \) input impedance, software-selectable bandwidth limit switch independent for each channel and pre-trigger and post-trigger capture with multiple record capability. The digitizer is provided with LabVIEW Virtual Instruments (VIs) that are integrated into the designed data acquisition system.

The DAQ card was setup for data acquisition with the following parameters:
**Channel A:** I/P reference voltage

**Channel B:** O/P measured voltage

**Coupling:** AC, 1 MΩ with a -3dB bandwidth of 10 Hz – 65 MHz

**Record Length:** 2000 points

**Number of Records:** 1 per channel

**Pre-Trigger Depth:** 256 points

**Clock:** Internal, positive edge triggered

**Sampling Rate:** set depending on the input signal frequency, needs to be greater than twice the maximum input frequency being sampled to avoid aliasing. Table 3 below shows the sampling rates that are set depending on the input frequency.

<table>
<thead>
<tr>
<th>Input Frequency (Hz)</th>
<th>Sampling Rate (S/s)</th>
<th>Sampling Points</th>
<th>Number of Cycles for 2000 Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>500 K</td>
<td>1000</td>
<td>2</td>
</tr>
<tr>
<td>1000</td>
<td>1 M</td>
<td>1000</td>
<td>2</td>
</tr>
<tr>
<td>1500</td>
<td>1 M</td>
<td>666.67</td>
<td>3</td>
</tr>
<tr>
<td>2000</td>
<td>2 M</td>
<td>1000</td>
<td>2</td>
</tr>
<tr>
<td>2500</td>
<td>1 M</td>
<td>400</td>
<td>5</td>
</tr>
<tr>
<td>3000</td>
<td>2 M</td>
<td>666.67</td>
<td>3</td>
</tr>
<tr>
<td>3500</td>
<td>1 M</td>
<td>285.71</td>
<td>7</td>
</tr>
<tr>
<td>4000</td>
<td>2 M</td>
<td>500</td>
<td>4</td>
</tr>
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<td>4500</td>
<td>1 M</td>
<td>222.22</td>
<td>9</td>
</tr>
<tr>
<td>5000</td>
<td>5 M</td>
<td>1000</td>
<td>2</td>
</tr>
<tr>
<td>5500</td>
<td>1 M</td>
<td>181.81</td>
<td>11</td>
</tr>
<tr>
<td>6000</td>
<td>2 M</td>
<td>333.33</td>
<td>6</td>
</tr>
</tbody>
</table>

*Table 3. Sampling rates.*

Where,

Sampling Points per cycle = Sampling Rate / Input Frequency

Number of cycles for 2000 points = 2000 / Sampling Points per cycle
The sampling rates satisfy the minimum criteria of greater than two times the maximum input frequency being sampled, and to minimize the jumps in phase from point to point, as there will be a trade off with how much phase noise is introduced into the system by sampling at a higher rate which will distort the phase. **Note:** The latest version of ATS460 offered by AlazarTech at the time of this writing has a few more enhanced features in comparison to the version used in the year 2006 at the time of conducting this experimental study.

### 4.1.6 Data Acquisition Flow Chart

Figure 14 on page 36 shows a flow chart with steps followed in the data acquisition process for both single and double metal samples. The data acquisition design was implemented in LabVIEW 8.0. For a given metal sample thickness, data is acquired from 500 Hz – 6 KHz frequency range in increments of 500 Hz and is written to a file in text format. Each file contains timestamps for individual data points and the file name contains single or double, thickness, date and time information. Data acquired is: input frequency (Hz), input voltage (V), output voltage (V), and phase (degrees). This step is repeated for lift-off ranging from 0.0” – 0.6” in increments of 0.1”. Data is acquired for every test metal sample thickness with the data acquisition going through the entire process as outlined above. Standard metal sample thicknesses are as follows: 0.016”, 0.020”, 0.025”, 0.032”, 0.040”, 0.050”, 0.063”, 0.080”, 0.090”, and 0.100”.
Figure 14. Data acquisition flow chart.
4.1.7 Feature Extraction & Characterization Algorithms

The data acquisition design implemented in LabVIEW 8.0 also includes algorithms to extract the output voltage and phase information. Figure 15 below shows a simple algorithm used to extract the output AC voltage minus any DC offset existing in the measured signal. The resultant output voltage signal is thus purely AC in nature.

![Figure 15. Amplitude algorithm.](image)

A phase algorithm (figure 16) was designed and implemented to measure the phase difference between the measured output AC signal and the reference input AC signal. The algorithm determines the phase of each signal individually and then subtracts them, i.e. phase is computed at each point and therefore prone to error in the result due to phase noise. “Phase noise is the frequency domain representation of rapid, short-term, random fluctuations in the phase of a waveform, caused by time domain instabilities (‘jitter’)” (Source: Wikipedia). The jitter in this case is due to sampling, and is more pronounced at higher frequencies. Thus optimizing the sampling rate depending on the input frequency is essential in order to minimize the effect of phase noise. Any DC component existing in the input and output signals is filtered out by subtracting it using the AC/DC Estimator. The idea here is to remove the presence of the DC component as it adds another unwanted component to the phase measurement, and to have only AC signals.
“The Hilbert transform is a linear operator which takes a function, \( u(t) \), and produces a function, \( H(u)(t) \), with the same domain” (Source: Wikipedia). “\( x = \text{hilbert}(xr) \) returns a complex helical sequence, sometimes called the \textit{analytic signal}, from a real data sequence. The analytic signal \( x = xr + j*xi \) has a real part, \( xr \), which is the original data, and an imaginary part, \( xi \), which contains the Hilbert transform. The imaginary part is a version of the original real sequence with a 90° phase shift. Sines are therefore transformed to cosines and vice versa. The Hilbert transformed series has the same amplitude and frequency content as the original real data and includes phase information that depends on the phase of the original data” (Source: The MathWorks, Inc.).

Further, to make the DC offset zero, whole number of cycles is acquired thus making the Hilbert transform more accurate across the whole waveform. There will be less error at the beginning and end (variation) of the final phase difference result. Next, the resultant complex signals are converted to polar form in order to extract the phase information. The phase signals are then unwrapped to eliminate discontinuities whose absolute values exceed \( \pi \) radians. The unwrapped input and output signals are subtracted to determine the phase difference between them, which in turn is fed into a polar to complex function \( (r = \text{constant 1}) \) and then into a complex to polar function to obtain the
phase difference in the range of -180 (-π) to +180 (+π) radians. Finally, radians are converted to degrees to compute the phase difference in degrees.

4.1.8 Data Processing, Analysis & Results

Raw data acquired during the data acquisition process is saved in “text” formatted files. A Windows dynamic link library (DLL) is designed and implemented in Microsoft® Visual Basic 6.0. The executable DLL reads raw data from each text file and outputs input reference voltage in volts, output measured voltage in volts and the phase difference in degrees that is in turn written to a text file for further analysis. Two text files are created one each for ‘Single’ and ‘Double’. DLL implementation in Visual Basic is not straight forward as in other programming applications, but code design and implementation is much faster and easier in Visual Basic. In order to implement a DLL in Visual Basic, wrapper (proxy) executables for the C2.exe and LINK.exe executables files need to be created and then linked to the corresponding original executables. A detailed explanation on the procedure to be followed is explained by Ron Petrusha [14].

Embedded within the DLL is Visual Basic code to compute the phase difference between the input and output signals by matching timestamps of individual data points as the phase algorithm computes the phase at each point and so it is much easier for error to creep into it since phase is much more sensitive to noise. This code reads in phase data for both input and output signals from a user specified data file that contains 2000 data points each. Phase data is parsed and stored in arrays. Next data in the arrays is matched as closely as possible using timestamp information and any large fluctuations is identified and eliminated before further processing. These fluctuations are usually noise data and the amount of acceptable deviation (tolerance) from the actual phase data is user
specified in the code. Noise corrected data is used to compute the phase difference and averaged. The final result accounts for the correct phase polarity before being displayed on a GUI and written to a file. Appendix B provides the Visual Basic code written for phase computation. The final two text files with processed data for Single and Double metal samples respectively is used to perform 2D analysis in Microsoft® Excel and graphical results are obtained for proximity and thickness (single/double) estimation.
Chapter 5

Results

In this chapter, a discussion of the experimental results for proximity and thickness estimation is presented. Proximity (lift-off or distance between the sensor and metal sample under test) information is obtained from the output voltage of the sensor, and thickness information (single or double) is obtained from the phase difference of the sensors’ output signal with reference to its input signal. “Single” refers to one metal sheet of a given thickness, and “Double” refers to two metal sheets of identical thickness in a stacked configuration.

5.1 Proximity Estimation using Output Voltage

For proximity estimation, sensor output voltage is plotted versus multiple frequencies for a given thickness (single and double) of the metal sample and lift-off distances varying from 0.0” (sensor flush on the metal sample) to 0.6” in increments of 0.1”. Frequency range of interest is from 500 Hz to 6 KHz in increments of 500 Hz. In general, as can be seen in figures 17-36 below, proximity information can be obtained at frequencies greater than 2 KHz and this minimum frequency tends higher as lift-off distance and thickness increase. In the plots below, solid lines indicate ‘single’, and dash lines indicate ‘double’. Each set of plots for a given thickness of Al 3003 metal sample consists of output voltage vs. frequency, and voltage difference between single and
double vs. frequency. As observed in the output voltage plots, an initial increase in output voltage amplitude is followed by a decreasing trend as frequency increases. This trend is caused due to an increasing back EMF, as eddy currents increase with increasing metal thickness (as long as metal thickness < skin depth). The net result is an increase in output voltage.

Considering an Al 3003 sample with a thickness of 16 thousandths of an inch (figures 17 and 18), proximity can be clearly estimated at 0.0”, 0.1” and 0.2” as the maximum output voltage difference between single and double is -201 mV at 2 KHz, -86 mV at 2 KHz, and -115 mV at 3.5 KHz respectively. Negative voltage difference indicates the output voltage for a single sheet is less than double and positive voltage difference indicates the output voltage for a single sheet is greater than double. The output voltage difference is less than 35 mV from 0.3” through 0.6”. As the skin depth or standard depth of penetration decreases at higher frequencies, it is observed that the output voltage difference has zero crossings at higher frequencies as the lift-off increases. Depending on the end application of the sensor, a minimum threshold for voltage difference needs to be set (in software) for accurate proximity estimation for a given thickness. As an example if we consider 50 mV as the minimum voltage, the threshold condition is satisfied at a frequency range of 500 Hz to 6 KHz at 0.0”, 750 Hz to 3 KHz at 0.1”, and 1 KHz to 6 KHz at 0.2”; thus proximity for a 0.016” thick metal sample (single or double) can be estimated at 0.0”, 0.1” and 0.2” in the indicated frequency range respectively. This threshold is not met for a lift-off of 0.3” through 0.6”. Similar observations for proximity estimation are made for the other Al 3003 alloy metal sample thicknesses.
Proximity Estimation of Al 3003
T = 0.016” (Solid: Single; Dash: Double)

**Figure 17.** Output voltage vs. Frequency for T = 0.016”.

Proximity Estimation of Al 3003: Voltage Difference between Single & Double for T = 0.016” with varying Lift-Off

**Figure 18.** Output voltage difference vs. Frequency for T = 0.016”.

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For 20 thousandths of an inch thickness (figures 19 and 20), the maximum output voltage difference is -186 mV at 2 KHz, 87 mV at 6 KHz, -109 mV at 2.5 KHz for a lift-off of 0.0”, 0.1”, and 0.2” respectively. The voltage difference is less than 44 mV for lift-off ranging from 0.3” through 0.6”.

Figure 19. Output voltage vs. Frequency for T = 0.020”.
Figure 20. Output voltage difference vs. Frequency for T = 0.020”.

Figure 21. Output voltage vs. Frequency for T = 0.025”.

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For 25 thousandths of an inch thickness (figures 21 and 22), the maximum output voltage difference is -127 mV at 1.5 KHz, 86 mV at 6 KHz, -91 mV at 3 KHz for a lift-off of 0.0”, 0.1”, and 0.2” respectively. The voltage difference is less than 32 mV for lift-off ranging from 0.3” through 0.6”.

Figure 22. Output voltage difference vs. Frequency for T = 0.025”.

For 32 thousandths of an inch thickness (figures 23 and 24), the maximum output voltage difference is -112 mV at 2 KHz, -55 mV at 1.5 KHz, -99 mV at 2.5 KHz for a lift-off of 0.0”, 0.1”, and 0.2” respectively. The voltage difference is less than 42 mV for lift-off ranging from 0.3” through 0.6”.
Figure 23. Output voltage vs. Frequency for $T = 0.032''$.

Proximity Estimation of Al 3003: Voltage Difference between Single & Double for $T = 0.032''$ with varying Lift-Off

Figure 24. Output voltage difference vs. Frequency for $T = 0.032''$. 

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For 40 thousandths of an inch thickness (figures 25 and 26), the maximum output voltage difference is 88 mV at 6 KHz, 75 mV at 5 KHz, -57 mV at 1.5 KHz for a lift-off of 0.0”, 0.1”, and 0.2” respectively. The voltage difference is less than 34 mV for lift-off ranging from 0.3” through 0.6”.

Figure 25. Output voltage vs. Frequency for T = 0.040”.
Figure 26. Output voltage difference vs. Frequency for T = 0.040”.

For 50 thousandths of an inch thickness (figures 27 and 28), the maximum output voltage difference is 64 mV at 5 KHz, 112 mV at 4.5 KHz, -29 mV at 2.5 KHz, 45 mV at 4 KHz, 38 mV at 3 KHz for a lift-off of 0.0”, 0.1”, 0.2”, 0.3”, and 0.4” respectively. The voltage difference is less than 30 mV for lift-off ranging from 0.5” through 0.6”.
Figure 27. Output voltage vs. Frequency for T = 0.050”.

Figure 28. Output voltage difference vs. Frequency for T = 0.050”.

Proximity Estimation of Al 3003: Voltage Difference between Single & Double for T = 0.050” with varying Lift-Off
For 63 thousandths of an inch thickness (figures 29 and 30), the maximum output voltage difference is 214 mV at 4.5 KHz, 76 mV at 5.5 KHz, -44 mV at 4.5 KHz for a lift-off of 0.0”, 0.1”, and 0.2” respectively. The voltage difference is less than 41 mV for lift-off ranging from 0.3” through 0.6”.

**Figure 29.** Output voltage vs. Frequency for T = 0.063”.

![Proximity Estimation of Al 3003 T = 0.063” (Solid: Single; Dash: Double)](image-url)
Proximity Estimation of Al 3003: Voltage Difference between Single & Double for T = 0.063” with varying Lift-Off

Figure 30. Output voltage difference vs. Frequency for T = 0.063”.

Proximity Estimation of Al 3003
T = 0.080” (Solid: Single; Dash: Double)

Figure 31. Output voltage vs. Frequency for T = 0.080”.

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For 80 thousandths of an inch thickness (figures 31 and 32), the maximum output voltage difference is 99 mV at 3 KHz, 59 mV at 3 KHz, -57 mV at 5.5 KHz for a lift-off of 0.0”, 0.1”, and 0.2” respectively. The voltage difference is less than 30 mV for lift-off ranging from 0.3” through 0.6”.

Figure 32. Output voltage difference vs. Frequency for T = 0.080”.

For 90 thousandths of an inch thickness (figures 33 and 34), the maximum output voltage difference is 113 mV at 3.5 KHz, 78 mV at 3 KHz, -58 mV at 4 KHz for a lift-off of 0.0”, 0.1”, and 0.2” respectively. The voltage difference is less than 37 mV for lift-off ranging from 0.3” through 0.6”. 

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Figure 33. Output voltage vs. Frequency for T = 0.090”.

Figure 34. Output voltage difference vs. Frequency for T = 0.090”.

Proximity Estimation of Al 3003: Voltage Difference between Single & Double for T = 0.090” with varying Lift-Off
For 100 thousandths of an inch thickness (figures 35 and 36), the maximum output voltage difference is 120 mV at 3.5 KHz, 79 mV at 4 KHz, -60 mV at 5.5 KHz for a lift-off of 0.0”, 0.1”, and 0.2” respectively. The voltage difference is less than 33 mV for lift-off ranging from 0.3” through 0.6”.

Figure 35. Output voltage vs. Frequency for T = 0.100”.
Figure 36. Output voltage difference vs. Frequency for T = 0.100”.

Table 4 on the following page provides a summary of the results for proximity estimation. Results for maximum output voltage difference between single and double are shown for a given frequency, lift-off, and metal thickness. In general, an increase in metal sample thickness results in a lower output voltage difference across the frequency bandwidth. Maximum separation of the curves occurs at various frequencies dependent on thickness and lift-off variations.
<table>
<thead>
<tr>
<th>Metal Thickness (in.)</th>
<th>Lift-off (in.)</th>
<th>Frequency (Hz)</th>
<th>Maximum Output Voltage Difference between Single &amp; Double (mV)</th>
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</thead>
<tbody>
<tr>
<td>0.016</td>
<td>0.0</td>
<td>2K</td>
<td>-201.267</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>2K</td>
<td>-86.264</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>3.5K</td>
<td>-115.51</td>
</tr>
<tr>
<td></td>
<td>0.3 – 0.6</td>
<td></td>
<td>&lt;35</td>
</tr>
<tr>
<td>0.020</td>
<td>0.0</td>
<td>2K</td>
<td>186.585</td>
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<tr>
<td></td>
<td>0.1</td>
<td>6K</td>
<td>87.579</td>
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<td></td>
<td>0.2</td>
<td>2.5K</td>
<td>-109.118</td>
</tr>
<tr>
<td></td>
<td>0.3 – 0.6</td>
<td></td>
<td>&lt;44</td>
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<td>127.571</td>
</tr>
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<td>6K</td>
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</tr>
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<td></td>
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<td>3K</td>
<td>-91.746</td>
</tr>
<tr>
<td></td>
<td>0.3 – 0.6</td>
<td></td>
<td>&lt;32</td>
</tr>
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<td>0.0</td>
<td>2K</td>
<td>112.304</td>
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<td>1.5K</td>
<td>-55.903</td>
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<td>2.5K</td>
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<td>0.3 – 0.6</td>
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<td>6K</td>
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<td>5K</td>
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<td></td>
<td>0.2</td>
<td>1.5K</td>
<td>-57.232</td>
</tr>
<tr>
<td></td>
<td>0.3 – 0.6</td>
<td></td>
<td>&lt;34</td>
</tr>
<tr>
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<td>0.0</td>
<td>5K</td>
<td>64.59</td>
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<td>4.5K</td>
<td>112.601</td>
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<td>0.2</td>
<td>2.5K</td>
<td>-29.576</td>
</tr>
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<td>0.3 – 0.6</td>
<td></td>
<td>&lt;46</td>
</tr>
<tr>
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<td>0.0</td>
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<td>4.5K</td>
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<td>0.3 – 0.6</td>
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<td>0.3 – 0.6</td>
<td></td>
<td>&lt;30</td>
</tr>
<tr>
<td>0.090</td>
<td>0.0</td>
<td>3.5K</td>
<td>113.24</td>
</tr>
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<td>0.1</td>
<td>3K</td>
<td>78.634</td>
</tr>
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<td>0.2</td>
<td>4K</td>
<td>-58.052</td>
</tr>
<tr>
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<td>0.3 – 0.6</td>
<td></td>
<td>&lt;37</td>
</tr>
<tr>
<td>0.100</td>
<td>0.0</td>
<td>3.5K</td>
<td>120.502</td>
</tr>
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<td>0.1</td>
<td>4K</td>
<td>79.704</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>5.5K</td>
<td>-60.152</td>
</tr>
<tr>
<td></td>
<td>0.3 – 0.6</td>
<td></td>
<td>&lt;33</td>
</tr>
</tbody>
</table>

*Table 4. Maximum output voltage difference for metal sample thicknesses.*
5.2 Thickness (Single/Double) Estimation using Phase

For thickness estimation, the phase difference between single and double is plotted versus multiple frequencies for a given lift-off and varying metal sample thicknesses. Lift-off distances vary from 0.0” (sensor flush on the metal sample) to 0.6” in increments of 0.1”. Frequency range of interest is from 500 Hz to 6 KHz in increments of 500 Hz. In general, as can be seen from the plots below, thickness (single/double) information can be obtained in the 500 Hz – 1 KHz frequency range as skin depth is inversely proportional to the square root of the inspection frequency. The phase difference decreases as frequency, lift-off and metal sample thickness increase; as we approach the higher end of the frequency range the phase difference decreases gradually for smaller thicknesses and more rapidly for larger thicknesses. Standard deviation in phase difference is a function of lift-off i.e. standard deviation increases with lift-off for a given frequency. As an example, the standard deviation in phase difference at 1 KHz for a lift-off of 0.0” was measured at ± 0.86°.

With the probe flush on the metal sample i.e. lift-off of 0.0”, the phase difference between single and double is in the range of -10 to -15 degrees at 500 Hz for thicknesses varying from 0.016” to 0.100” (figures 37 and 38). The rate of decay in phase difference is much more pronounced for larger thicknesses at the higher end of the frequency range similar to a slowly varying exponential behavior is observed. At 500 Hz, as lift-off is increased a wider spread in phase difference is observed compared to a narrower spread for a lift-off of 0.0”. In general, a high phase difference is observed at low frequency (500 Hz – 1 KHz) which is good for single/double estimation, and decreases at higher frequencies. Table 5 summarizes the phase difference spread at 500 Hz and 1 KHz for
lift-off varying from 0.0” through 0.6”. For lift-off of 0.0” and 0.1”, the phase difference exhibited a “resonance” type behavior for most of the metal sample thicknesses in the 1.5 KHz to 3.5 KHz frequency range. This “resonance” type behavior was attenuated at lift-off of 0.2” and above, and was seen only at larger thicknesses and higher end of the frequency range.

![Diagram](image)

Figure 37. Phase vs. Frequency for Lift-off = 0.0”. 
Figure 38. Phase difference vs. Frequency for Lift-off = 0.0”.

The abrupt random fluctuations in phase difference in the 1.5 KHz to 3.5 KHz frequency range is primarily due to the resonance point of the coils shifted downward in frequency at a lift-off of 0.0” and 0.1” under the influence of metal. Therefore the 1.5 KHz to 3.5 KHz frequency range needs to be avoided for thickness estimation. Variations in metal sample composition which is unavoidable could be a source of random error contribution to both the output voltage and phase difference results. A source of systematic error contribution to the phase difference results could be the limited choice of internal sample rates of the data acquisition (DAQ) card. The internal sample rates of the DAQ card provided by the manufacturer is as follows: 125 MS/s, 100 MS/s, 50 MS/s, 20 MS/s, 10 MS/s, 5 MS/s, 2 MS/s, 1 MS/s, 500 KS/s, 200 KS/s, 100 KS/s, 50 KS/s, 20 KS/s, 10 KS/s. Considering that the input frequency range is from 500 Hz – 6 KHz, the
maximum usable sampling rate is 10 MS/s at 5 KHz in order to obtain whole number of
cycles for 2000 points (record length). Acquiring whole number of cycles makes the
Hilbert transform used in the phase algorithm more accurate across the whole waveform.
This in turn reduces the error in computing the phase difference. A better accuracy can be
further achieved if whole number of points per cycle are obtained for a given input
frequency and sampling rate. But for the sampling rates mentioned above, whole number
of points per cycle cannot be obtained for the following input frequencies: 1.5 KHz, 3
KHz, 3.5 KHz, 4.5 KHz, 5.5 KHz, and 6 KHz.

**Figure 39.** Phase vs. Frequency for Lift-off = 0.1”.
Thickness (Single/Double) Estimation of Al 3003: Phase Difference between Single & Double for Lift-off = 0.1” with varying Metal Thickness

Figure 40. Phase difference vs. Frequency for Lift-off = 0.1”.

Thickness (Single/Double) Estimation of Al 3003
Lift-off = 0.2”

Figure 41. Phase vs. Frequency for Lift-off = 0.2”.

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Figure 42. Phase difference vs. Frequency for Lift-off = 0.2”.

Figure 43. Phase vs. Frequency for Lift-off = 0.3”.
**Figure 44.** Phase difference vs. Frequency for Lift-off = 0.3”.

**Figure 45.** Phase vs. Frequency for Lift-off = 0.4”.

Thickness (Single/Double) Estimation of Al 3003: Phase Difference between Single & Double for Lift-off = 0.3” with varying Metal Thickness.
Thickness (Single/Double) Estimation of Al 3003: Phase Difference between Single & Double for Lift-off = 0.4" with varying Metal Thickness

![Graph showing phase difference vs. frequency for lift-off = 0.4".]

**Figure 46.** Phase difference vs. Frequency for Lift-off = 0.4”.

Thickness (Single/Double) Estimation of Al 3003
Lift-off = 0.5"

![Graph showing phase vs. frequency for lift-off = 0.5".]

**Figure 47.** Phase vs. Frequency for Lift-off = 0.5”.
Thickness (Single/Double) Estimation of Al 3003: Phase Difference between Single & Double for Lift-off = 0.5\" with varying Metal Thickness

**Figure 48.** Phase difference vs. Frequency for Lift-off = 0.5\".

Thickness (Single/Double) Estimation of Al 3003
Lift-off = 0.6\"

**Figure 49.** Phase vs. Frequency for Lift-off = 0.6\".
Thickness (Single/Double) Estimation of Al 3003: Phase Difference between Single & Double for Lift-off = 0.6” with varying Metal Thickness

Figure 50. Phase difference vs. Frequency for Lift-off = 0.6”.

<table>
<thead>
<tr>
<th>Lift-off (in.)</th>
<th>Spread of Phase Difference between Single &amp; Double (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency = 500 Hz</td>
</tr>
<tr>
<td></td>
<td>Range (deg.)</td>
</tr>
<tr>
<td>0.0</td>
<td>-10.22 – -14.96</td>
</tr>
<tr>
<td>0.1</td>
<td>-2.52 – -14.28</td>
</tr>
<tr>
<td>0.2</td>
<td>-6.75 – -13.79</td>
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<tr>
<td>0.3</td>
<td>0.72 – -14.61</td>
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<td>0.4</td>
<td>-6.91 – -25.39</td>
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<td>0.5</td>
<td>-2.00 – -47.97</td>
</tr>
<tr>
<td>0.6</td>
<td>-1.08 – -19.27</td>
</tr>
</tbody>
</table>

Table 5. Spread of phase difference between single & double
Chapter 6

Conclusion

6.1 Thickness (Single/Double) Estimation

Single/Double aluminum 3003 alloy metal sheet thickness in the range of 0.016”-0.063” can be detected independent of lift-off as shown in figure 51, which is a plot of phase difference between single and double versus metal thickness at a frequency of 1 KHz. The non-contact functionality of the test sensor is demonstrated for a lift-off.

Figure 51. Thickness (single/double) estimation at F = 1 KHz.
ranging from 0.1” to 0.6”. The curve shown as a dashed line is for the case when the test sensor is flush on the metal sample (lift-off = 0.0”). Further, as can be observed in figure 51, thickness estimation range can be increased to 0.080”, if the lift-off range is limited from 0.1” to 0.5”.

![Thicknes (Single/Double) Estimation of Al 3003 at F = 1.5 KHz, Lift-off = 0.0”-0.6”](image)

**Figure 52.** Thickness (single/double) estimation at F = 1.5 KHz.

The detectable range of single/double thickness estimation reduces as the inspection frequency is increased. If the frequency is increased to 1.5 KHz as shown in figure 52, the single/double thickness can be detected in the range of 0.016”-0.050” independent of lift-off. Similarly, if the frequency is further increased to 2 KHz as shown in figure 53 on page 69, the single/double thickness can be detected in the range of 0.016”-0.040” independent of lift-off. The maximum phase difference for the three different frequencies discussed is approximately -7.0 degrees.
Thus, we see a definite trend in single/double thickness estimation independent of lift-off as the inspection frequency is increased. When these experimental results are compared with the average theoretical skin depth for aluminum 3003 alloy at the frequencies of interest discussed above, there is an excellent agreement between the experimental and theoretical results as shown in figure 54 on page 70. The important boundary condition for the agreement between the experimental and theoretical results is that the (average) skin depth should be greater than or equal to the maximum detectable metal sheet thickness at a given frequency. Also, recall that the skin depth equation

\[ S = 1980 \sqrt{\frac{\rho}{\mu f}} \text{ in.} \]

is independent of lift-off. Referring to figure 54, the average theoretical skin depth at 1 KHz is \( \approx 0.126'' \), which exactly equals the experimental result that determined the maximum detectable double sheet thickness to be 0.126” (2x 0.063”).

Figure 53. Thickness (single/double) estimation at F = 2 KHz.
Similarly, at 1.5 KHz, the average theoretical skin depth is ≈0.103”, which is greater than the equivalent experimental result, that determined the maximum detectable double sheet thickness to be 0.100” (2x 0.050”), independent of lift-off. Again at 2 KHz frequency, the average theoretical skin depth is ≈0.089”, which is greater than the equivalent experimental result, that determined the maximum detectable double sheet thickness to be 0.080” (2x 0.040”), independent of lift-off.

Figure 54. Average theoretical skin depth for F = 1 KHz, 1.5 KHz, 2 KHz.
6.2 Proximity Estimation

Proximity can be estimated by plotting voltage difference between single and double versus metal sample thicknesses for lift-off ranging from 0.0”-0.6” at a specific frequency (5.5 KHz in this case) as shown in figure 55. Proximity can be estimated at 0.1” (demonstrating non-contact functionality), and also at 0.2” provided the metal sheets are hard constrained to limit lateral movement. However, in real world applications, there exists some amount of lateral movement of the metal sheets even after hard constraining them to the conveyor belt, and in this scenario it may be prove to be difficult to estimate proximity because the voltage difference curve would lie somewhere in the region between the curves for 0.1” and 0.2”. Proximity cannot be estimated for a lift-off of 0.3” and beyond as the voltage difference between single and double is either close to zero or

**Figure 55.** Proximity estimation at F = 5.5 KHz.
fluctuates between positive and negative regions around zero. Also, when the sensor is flush on the metal sheet (dashed curve in figure 55), the output voltage difference is neither completely positive nor negative for smaller thicknesses, and trends into positive voltage difference territory for metal thicknesses of 0.040” and beyond.

Experimental results have shown feasibility for proximity and thickness estimation of Al 3003 alloy metal sheets using a single probe dual coil non-contact sensor based on eddy current technology. Results have shown that proximity estimation requires sensing at higher frequencies and thickness estimation requires sensing at lower frequencies as skin depth or standard of penetration is inversely proportional to the inspection frequency.

6.3 Future Work

• As explained in the “Results” chapter, resonance type behavior was exhibited by the coils. In the case of output voltage difference, the (yellow) curve for a lift-off of 0.2” was always negative with no zero crossing or transition point, with the only exception for a metal thickness of 0.100”. And in the case of phase difference, abrupt, random fluctuations were seen in the frequency range of 1.5 KHz to 3.5 KHz at a lift-off of 0.0” and 0.1”. In order to better understand this resonance type behavior, the coils need to be electrical characterized under the influence of metal sheet thicknesses and variable lift-off to study the effect on coil impedance and resistance.

• Systematic errors due to environmental effects (EMI, noise, temperature, etc.) can be minimized by choosing an effective design that meets the housing and shielding requirements of the sensor for a given application. Another potential
source of systematic error could be in instrumentation such as the positioning slides due to incorrect initialization, programmed travel, etc.

- Sensitivity of inductive coils [20] can be increased by using larger diameter coils (also increases the detectable thickness range), increased number of turns, thinner copper wire, well compensated differential arrangements for optimal usage of the dynamic range of sensor electronics, shielding from external noise (EMI) sources. But the physical size of the coils is often limited by the end application and a design trade-off between sensor performance and size needs to be achieved.

- Experimenting with different types of bridge circuits for differential impedance measurement that is less sensitive to variations in lift-off.

- Experimenting with other coil modes of operation (absolute, differential, hybrid, etc.) in order to achieve greater depth of penetration.

- Experimenting with phase algorithms for extracting a more accurate phase signature for a given metal type. Accuracy of the phase algorithm proposed in this thesis can be improved by normalizing the input and output signals before Hilbert transformation if the phase of the respective signals is constant over the entire cycle. Optimizing sampling rates to minimize phase noise.

- Proximity and thickness estimation of other nonmagnetic metals such as stainless steel 303 and 304 series.
References


Appendix A

Al 3003 Alloy Types

Al 3000 series is alloyed with Manganese (Mn) and can be work-hardened. Al 3003 alloy is a non-ferrous metal. Table 6 below gives the metal composition of Al 3003.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon (Si)</td>
<td>0.6%</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>0.7%</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>0.05% - 0.20%</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>1.0% - 1.5%</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>0.10%</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>96.9% - 97.55%</td>
</tr>
</tbody>
</table>

*Table 6. Aluminum 3003 alloy metal composition.*

Conductivity and Resistivity of various types of Al 3003 series alloys that are commercially available is given in table 7 below.

<table>
<thead>
<tr>
<th>Al 3003 Type</th>
<th>% IACS</th>
<th>Conductivity (Siemens/m)</th>
<th>Resistivity (Ω-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3003-O</td>
<td>44.70-49.80</td>
<td>2.741 x 10⁷</td>
<td>3.649 x 10⁻⁸</td>
</tr>
<tr>
<td>3003-O</td>
<td>50.00</td>
<td>3.400 x 10⁻⁸</td>
<td></td>
</tr>
<tr>
<td>3003-H14 &amp; -H12</td>
<td>37.80-51.50</td>
<td>2.590 x 10⁷</td>
<td>3.861 x 10⁻⁸</td>
</tr>
<tr>
<td>3003-H12</td>
<td>42.00</td>
<td>4.100 x 10⁻⁸</td>
<td></td>
</tr>
<tr>
<td>3003-H14</td>
<td>41.00</td>
<td>4.200 x 10⁻⁸</td>
<td></td>
</tr>
<tr>
<td>3003-H18</td>
<td>40.00</td>
<td>4.300 x 10⁻⁸</td>
<td></td>
</tr>
<tr>
<td>3003-H24 &amp; -H28</td>
<td>37.80-47.50</td>
<td>2.474 x 10⁷</td>
<td>4.043 x 10⁻⁸</td>
</tr>
</tbody>
</table>

*Table 7. Conductivity & resistivity of aluminum 3003 alloy types.*
The first alpha character and the first numeric digit (if indicated) following it for the type of Al 3003 alloy is the temper designation. Table 8 below indicates the temper designation.

<table>
<thead>
<tr>
<th>Temper Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-O</td>
<td>Full soft (annealed)</td>
</tr>
<tr>
<td>-H</td>
<td>Strain hardened (cold worked) with or without thermal treatment</td>
</tr>
<tr>
<td>-H1</td>
<td>Strain hardened without thermal treatment</td>
</tr>
<tr>
<td>-H2</td>
<td>Strain hardened and partially annealed</td>
</tr>
<tr>
<td>-H3</td>
<td>Strain hardened and stabilized with low temperature heating</td>
</tr>
</tbody>
</table>

*Table 8. Temper designation.*

The second numeric digit gives the degree of hardness as shown in table 9 below.

<table>
<thead>
<tr>
<th>Degree of Hardness</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-HX2</td>
<td>¼ hard</td>
</tr>
<tr>
<td>-HX4</td>
<td>½ hard</td>
</tr>
<tr>
<td>-HX6</td>
<td>¾ hard</td>
</tr>
<tr>
<td>-HX8</td>
<td>Full hard</td>
</tr>
<tr>
<td>-HX9</td>
<td>Extra hard</td>
</tr>
</tbody>
</table>

*Table 9. Degree of hardness.*

Information provided in this appendix is obtained from the following online sources: Wikipedia and NDT Education Resource Center.
Appendix B

Visual Basic Code for Phase Difference

Option Explicit

' Procedure which computes the phase difference between the I/P and O/P signals

Private Sub cmdGo_Click()
    Dim filename As String
    Dim whole_file As String
    Dim lines() As String
    Dim one_line() As String
    Dim num_rows As Long, num_cols As Long
    Dim phase_data() As String
    Dim zero_crossing As Double, zero_crossing_in() As Double,
    zero_crossing_out() As Double
    Dim R As Long, C As Long
    Dim sign As Boolean
    Dim count_in As Integer, count_out As Integer
    Dim i As Integer, j As Integer, k As Integer
    Dim temp As Integer, max_temp As Integer
    Dim lambda() As Double, sum_lambda As Double, avg_lambda As Double
    Dim delta_size As Integer, delta() As Double, sum_delta As Double, avg_delta
    As Double
    Dim phase As Double

    ' Initialize counter variables for 'zero crossing in' and 'zero crossing out' arrays count_in = 0: count_out = 0

    ' Initialize/Reset all output display boxes to blank
    txtInput.Text = ""
    txtOutput.Text = ""
    lstInputZero.Clear
    lstOutputZero.Clear
    txtLambdaSize.Text = ""
    lstLambda.Clear
    txtLambdaSum.Text = ""
    txtLambdaAvg.Text = ""
    txtDeltaSize.Text = ""

lstDelta.Clear
txtDeltaSum.Text = ""
txtDeltaAvg.Text = ""
txtPhase.Text = ""

' Read the entire contents of the data file into a string
whole_file = ReadTextFileContents(CommonDialog1, filename)

' Break the file into lines
lines = Split (whole_file, vbCrLf)

' Dimension the array into rows and columns
num_rows = UBound(lines)
one_line = Split(lines(0), vbTab)
num_cols = UBound(one_line): Debug.Print num_cols

' Redimension the 'phase data' array into the number of rows and columns calculated from above
ReDim phase_data(num_rows, num_cols)

' Copy the data into the array
For R = 0 To num_rows
    one_line = Split(lines(R), vbTab)
    For C = 1 To num_cols - 1
        phase_data(R, C) = one_line(C)
    Next C
Next R

' Prove we have the data loaded correctly
For R = 0 To num_rows
    Debug.Print R & vbTab;
    For C = 1 To num_cols
        Debug.Print phase_data(R, C) & vbTab;
    Next C
    Debug.Print
Next R
Debug.Print "========"

' Find the zero crossings in both the I/P and O/P voltage columns
For C = 1 To num_cols - 1
    For R = 0 To num_rows
        If R <> num_rows Then
            sign = (Sgn(CDbl(phase_data(R, C))) < Sgn(CDbl(phase_data(R+1, C))))
        Else
            sign = false
        End If
    Next R
Next C

' Identify the zero crossing (defined as the waveform transitioning from 'low' to 'high')

If sign = True Then

    ‘ Identify and eliminate "noise" data
    temp = R + 1

    If R >= num_rows - 10 Then
        max_temp = num_rows - R
    Else
        max_temp = temp + 10
    End If

    For i = temp To max_temp
        If Sgn(CDbl(phase_data(i, C))) = -1 Then
            GoTo NextNo
        Elself Sgn(CDbl(phase_data(i, C))) = 1 Then
            GoTo NextRow
        End If
    NextRow:  Next i

    ‘ Compute the exact zero crossing point
    zero_crossing = R + (Abs(CDbl(phase_data(R, C))) / 
                    (Abs(CDbl(phase_data(R, C))) + 
                     Abs(CDbl(phase_data(R+1, C)))))

    ‘ Zero crossings computed from the I/P voltage column stored in ‘zero crossing in’ array
    If C = 1 Then
        ReDim Preserve zero_crossing_in(count_in) As Double
        zero_crossing_in(count_in) = zero_crossing
        count_in = count_in + 1
    End If

    ‘ Zero crossings computed from the O/P voltage column stored in ‘zero crossing out’
    array
    If C = 2 Then
        ReDim Preserve zero_crossing_out(count_out) As Double
        zero_crossing_out(count_out) = zero_crossing
        count_out = count_out + 1
    End If
    End If
Else
    Exit For
End If
NextNo:  Next R
Next C
' Output results to form
txtInput.Text = UBound(zero_crossing_in) + 1
txtOutput.Text = UBound(zero_crossing_out) + 1

For i = 0 To UBound(zero_crossing_in)
    lstInputZero.AddItem zero_crossing_in(i)
Next

For i = 0 To UBound(zero_crossing_out)
    lstOutputZero.AddItem zero_crossing_out(i)
Next

' Compute the wavelength (lambda) of both I/P and O/P signals and find ‘average lambda’
If UBound(zero_crossing_in) = 0 Then
    j = 0
    ReDim Preserve lambda(j) As Double
    lambda(j) = zero_crossing_in(j)
Else
    For j = 0 To UBound(zero_crossing_in) - 1
        ReDim Preserve lambda(j) As Double
        lambda(j) = zero_crossing_in(j + 1) – zero_crossing_in(j)
    Next j
End If

If UBound(zero_crossing_in) = 0 Then
    j = 0
Else
    j = j - 1
End If

If UBound(zero_crossing_out) = 0 Then
    j = j + 1: k = 0
    ReDim Preserve lambda(j) As Double
    lambda(j) = zero_crossing_out(k)
Else
    For k = 0 To UBound(zero_crossing_out) - 1
        j = j + 1
        ReDim Preserve lambda(j) As Double
        lambda(j) = zero_crossing_out(k + 1) – zero_crossing_out(k)
    Next k
End If

For i = 0 To UBound(lambda)
    sum_lambda = sum_lambda + lambda(i)
Next
avg_lambda = sum_lambda / (UBound(lambda) + 1)

' Output results to form
txtLambdaSize.Text = UBound(lambda) + 1

For i = 0 To UBound(lambda)
    lstLambda.AddItem lambda(i)
Next

txtLambdaSum.Text = sum_lambda
txtLambdaAvg.Text = avg_lambda

' delta - difference between the corresponding zero crossings of the I/P and O/P signals
' Determine the size of the 'delta' array
If UBound(zero_crossing_out) > UBound(zero_crossing_in) Then
    delta_size = UBound(zero_crossing_in)
ElseIf UBound(zero_crossing_out) < UBound(zero_crossing_in) Then
    delta_size = UBound(zero_crossing_out)
ElseIf UBound(zero_crossing_out) = UBound(zero_crossing_in) Then
    delta_size = UBound(zero_crossing_in) - - -
End If

' Compute 'average delta'
For i = 0 To delta_size
    ReDim Preserve delta(i) As Double
    delta(i) = zero_crossing_out(i) – zero_crossing_in(i)
Next

For i = 0 To UBound(delta)
    sum_delta = sum_delta + delta(i)
Next
avg_delta = sum_delta / (UBound(delta) + 1)

' Output results to form
txtDeltaSize.Text = UBound(delta) + 1

For i = 0 To UBound(delta)
    lstDelta.AddItem delta(i)
Next

txtDeltaSum.Text = sum_delta
txtDeltaAvg.Text = avg_delta

' Compute the ‘phase shift’ in degrees and account for correct polarity (+/-1) for the phase
phase = (avg_delta / avg_lambda) * 360
If Abs(phase) > 180 Then
  If Sgn(phase) = -1 Then
    phase = phase + 360
  ElseIf Sgn (phase) = 1 Then
    phase = phase - 360
  End If
End If

With txtPhase.Font
  .Name = "Arial"
  .Bold = True
  .Size = 24
End With
txtPhase.Text = phase

' Function which reads contents from a user selected (Text) file

Private Function ReadTextFileContents(CD As CommonDialog, filename As String) As String
  Dim fnum As Integer
  On Error GoTo ExitNow

  With CD
    .Filter = "All files (*. *) | *. * | Text files | *.txt | LabVIEW Measurement Files | *.lvm"
    .FilterIndex = 2
    .DefaultExt = "txt"
    .Flags = cdlOFNReadOnly Or cdlOFNFileMustExist Or cdlOFNCreatePrompt Or cdlOFNNoReadOnlyReturn
    .DialogTitle = "Select a file to read"
    .filename = filename
  'Exit if user presses Cancel.
    .CancelError = True
  .ShowOpen

  fnum = FreeFile()
  Open filename For Input As #fnum
  'Read the entire contents in one single operation.
  ReadTextFileContents = Input$(LOF(fnum), fnum)
  Close #fnum

  ExitNow:
Private Sub cmdQuit_Click()
    Unload Me
End Sub