Pulsed Eddy-Currents for Corrosion Detection

by

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Pulsed Eddy-Currents
for Corrosion Detection

by

Captain Sylvain Giguère
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A thesis submitted
to the School of Graduate Studies
in the
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Kingston, Ontario

In partial fulfilment of the requirements for
the degree
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Pulsed Eddy-Currents
for Corrosion Detection

ABSTRACT

Aging of commercial and military aircraft fleets poses new challenges to engineering authorities responsible for granting and ensuring airworthiness. In-service inspection has thus become critical for the safe and economical management of these fleets. One major problem experienced is corrosion. Although the detection of corrosion by ultrasonic and eddy-currents is not inherently difficult, there are problems with identification and characterization for multi-layer structures. The pulsed eddy-current technique offers an alternative to these conventional techniques. Its inherently wideband frequency spectrum allows the determination of a large number of parameters, such as defect size, location, and probe lift-off during inspection. However, the pulsed eddy-current technique is not widely used by the engineering community, principally because the interpretation of the transient response is still in its infancy. This thesis is a first step for a better interpretation of the transient response. In particular, it addresses the ability to detect the presence of corrosion and identify its location independently of lift-off. These objectives are achieved by considering time domain features which are totally independent of lift-off contributions. Depending on the type of transducer, the features change; however, each has distinct features which allow the characterization of corrosion in a multi-layer structure.
ACKNOWLEDGMENTS

The work required to write a thesis cannot be explained in just a few words nor can acknowledgments. There are so many people that have lent a hand, provided equipment or advice: Personnel from the Chemistry and Chemical Engineering department, Physics Department, Science Library, Air Vehicle Research Detachment, etc. Of all these people, special thanks go to Dr. Pierre Roberge and Dr. Stéphane Dubois of the Royal Military College (RMC) of Canada. Both of them have provided guidance and/or supervised the work detailed in this thesis. Their concern and availability were greatly appreciated.

For the past two years, I have devoted time and energy to furthering my knowledge in the field of nondestructive testing. Thankfully, I received encouragements and continual support from my wife Dominique and plenty of smiles from my three daughters, Violette, Valérie and Marguerite. To them, I am forever indebted.
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<td>AWG</td>
<td>American Wire Gage</td>
</tr>
<tr>
<td>A/D</td>
<td>analog to digital</td>
</tr>
<tr>
<td>BOB</td>
<td>bottom of bottom</td>
</tr>
<tr>
<td>BOT</td>
<td>bottom of top</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>Gb</td>
<td>gigabytes</td>
</tr>
<tr>
<td>GMR</td>
<td>giant magneto-resistive</td>
</tr>
<tr>
<td>HPIB</td>
<td>Hewlett-Packard interface bus</td>
</tr>
<tr>
<td>Hi Res</td>
<td>high resolution</td>
</tr>
<tr>
<td>I/O</td>
<td>input/output</td>
</tr>
<tr>
<td>Mb</td>
<td>megabytes</td>
</tr>
<tr>
<td>MKSA</td>
<td>meter, kilogram, second, ampere</td>
</tr>
<tr>
<td>MPIS</td>
<td>multi-purpose inspection system</td>
</tr>
<tr>
<td>PC</td>
<td>personal computer</td>
</tr>
<tr>
<td>PEC</td>
<td>pulsed eddy-current</td>
</tr>
<tr>
<td>RAM</td>
<td>random access memory</td>
</tr>
<tr>
<td>RMC</td>
<td>Royal Military College of Canada</td>
</tr>
<tr>
<td>SQUID</td>
<td>superconductive quantum interference device</td>
</tr>
<tr>
<td>TOB</td>
<td>top of bottom</td>
</tr>
<tr>
<td>% IACS</td>
<td>percent International Annealed Copper Standard</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>$\vec{A}$</td>
<td>magnetic vector potential</td>
</tr>
<tr>
<td>$\vec{B}$</td>
<td>magnetic flux density</td>
</tr>
<tr>
<td>$B_n$</td>
<td>normal component of magnetic flux density</td>
</tr>
<tr>
<td>$C$</td>
<td>capacitance</td>
</tr>
<tr>
<td>$\vec{D}$</td>
<td>electric flux density</td>
</tr>
<tr>
<td>$D_i$</td>
<td>coil inside diameter</td>
</tr>
<tr>
<td>$D_o$</td>
<td>coil outside diameter</td>
</tr>
<tr>
<td>e</td>
<td>electron charge</td>
</tr>
<tr>
<td>$\vec{E}$</td>
<td>electrical field intensity</td>
</tr>
<tr>
<td>$f_0$</td>
<td>resonance frequency</td>
</tr>
<tr>
<td>$f_i$</td>
<td>lower half-power frequency</td>
</tr>
<tr>
<td>$f_u$</td>
<td>upper half-power frequency</td>
</tr>
<tr>
<td>$F_e$</td>
<td>transverse force on electron</td>
</tr>
<tr>
<td>$\vec{H}$</td>
<td>magnetic field intensity</td>
</tr>
<tr>
<td>$H_s(t)$</td>
<td>magnetic field of coil in air</td>
</tr>
<tr>
<td>$H_f(t)$</td>
<td>magnetic field scattered by a flaw</td>
</tr>
<tr>
<td>$H_m(t)$</td>
<td>magnetic field of coil on specimen</td>
</tr>
<tr>
<td>$H_r(t)$</td>
<td>magnetic field scattered from specimen</td>
</tr>
<tr>
<td>$H_xR$</td>
<td>reflected magnetic field intensity</td>
</tr>
<tr>
<td>I</td>
<td>current</td>
</tr>
<tr>
<td>I_c</td>
<td>control current</td>
</tr>
<tr>
<td>$\vec{J}$</td>
<td>current density</td>
</tr>
<tr>
<td>$\vec{J}_e$</td>
<td>induced eddy-current density</td>
</tr>
<tr>
<td>$\vec{J}_s$</td>
<td>source current density</td>
</tr>
<tr>
<td>$\vec{J}_x$</td>
<td>eddy-current density at a given depth x</td>
</tr>
<tr>
<td>k</td>
<td>coefficient of coupling</td>
</tr>
<tr>
<td>$\hat{k}$</td>
<td>wave number</td>
</tr>
<tr>
<td>$K_{hl}$</td>
<td>Hall coefficient</td>
</tr>
<tr>
<td>L</td>
<td>inductance</td>
</tr>
<tr>
<td>$L_o$</td>
<td>inductance of coil in air</td>
</tr>
<tr>
<td>M</td>
<td>mutual inductance</td>
</tr>
<tr>
<td>N</td>
<td>number of turns in a coil</td>
</tr>
<tr>
<td>$P_m$</td>
<td>perimeter of mean turn</td>
</tr>
<tr>
<td>r</td>
<td>coil radius</td>
</tr>
<tr>
<td>$\bar{r}$</td>
<td>mean coil radius</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>R</td>
<td>resistance</td>
</tr>
<tr>
<td>R&lt;sub&gt;i&lt;/sub&gt;</td>
<td>resistance of wire per inch of length</td>
</tr>
<tr>
<td>R&lt;sub&gt;L&lt;/sub&gt;</td>
<td>equivalent resistance for load</td>
</tr>
<tr>
<td></td>
<td>secondary to primary loop</td>
</tr>
<tr>
<td>R&lt;sub&gt;o&lt;/sub&gt;</td>
<td>resistance of coil in air</td>
</tr>
<tr>
<td>R&lt;sub&gt;p&lt;/sub&gt;</td>
<td>resistance of primary loop (i.e., coil)</td>
</tr>
<tr>
<td>R&lt;sub&gt;s&lt;/sub&gt;</td>
<td>resistance of secondary loop (i.e., sample)</td>
</tr>
<tr>
<td>R&lt;sub&gt;T&lt;/sub&gt;</td>
<td>resistance at temperature T</td>
</tr>
<tr>
<td>s</td>
<td>speed</td>
</tr>
<tr>
<td>t</td>
<td>plate thickness</td>
</tr>
<tr>
<td>v</td>
<td>velocity</td>
</tr>
<tr>
<td>V (or φ)</td>
<td>electric potential</td>
</tr>
<tr>
<td>V&lt;sub&gt;h&lt;/sub&gt;</td>
<td>output Hall voltage</td>
</tr>
<tr>
<td>x</td>
<td>depth below the surface</td>
</tr>
<tr>
<td>X&lt;sub&gt;L&lt;/sub&gt;</td>
<td>inductive reactance</td>
</tr>
<tr>
<td>β</td>
<td>phase lag</td>
</tr>
<tr>
<td>δ</td>
<td>standard depth of penetration</td>
</tr>
<tr>
<td>ε</td>
<td>electric permittivity</td>
</tr>
<tr>
<td>μ</td>
<td>permeability</td>
</tr>
<tr>
<td>μ&lt;sub&gt;r&lt;/sub&gt;</td>
<td>relative permeability</td>
</tr>
<tr>
<td>ρ</td>
<td>volume charge density</td>
</tr>
<tr>
<td>σ</td>
<td>conductivity</td>
</tr>
<tr>
<td>φ</td>
<td>magnetic flux</td>
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<tr>
<td>ω</td>
<td>angular frequency</td>
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Chapter 1

INTRODUCTION

1.1 Airworthiness and Corrosion

In the world of aviation, maintenance programs are required to ensure safe operation of aircraft within a given fleet. To this end, maintenance actions are carried out to correct failures and deficiencies, but also to detect and prevent impending failures. A maintenance program evolves with time to meet new safety standards or to simply ensure airworthiness. With more than 25% of the world's commercial airline fleets composed of aircraft over 20 years [1], the issue of in-service inspection has become critical for the safe and economical management of these fleets. In this context, starting in 1988, several conferences on aging airplanes were held and, as a result, established multiple-site fatigue cracking and corrosion as major issues affecting the airworthiness of airplanes [2].

Although corrosion may seem unimportant and, to some, a problem to be dealt with later on, it should not be overlooked as it greatly impacts flight safety. From a design standpoint, corrosion can wreak havoc as it can lead to early crack initiation, enhanced crack growth rates (corrosion fatigue), thickness loss (increased stress), inter-granular and stress corrosion cracking, and pitting (stress risers) [3]. Hence, the effect of corrosion on the maintenance program of an aging aircraft fleet translates into an increase in inspection frequency. This solution, however, does not solve all problems, the reason being that inspection techniques used to detect corrosion are questionable. In fact, the detection and characterization of corrosion in aging aircraft is currently one of the major problems in aircraft inspection [4], and according to the Federal Aviation Administration's (FAA) National Aging Aircraft Research Program, improvements must be made to existing inspection techniques and devices for more reliable corrosion detection capabilities [5].

1.2 Corrosion Detection

Most parts of an aircraft can be affected by corrosion. However, corrosion in fuselage lap splices are of particular interest to researchers [1-11]. The basic types of fuselage lap splices are shown in Figure 1-1. Although they have their own characteristics, they have one common feature. Their design is such that a crevice exists where conditions are favorable for corrosion. Ultimately, corrosion in the lap splice will lead to the loss of pressure integrity of the fuselage. Specifically for this thesis, it is the basic lap splice and the basic butt splice that are simulated by the test samples.
When corrosion takes place between layers, the metal lost to corrosion product can force the plates apart thus causing an air gap. Because of this surface distortion, the traditional means used for detecting corrosion in lap splices is the visual inspection of the external aircraft fuselage. For this inspection, the signs being looked at are:

a. skin bulges between fasteners (i.e., pillowing);

b. cracked or missing fastener heads; and

c. visible corrosion product.

This visual detection of pillowing due to corrosion can be enhanced via an optical double-pass retroreflection surface inspection technique. This technique can detect a change in surface topography greater than 10 μm [12]. However, it does not provide a foolproof indication that the deformation is due to corrosion. Plate separation can also exist as a result of poor quality control during manufacture. The distortion can also be due to previous repairs. Hence, for corrosion detection, it is desirable to be able to distinguish between loss of metal and variation of plate separation since they frequently occur together.

The aim is thus to detect and characterize regions in a structure with a physical state being outside the limits considered acceptable by the designer, such as is the case involving lap splice corrosion. However, as an inspection involves maintenance manhours and aircraft downtime, "false calls" must be minimized and inspection preparation must be avoided if at all possible. It is with this perspective in mind that conventional nondestructive evaluation techniques used for corrosion detection in multi-layer structures must be viewed.
At present, an aircraft can be operated until corrosion thinning reaches 10% of a fuselage skin i.e., the skin is 90% of its original thickness. Beyond this 10% thinning, repair action is mandated - corrosion removal and repair patch application are typically required [7]. The detection of corrosion by ultrasonic and eddy-current is not inherently difficult; however, there are problems with the identification and characterization because of the complexity of the structure. The lap splice is a multiple layer structure and to quantify the thinning, it is required to know in which layer corrosion has occurred. Ultrasounds will not easily penetrate beyond the first layer. On the other hand, eddy-current techniques have the ability to perform multi-layer inspections without requiring a mechanical bond. However, a FAA review of nondestructive inspection methods used by commercial operators found that carrying out a visual inspection followed by low-frequency eddy-current inspections are not capable of isolating corrosion below 10% thinning in the first layer. They also found that second and third-layer corrosion may progress to much greater amount of thinning before they are finally detected during Depot Level Inspection and Repair requiring the removal of the airplane interior [7]. Apart from the previously described nondestructive techniques (i.e., visual and low frequency eddy-current inspections), no other technique finds application for corrosion detection in aircraft lap splices which leads to the conclusion that the efficiency of present conventional nondestructive methods is questionable.

1.3 Eddy-Current Inspection

The quantitative determination of corrosion, or thinning, of a test part is somewhat complicated with conventional eddy-current techniques. This assessment comes from the fact that the depth of penetration of eddy-currents into the part is governed by operating frequency, material conductivity, and magnetic permeability [5]. For single layer structures, a single frequency eddy-current inspection is sufficient to detect corrosion, with the frequency chosen as a function of the material's thickness [13]. To obtain accurate thinning readings, a test frequency that matches one skin depth for the uncorroded skin material is chosen, and the quantitative determination of thinning is achieved by the use of calibration samples.

The detection of corrosion for a two-layer structure is more complicated and is considered inefficient for the adequate identification and characterization of corrosion. In this case, by decreasing the operating frequency, greater eddy-current penetration can be achieved. At a certain point, the second layer will be penetrated by the eddy-currents. It is therefore possible to determine the loss of material due to corrosion in the second layer; however, a varying gap size produces a noise response very similar to that of material loss due to corrosion in the second layer. This condition, as shown in Figure 1-2, is the reason why a single frequency eddy-current instrument cannot reliably be used to detect second layer corrosion [6].
Figure 1-2
Corrosion Indication Due to a) Second Layer Corrosion and b) Variable Gap from [6]

This problem has been resolved with the use of dual frequency methods and signal mixing techniques. Thus, second layer corrosion detection can be performed by using at least two frequencies and combining the signals in a way that removes unwanted effects from air gaps caused by plate separation. However, it is still difficult to completely discriminate between first and second layer corrosion and to infer the actual amount of material loss from a given signal [13].

1.4 Pulsed Eddy-Currents

The pulsed eddy-current technique differs from the conventional eddy-current as it is driven by a square wave. This pulsed driving current produces an inherently wideband frequency spectrum which allows the determination of a large number of parameters, such as defect size, defect location and probe lift-off during inspection.

The pulsed excitation causes the propagation of a highly attenuated traveling wave, which is governed by the diffusion equation [14]. Dissipation and interaction with cracks and other electrical discontinuities cause the radiation to be scattered back to the surface where it can be measured by the field sensor in the form of a bipolar series of magnetic field transients. The transients can therefore yield information about the depth of any defect present. Effectively, the metal attenuates and delays the pulsed field as it passes through the metal. The magnitude or the delay, or both, may then be used as indicators of the conditions inside the metal [15]. Hence, the different parts of the transients contain information about different depths i.e., the shape of a scattered field pulse contains information that characterizes the interior of the specimen.
Chapter 1 Introduction

By using synchronous gating methods, different parts of the transients may be selected and integrated to give an output that is estimated from the total amount of radiation scattered from the corresponding depth band. This signal processing allows the analysis of cracks and defects present at a given depth.

The main advantage of this technique lies in the fact that this pulsed driving current produces an inherently wideband frequency spectrum. Effectively, one pulse contains the information from a range of frequencies so the equivalent information of a swept-frequency measurement can be acquired on the order of milliseconds instead of minutes [16]. This characteristic provides the maximum amount of available information at each position, thus enhancing the detectability of flaws [17].

1.5 Thesis Objectives

Future applications of the pulsed eddy-current technique will rely on the ability to interpret the transient response. On the premise that the pulsed eddy-current transient response is a direct representation of the broadband modulation carried out by the sample, it is possible to determine the presence of corrosion and its location in a layered sample from certain time domain features. These conclusions are based on the fact that lift-off is kept constant. However, in real life application, the distance between the probe and test object surface may vary. In that case, the inconsistent lift-off distances may lead to false indications.

For this emerging technique to become a main stream application, it is of paramount importance to distinguish between lift-off effects and defect signals. Therefore, the first objective of this thesis is to identify means to detect corrosion independently of lift-off. The second objective is to ascertain the feasibility of determining the location of defects in a two-plate assembly independently of lift-off. These objectives will pursued for three different types of transducers, namely single coil, driver-pickup coils, and single coil with Hall effect detector as the sensor.

1.6 Thesis Methodology

This thesis contains three groups of subject matter: theory, instrumentation and experimental results. They are divided in five other chapters for which a description is provided below.

Chapter 2 presents the underlying principles related to eddy-currents. It provides a more theoretical treatment of eddy-currents. It will be used to clarify and support the experimental results and highlight the interdependence of variables in eddy-current testing.

Chapter 3 presents the pulsed eddy-current experimental technique. The style adopted for the presentation of the information is the building block approach. The first issue covered is the generation of eddy-currents by an excitation pulse from an excitation coil. This description
includes the effects of coil and pulse characteristics on the technique. The second issue presented is the detection of the transient response, in particular, the various types of sensors that can be used for that purpose. In real life, these two issues are essential for the establishment of any technique. The third issue is data processing. This particular issue is a fundamental element in establishing a nondestructive evaluation technique since it provides a method to quantify a given defect. Finally, the chapter wraps up with a series of brief description of pulsed eddy-current inspection techniques developed by researchers.

Chapter 4 describes the experimental set-up. The discussion starts with an overview of the architecture. The system's components and set-up considerations are then described in six categories associated with electromagnetic nondestructive test equipment functions.

Chapter 5 provides an account of the design of an experimental transducer as well as an insight into its effectiveness. It details the various design considerations, but also provides the theoretical coil characteristics and related experimental confirmation. Finally, two other aspects are addressed, namely Hall effect detector and shielding.

Chapter 6 presents the experimental results for three types of transducer. The time domain transient response is analyzed to determine possibilities of identifying the presence of corrosion and its location in a two-layer plate arrangement. The salient point in this analysis is the determination of features which are independent of lift-off variations. These features are then validated against a second test sample and imaging is used to present the results.

Chapter 7 provides the conclusions and recommendations. The perspective used when writing that chapter is that pulsed eddy-current is still an experimental technique. The transient response analysis is still in its infancy and continuing research in that field may yield a powerful new inspection technique.

Finally, the last portion of this thesis is composed of two annexes. Annex A provides the experimental verification of the coil characteristics specific to the transducer designed during this thesis. Annex B details the assumptions, the development and results of a model created to validate the results obtained for a single coil transducer.
Chapter 2

EDDY-CURRENT THEORY

2.1 Introduction

When a loop of wire is subjected to a time-varying magnetic field, the changing magnetic flux produces a voltage, which causes a current to flow through the wire when the circuit is closed. This is known as Faraday's law. If the conducting body is not a wire filament, but an object with significant size, the effects of a changing magnetic field are more complex. The voltages induced at different points within the object give rise to internal currents, called eddy-currents. The principle of magnetic induction is the basis on which eddy-current methods rely for the inspection of test samples; the testing essentially consists of monitoring the flow and distribution of eddy-currents in test material.

The varying magnetic field, called the primary field, is set up by currents flowing through a test coil, as shown in Figure 2-1. When the coil is brought in close proximity to a material, a flow of eddy-currents is induced within the test material. These eddy-currents flowing in the test object at any depth produce a magnetic field, called the secondary field, which opposes the primary field, thus reducing its effect and causing a decrease in eddy-current flow as depth increases. Effectively, the eddy-currents are concentrated near the surfaces adjacent to the excitation coil and decrease exponentially or approximately exponentially with depth, and the phase angle of the current becomes increasingly lagging as depth increases. This phenomenon is referred to as skin effect [14].

![Figure 2-1](image_url)

Alternating Current Coil
Over a Conducting Specimen
Chapter 2  Eddy-Current Theory

The previous description is a quick overview of the eddy-current induction process. It infers that magnetic effects of electric currents are of vital interest in eddy-current testing. Hence, this chapter deals with the theory underlying the physical phenomena. Also presented is a tool used for the interpretation and analysis of eddy-current inspection, namely the impedance plane diagram.

2.2 Equations Governing the Eddy-Current Phenomena

The electromagnetic phenomena on a macroscopic scale are described by Maxwell's equations. These equations are general in nature and can be simplified to represent better the conditions present during eddy-current testing. Specifically, it is possible to assume that:

a. the electromagnetic wave propagating in the test sample is a plane wave; and
b. the test sample is a good conductor.

For this case, Maxwell's equations can be expressed as:

\[ \mathbf{\nabla} \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \]  
Faraday's law of induction  \hspace{1cm} (2-1)

\[ \mathbf{\nabla} \times \mathbf{H} = \mathbf{J} \]  
Ampere's law  \hspace{1cm} (2-2)

Note: The displacement current term ( \( \frac{\partial \mathbf{D}}{\partial t} = 0 \) ) is neglected in equation (2-2) because conduction current dominates in a good conductor.

\[ \mathbf{\nabla} \cdot \mathbf{B} = 0 \]  
Gauss' law (magnetic fields)  \hspace{1cm} (2-3)

\[ \mathbf{\nabla} \cdot \mathbf{D} = 0 \]  
Gauss' law (electric fields)  \hspace{1cm} (2-4)

Note: With the assumption that the test object is a good conductor, it can be assumed that the charge density is equal to zero. The foundation for this assumption is the fact that the charge relaxation time for metals is very short i.e., \( 10^{-13} \) second.
Given these equations, it is possible to solve eddy-current problems. However, these equations must be expressed in terms of an appropriate formulation. This formulation can be achieved by the manipulation of the partial differential equations to obtain other differential equations that are easier to solve. Starting with equation (2-3), it can be satisfied automatically by using the magnetic vector potential $\vec{A}$, defined as

$$\vec{B} = \vec{\nabla} \times \vec{A} \quad (2-5)$$

Next, the static case is considered i.e., $\vec{\nabla} \times \vec{E} = 0$, the electric field intensity can be expressed as $\vec{E} = -\vec{\nabla} \phi$. However, the conditions are those of a non-static case. Therefore, by using the time derivative of equation (2-5) and substituting it in equation (2-1), it is possible to derive the relation describing the electric field. It is expressed as equation (2-6):

$$\vec{E} = -\vec{\nabla} \phi - \frac{\partial \vec{A}}{\partial t} \quad (2-6)$$

From equation (2-4), it is possible to write that $\vec{\nabla} \cdot \vec{E} = 0$ since $\vec{D} = \varepsilon \vec{E}$. Substituting in equation (2-6),

$$\vec{\nabla} \left( -\vec{\nabla} \phi - \frac{\partial \vec{A}}{\partial t} \right) = 0$$

$$-\vec{\nabla}^2 \phi - \frac{\partial (\vec{\nabla} \cdot \vec{A})}{\partial t} = 0 \quad (2-7)$$

Equation (2-7) constitutes the first coupled differential equation. To create this coupled differential equation, three of Maxwell's equations were used. The remaining equation is (2-2). To simplify the solution of eddy-current problems, this equation must also be expressed in terms of scalar potential ($\phi$) and vector potential ($\vec{A}$). Given that $\vec{B} = \mu \vec{H}$ and $\vec{B} = \vec{\nabla} \times \vec{A}$, equation (2-2) can be rewritten as

$$\vec{\nabla} \times \left( \frac{1}{\mu} \vec{B} \right) = \vec{J}$$

$$\vec{\nabla} \times (\vec{\nabla} \times \vec{A}) = \mu \vec{J}$$
\[ \nabla ( \nabla \cdot \vec{A} ) - \nabla^2 \vec{A} = \mu \vec{J} \]

Since \( \vec{J} = \sigma \vec{E} \), it is possible to write

\[ \nabla ( \nabla \cdot \vec{A} ) - \nabla^2 \vec{A} = \mu \sigma \left( - \nabla \phi - \frac{\partial \vec{A}}{\partial t} \right) \] (2-8)

At this point, the Maxwell's equations are reduced to two coupled second order differential equations i.e., equations (2-7) and (2-8). To uncouple these equations, one may make a gauge transformation with the Coulomb gauge i.e., \( \nabla \cdot \vec{A} = 0 \). This gauge transformation provides the means to simplify problems dealing with static fields. It should be noted that it would be inadequate to use the Lorentz gauge since there is no displacement current. Hence, equations (2-7) and (2-8) become:

\[ \nabla^2 \phi = 0 \] (2-9)

\[ \nabla^2 \vec{A} = \mu \sigma \nabla \phi + \mu \sigma \frac{\partial \vec{A}}{\partial t} \] (2-10)

Equation (2-9) is Laplace's equation. Equation (2-10) confirms the presence of a diffusion process since this equation has the same form as the diffusion equation, which is

\[ \nabla^2 u = \frac{1}{\alpha^2} \frac{\partial u}{\partial t} \]

Finally, equation (2-10) can be expressed in terms of current densities,

\[ \nabla^2 \vec{A} = \mu \left( -\vec{J}_s \right) + \mu \sigma \left( -\vec{J}_e \right) \] (2-11)

where \( \vec{J}_s = -\frac{\partial \vec{A}}{\partial t} \) is the internally generated eddy-current density (induced eddy-currents) and \( \vec{J}_e = -\sigma \nabla \phi \) is the externally impressed source current density. In essence, this quasi-static equation governs the properties of an electromagnetic nondestructive test.
2.3 Equation for Skin Effect

As previously indicated in section 2.1, eddy-currents are concentrated near the surface of a conductor and decrease exponentially with depth. This can be shown mathematically. In effect, equations defining the propagation and distribution of eddy-currents in conducting materials can be derived from Maxwell’s equations. For this development, a planar magnetic field is assumed to be propagating perpendicularly to a semi-infinite conductor. Each component of this field satisfies the plane wave equation which has the form

$$ \nabla^2 u - \frac{1}{v^2} \frac{\partial^2 u}{\partial t^2} = 0 $$

having for solution $u = e^{i(k \cdot x - \omega t)}$. Hence, it is possible to write solutions to the uncoupled Maxwell’s equations as:

$$ \mathbf{E} = \mathbf{E}_o e^{i(k \cdot x - \omega t)} \quad (2-12) $$

$$ \mathbf{H} = \mathbf{H}_o e^{i(k \cdot x - \omega t)} \quad (2-13) $$

The next step that must be taken is to find the relationship between $\omega$ and the wave number ($k$). To find it, equations (2-12) and (2-13) must be substituted back into Maxwell’s equations i.e., (2-1) to (2-4), which would yield:

Equation (2-1)

$$ k \times \mathbf{E}_o = \omega \mathbf{B}_o \quad (2-14) $$

Equation (2-2)

$$ \frac{1}{\mu} (k \times \mathbf{B}_o) = \sigma \mathbf{E}_o \quad (2-15) $$

Equation (2-3)

$$ k \cdot \mathbf{B}_o = 0 \quad (2-16) $$

Equation (2-4)

$$ k \cdot \mathbf{E}_o = 0 \quad (2-17) $$
Equation (2-16) and (2-17) are already satisfied and do not shed light on the relationship between \( \omega \) and \( \vec{k} \). The relation will be achieved via the remaining two relations. Substituting (2-14) in (2-15) yields:

\[
\frac{i}{\omega \mu} \vec{k} \times (\vec{k} \times \vec{E}_o) = \sigma \vec{E}_o \tag{2-18}
\]

With the vector formula \( \nabla \times \nabla \times \vec{a} = \nabla (\nabla \cdot \vec{a}) - \nabla^2 \vec{a} \) and since \( \nabla \cdot \vec{E} = 0 \) (i.e., there is no source in the region of interest), it is possible to write

\[- \frac{i}{\omega \mu} k^2 \vec{E}_o = \sigma \vec{E}_o\]

For this relation to be true, it is necessary that

\[- \frac{i}{\omega \mu} k^2 = \sigma \quad \text{or} \quad k^2 = i \sigma \omega \mu\]

Hence,

\[k = \frac{1 + i \sqrt{\sigma \omega \mu}}{\sqrt{2}} \tag{2-19}\]

"k" is known as the propagation constant of the plane wave solution within the conductor. It can be expressed as \( k = \alpha + i \beta \). where \( \alpha \) is the attenuation factor and \( \beta \) is the phase shift constant.

Substituting (2-19) back into (2-13) yields:

\[\vec{H} = \vec{H}_o e^{i(k \hat{k} \cdot \vec{x} - \omega t)} \tag{2-20}\]

where

\[e^{i(k \hat{k} \cdot \vec{x} - \omega t)} = \exp \left( - \sqrt{\frac{\sigma \omega \mu}{2}} \hat{k} \cdot \vec{x} \right) \exp \left( i \sqrt{\frac{\sigma \omega \mu}{2}} \hat{k} \cdot \vec{x} - \omega t \right)\]
Chapter 2  
Eddy-Current Theory

The attenuation factor referred to earlier and shown in equation (2-20) is used to derive another variable widely used in eddy-current testing, namely the skin effect. It is defined as $\delta = \frac{1}{\alpha}$ and can be written as:

$$\delta = \sqrt{\frac{2}{\omega \sigma \mu}} \quad (2-21)$$

The skin effect is related to the electromagnetic wave. When considering eddy-currents, the term normally used is skin depth. It expresses the same effect but is simply a different terminology. Its name comes from the fact that eddy-currents concentrate near the surface adjacent to the excitation coil. Equation (2-21) does not address the fact that eddy-current density decreases exponentially with depth, which can be easily proven mathematically. Taking the curl of (2-1) yields

$$\nabla \times \nabla \times \mathbf{E} = -\frac{\partial (\nabla \times \mathbf{B})}{\partial t}$$

With the vector formula $\nabla \times \nabla \times \mathbf{a} = \nabla (\nabla \cdot \mathbf{a}) - \nabla^2 \mathbf{a}$ and since $\nabla \cdot \mathbf{E} = 0$ (i.e., there is no source in the region of interest), it is possible to write

$$\nabla^2 \mathbf{E} = \frac{\partial (\nabla \times \mathbf{B})}{\partial t}$$

Replacing $\mathbf{B}$ by $\mu \mathbf{H}$, $\mathbf{E}$ by $\mathbf{J}/\sigma$ (i.e., Ohm's law), and substituting (2-2) in the last equation yields

$$\nabla^2 \mathbf{J} = \mu \sigma \frac{\partial \mathbf{J}}{\partial t} \quad (2-22)$$

Equation (2-22) is the relation expressing the flow of induced eddy-currents. As expected, this equation has the form of a diffusion equation. For a semi-infinite conductor excited with a sinusoidal varying field, the solution is:

$$J_x = J_o e^{-\alpha x} \sin (\omega t - \beta) \quad (2-23)$$
which can be separated into two components:

\[ \frac{J_x}{J_o} \propto e^{-x / \delta} \]

which describes the exponential decrease in eddy-current density with depth; and

\[ \frac{J_x}{J_o} \propto \sin (\omega t - x / \delta) \]

which describes the phase lag of the sinusoidal signal with depth.

2.4 - Impedance Plane Diagram

The role of the test coil in eddy-current testing is very important. It is through the coil that, in most cases, the information about the condition of the test object is obtained. The discussion presented here will be simplified by restricting it to a system using a single coil; however, the principles can be extended to multiple coil systems [18]. During an inspection, conductivity, defects, paint thickness and many other parameters can be determined by measuring the probe resistance and inductance. To represent these changes and make sense of them, one can use a powerful tool in conventional eddy-current inspections, namely the impedance plane diagram. To understand how it works, one can look at a model representing the typical arrangement associated with an eddy-current inspection. The exciting coil and test material can be considered analogous to that of two-winding transformers with air cores, as shown in Figure 2-2. The coil acts as a multi-turn primary and the test material as a single turn secondary. The primary loop has a resistance \( R_p \) due to the coil and the secondary also has a load \( R_s \) associated with the sample resistance.

![Figure 2-2](https://example.com/figure2_2.png)

Figure 2-2
Ideal Air Core Transformer Circuit
Chapter 2  
Eddy-Current Theory

The primary and secondary currents are inversely related to the ratio of the turns, for the ideal transformer representing mutual inductance effects. Assuming the current $I_2$ is flowing in the test material, then the component of primary coil voltage corresponding to the secondary or test material reaction can be determined as:

$$V_1' = \frac{N_1}{N_2} I_2 R_s = \left( \frac{N_1}{N_2} \right)^2 I_1 R_s$$  \hspace{1cm} (2-24)

Thus, the total voltage appearing across the terminals of a practical test coil is given by:

$$V_1 = \left[ R_p + \left( \frac{N_1}{N_2} \right)^2 R_s \right] I_1 + L_1 \frac{dI_1}{dt}$$  \hspace{1cm} (2-25)

Effectively, the representation of Figure 2-2 can be further simplified [19] as shown in Figure 2-3. The main change reflects the relation expressed in equation (2-25) which consists in the transfer of the load resistance $R_s$ from the secondary back to the primary loop by multiplying it by the turns ratio squared. It is reflected by $R_L$ in the equivalent series circuit.

![Equivalent Series Circuit](image)

Figure 2-3
Equivalent Series Circuit from [14]

The representation of the eddy-current transducer by a series, lumped circuit with resistive and inductive elements is an approximation applicable primarily to probe coils over thin sheet materials [14]. However, it does not apply to test materials that are thick compared to the eddy-current depth of penetration. In this case, an additional factor enters the problem. The phase displacement of eddy-currents (time lag) at greater depths produces considerable differences in test coil performance compared to test conditions for lumped series R-L circuits [19].
From this equivalent series circuit, it is possible to develop a tool for the interpretation of the test coil resistance and inductance. Assuming an alternating current flowing through a series connection of a pure resistance and a pure self-inductance, the voltage can be expressed as \( V = I (R + j\omega L) = I (R + jX_L) \). The voltage drop across the inductive reactance leads the current by 90 degrees while the voltage drop across the resistance is always in phase with the current. When the values of R and L are varied, the voltage drop across the circuit varies, and depending upon these values the voltage drop is represented by different phasors on a phasor diagram. Because the vectors are at right angles, the locus of the end of the vector IR is a semicircle.

The phasor diagram representing the voltage drop across the circuit can also represent the impedance of the circuit. This new plot, the impedance plane diagram, has for ordinate the inductive reactance \( \omega L \) and for abscissa the resistance (R). Although this new diagram is related to the quantities measured during an eddy-current inspection, it has certain limitations. In effect, changing the operating frequency increases the empty coil reactance in direct proportion to the frequency; thus, the impedance diagram grows in size. This complicates the interpretation of eddy-current measurements. The solution is to normalize the impedance curves by dividing both reactance and resistance values by the impedance or reactance of the empty coil. The result is a universal curve which can be used for any frequency.

In the normalized impedance plane diagram (Figure 2-4), the ordinate axis represents values of normalized inductive reactance \( \omega L/\omega L_0 \). The abscissa axis represents values of the normalized variation in coil resistance \( (R - R_0)/\omega L_0 \). In the absence of a test object, the empty test coil impedance is represented by the initial point A corresponding to the value of 1.0 on the vertical axis. It is referred to as the empty coil point (or air point) and is the initial point on the impedance locus. During eddy-current testing, a relative impedance point is obtained by placing the coil against the sample. Specifically, when a nonmagnetic test object is brought into the magnetic field of the transducer, the coil’s inductive reactance is decreased by the opposing magnetic reaction of the eddy-current field, whereas its apparent resistance is increased by virtue of the heating and resistance losses caused by the flow of eddy currents in the test material. On the normalized impedance plane diagram, the apparent transducer impedance would be displaced clockwise from point A to some new point around the impedance locus circle [18,19]. The actual location of the test signal point along the locus will vary in a nonlinear fashion with the size and conductivity of the test objects, and will change location along the test signal locus curves with changes in the test conditions.
Figure 2-4
Normalized Impedance Plane Diagram and
the Effects Due to Variation of Parameters [18,19]

The change in coil impedance with lift-off can also be derived from the impedance plane diagram. When the coil is suspended in air away from the conductor, impedance is at the upper end of the curve (point A). As the coil approaches the conductor, the impedance moves in the direction indicated by the dashed lines until the coil is in contact with the conductor. When contact occurs, the impedance is at a point corresponding to the impedance of the part being inspected. The largest semicircle corresponds to the maximum possible coupling between the two circuits, i.e. minimum lift-off. As the coupling is decreased (or lift-off increased), the diameter of the semicircle decreases. The variation is nonlinear and the lift-off effect is so pronounced that small variations in spacing can mask many indications resulting from the condition or conditions of primary interest.

Changes to the test object also affect the coil impedance. For example, an increase in test object thickness, $t$, provides an increased cross-sectional area within which eddy-currents can be induced to flow (up to the penetration depth limitations). The effect is an increase in the total magnitude of eddy-current flow which results in a greater eddy-current reaction field (or secondary field). On the impedance plane diagram, an increase in the test object thickness would result in a clockwise rotation around the impedance point locus.
The two previous examples demonstrate the usefulness of the impedance plane diagram for conventional eddy-current testing. Many other parameters can influence the location of the points on the impedance locus such as frequency and conductivity. Figure 2-4 shows the effect of an increase in frequency and conductivity. However, the use of the impedance plane diagram is not limited to what is mentioned above. It serves many other purposes and a complete description of its uses can be found in references [14] and [19]. However, it should be noted that it is possible to relate the physical phenomena of eddy-current induction to the position on the impedance point locus. In general, any increase in the magnitude of eddy-current flow will increase the horizontal (real) component of the test signal, and reduce the vertical (imaginary) component. In other words, the displacement of the coil impedance point (clockwise from A) corresponds to an increased magnitude of eddy-currents induced in the test material.
Chapter 3

STATE-OF-THE-ART

3.1 Introduction

The generation of eddy-currents in a conductor is due to the variation of the magnetic field, which can be achieved by alternating the current passing through a coil. For the conventional eddy-current technique, the field source is driven by a sinusoidal waveform at a single frequency. On the other hand, the pulsed eddy-current technique is driven by a square wave current (see Figure 3-1a). This square shape current excitation provides a wide range of frequency excitation which causes the propagation of a highly attenuated traveling wave governed by the diffusion equation [14]. It should be noted that eddy-current induction is discontinuous because the magnetic field created by the coil remains constant between the square pulse edges [20].

The metal attenuates and delays the pulsed field as it passes through it. Also, cracks and other electrical discontinuities cause the electromagnetic radiation to be scattered back to the surface. These characteristics can be used as indicators of the conditions inside the metal [15]. Therefore, the output signal (Figure 3-1b) can be analyzed and yield information about the presence and depth of any defects.

![Figure 3-1](image)

Figure 3-1
Probe Coil Drive and Hall Sensor Signals from [11]
Different parts of the sensor signal contain information about different depths i.e., the shape of a scattered field pulse contains information that characterizes the interior of the specimen. Because of the finite time taken for the electromagnetic radiation to propagate down to a defect and back, the deeper the defect, the longer the delay in the arrival back at the surface of the associated scattered field pulse. The signal due to a defect near the surface arrives back first while the corresponding signal from a deep defect arrives later and is characteristically broadened as a consequence of its longer path through the highly dispersive conductor. This could also be viewed in terms of phase velocity. The fact is that the lower-frequency components propagate at slower rates through the material whereas higher frequency components take less time. Consequently, effects from shallower defects appear at an earlier time on the detected waveform, and deeper flaws affect the waveform later in time as shown in Figure 3-2 [21]. The separation in time of flaw signals from different layers provides a means to discriminate flaws based on time-gating.

**Figure 3-2**
Portions of Transient Response Signal
Affected by Given Defect Depths from [11]

Time-gating simply means that a “gate” is set to start at a certain time after the start of each pulse, and with a width that covers a range of depths as shown in Figure 3-3. The width setting is determined through the use of a test standard prior to actually testing the component. The output will be an estimate of the total amount of radiation scattered from the corresponding depth band [17,22]. By altering the gates and the gain applied to the signal, the instrument sensitivity can be altered for both flaw size and depth [22]. The initial part of each measured transient is discarded as it predominantly contains information about defects at or close to the surface.
3.2 Pulse Excitation

The propagation of electromagnetic fields within conductors depends on the time dependence and spatial distribution of the source electric field at the surface \([21]\). The total magnetic flux induced is proportional to the probe inductance \((L)\) and current \((I)\).

\[
\phi = \frac{L I}{N} \tag{3-1}
\]

To maximize the electric field transients produced by the coil, it is desirable to change the coil current as rapidly as possible since the electric field is proportional to the time derivative of the coil current. Ideally, a square-wave current would give optimum results. In practice, the rate at which the current through a coil can be changed is limited by its time constant \([21]\). The characteristics of this input pulse have a direct impact on the pulsed eddy-current technique. However, when looking at the pulse, one must also look at the probe/coil which is used to generate the input signal. The reason is that the factor governing coupling and induced voltage in the test material is the magnetic flux surrounding the coil.

From Faraday's law, it can be deduced that varying the voltage across the excitation coil will cause a variation in the rate of change of \(\phi\) for a given number of turns in the coil \((N)\).

\[
V = -N \frac{d\phi}{dt} \tag{3-2}
\]

Hence, when the coil is voltage-driven, the magnitude and shape of the excitation current will depend on the resistance and inductance of the coil. This means that the resulting current rises up to its DC limit in a manner that is determined by the impedance of the coil. Let us examine this issue more closely by defining two dimensionless quantities \([23]\):
the damping constant

\[ k = \frac{\sqrt{a}}{2} \left( \frac{1}{R_T} \sqrt{\frac{L}{C_p}} + R_P \sqrt{\frac{C_p}{L}} \right) \quad (3-3) \]

and the time constant

\[ x = t / \tau_p \quad (3-4) \]

where the period \( \tau_p \) is defined as

\[ \tau_p = 2\pi \sqrt{L C_p a} \quad (3-5) \]

Figure 3-4
Equivalent Circuit of an Inductive Probe from [23]

The variables found in equations (3-3) to (3-5) represent elements of the equivalent circuit for an inductive probe as shown in Figure 3-4 i.e., \( L \) is the coil inductance, \( R_p \) and \( C_p \) are the probe resistance and capacitance (due to leads and connectors), \( R_T \) is the resistance matching the characteristic impedance of the coaxial cable, and \( a \) is the DC attenuation factor. The response of the equivalent circuit to a step function input would give three solutions according to whether \( k < 1 \) (underdamped, oscillatory circuit), \( k > 1 \) (overdamped circuit), or \( k = 1 \) (critically damped circuit), as shown in Figure 3-5. The conclusion that can be drawn is that, in general, an inductive magnetic probe will provide a pulse that is distorted. Hence, to obtain the best frequency response, the period \( \tau_p \) should be as short as possible. This conclusion confirms the earlier statement to the effect that the rate at which the current through a coil can be changed is limited by its time constant.
3.2.1 Pulse Rate

The characteristics of the excitation pulse may affect the transient response. In effect, the time interval between successive transients must be sufficient to allow each transient to decrease to zero. Because the velocity of the eddy-current signal is heavily dependent upon the material, there are conditions where the currents induced by one pulse might still be large enough to interfere with those from the next pulse. This interval increases with the thickness of the specimen [11]. Thus, lower pulse rates are necessary for improved depth performance.

3.2.2 Pulse Width

Sather [24] investigated the relationship between pulse length and depth of electromagnetic plane-wave penetration. His results indicate that by lengthening the pulse duration, an increase in penetration depth can be achieved which decreases the lowest-frequency components present in the pulse.

3.3 Detection and Sensors

Different means can be used for the detection of pulsed fields. Researchers have used eddy-current coil transducers, semiconductor detectors (or Hall effect detectors), giant magneto-resistive (GMR) sensors, and superconductive quantum interference devices (SQUIDs). Even though the nature of the magnetic field detector has no influence on the basic interactions between the magnetizing coil and the fields or eddy-currents induced with the test material, different test parameters are measured by these different detectors. For example, conventional coil transducers respond directly to the time rate of change of total flux linkage, \(N(\frac{d\phi}{dt})\), which couples with the detection coil. Hall probes respond to the normal components of the magnetic flux density, and not to its time derivative at the specific area of the sensor. There are other
specific differences which can also exert a large influence on the test capabilities of the electromagnetic test systems. They consist of the test object area included in the measurement, the response to test frequency and magnetizing waveform, the response to the magnetic field direction, and the degree of coupling between the detector and the test object.

3.3.1 Detection Coil

In most in-service applications, coils are used both as field source and field sensor [4]. The principle of operation of this sensor is quite simple. A magnetic flux is induced by passing a time-varying current through the excitation coil. When the coil is brought close to the test object, eddy-currents are induced within the test object. The magnetic flux associated with the eddy-currents oppose the coil's magnetic flux, thereby decreasing the net flux. The result is a change in the probe impedance which is determined by monitoring the voltage drop across the coil. In other words, the variation of the magnetic flux (φ) with time induces a voltage (V) across the test coil which, by Faraday's law, depends on the magnitude and rate of change of φ and on the number of turns in the coil (N).

\[ V = - L \frac{dI}{dt} \quad \text{since} \quad \phi = \frac{L}{N} I \]  

(3-6)

While eddy-current techniques are effective for detecting surface-breaking flaws, they suffer from several drawbacks when applied to flaws located significantly below the surface [4]. This is due to the fact that deep penetration requires low frequencies so that the skin depth is large enough for eddy-currents to penetrate into the material to the depth of the flaw. However, low frequency eddy-current methods cause tremendous difficulties in probe design and also affect the sensitivity of the pulsed eddy-current methods:

a. To achieve the large inductance needed to operate at frequencies below 1 kHz, a large number of turns is needed. This adds to the resistance of the coil and reduces the energy available to couple into the test piece [16]. Hence, not all turns of winding can be equally well coupled with the test object and only those lines of magnetic flux around the test material which reach the detector provide useful information [19].

b. The flux through a coil can only generate a current in the coil if the magnetic field changes as a function of time. Specifically, the curl of the electric field vector, which generates the current flow in the coil, is defined by the change in the magnetic field orthogonal to the plane of the coil as described by Maxwell's equation:
\[ \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]  

(3-7)

This equation demonstrates the problem associated with using coil-based sensors to detect low-frequency magnetic signals. As the frequency of the applied signal is reduced, so is the rate of change of the magnetic flux density with respect to time. In turn, the coil current is also reduced [25]; consequently, the voltage induced in both an exciting coil (i.e., driver) and a detection coil (i.e., pick-up) is proportional to the test frequency. Thus, a problem exists at very low test frequencies since the test signal magnitudes can be decreased to levels where signal-to-noise ratios are too low for reliable detection [19].

Hence, improving coil performance means increasing the coil response sensitivity. To achieve this, it is necessary to increase the flux through the circular coil. Given that the flux through a circular coil can be described by

\[ \phi = B \pi r^2 \]  

(3-8)

where \( B \) is the magnitude of the magnetic flux density perpendicular to the surface defined by the coil of radius \( r \), a higher sensitivity could theoretically be achieved by building larger inducing coils as they would allow a high depth of penetration of the magnetic fields. On the other hand, if the same large coil is used for detection purposes, a low resolution and sensitivity would be achieved [26]. The reason is that they respond to all magnetic flux lines passing through the coil winding, regardless of their spatial direction and orientation. This characteristic together with the size of the coil can impact the sensitivity of this sensor. Using a smaller coil would provide a better sensitivity but would limit eddy-current penetration within the test object. Therefore, the solution is to use a large diameter inducing coil and a small diameter detection coil to achieve high resolution and high sensitivity.

Better resolution and sensitivity are easily achievable by the fact that there are two methods of sensing changes. The first method implied thus far consists in the monitoring of the voltage drop across the primary coil (Figure 3-6a). This method has severe limitations as stated in the previous paragraph. The second method uses two coils (Figure 3-6b) and is referred to as the "Send-Receive" method. In this case, it is possible to take advantage of the large diameter inducing coil and small diameter detection coil. One typical transducer of this type is the driver-pickup transducer. Its principle of operation is such that the current flowing in the inducing coil produces a magnetic field, part of which is transmitted through the test article. The field is then detected by the receiver, inducing a voltage.
3.3.2 Semiconductor Detector

Semiconductor detectors, commonly referred to as Hall effect detectors, are eminently suitable as magnetic field sensors. Firstly, by virtue of their small size (typically 5mm x 10 mm x 0.1 mm), they provide an excellent spatial resolution [23]. Secondly, they do not exhibit the loss of performance at low frequencies associated with impedance methods. The reason is that Hall detector signals are directly proportional to the actual magnitudes of the magnetic flux density and have uniform sensitivity over a wide frequency range, including the lowest possible test frequency (DC). This allows the measurement of magnetic field intensity directly from DC to an upper frequency limit which depends on the chosen device, but is generally in excess of 25 kHz [21]. Consequently, they can also be used as detectors with pulsed, square waves, multiple frequencies, and other complex waveforms within their frequency spectrum [19].

A certain transducer configuration is to use a circular coil for induction and mount a Hall device on the axis of the coil as shown in Figure 3-7. With this configuration, coil size and excitation frequency can be chosen solely for the purpose of enhancing the field propagation characteristics, e.g. a large diameter magnetizing coil can be used to obtain an axial magnetic field that penetrates to greater depths in the test object, while small area Hall effect detectors are used to detect the effects of eddy-currents at relatively great depths with greater sensitivity and resolution [19]. The unique characteristics of Hall detectors allow not only the duplication of all effects described for conventional coil impedance or coil voltage signals (including complex plane analyses), but add novel possibilities for new arrangements of detectors within the exciting coil [19].
The principle of operation of a Hall effect detector relies on the fact that when a strip of current carrying material is placed in a magnetic field, a potential difference appears across the strip [19]. This is referred to as the Hall effect. The output Hall voltage signal is responsive to the angle that the local external magnetic field makes with the normal axis of the Hall element i.e., a line perpendicular to the face of the rectangular Hall element. If the angle between the magnetic field direction and the normal axis is taken as $\theta$, the output signal is given by

$$V_H = K_H I_C B_n$$  \hspace{1cm} (3-9)

where $K_H$ is the Hall coefficient, $I_C$ is the control current magnitude and $B_n$ (or $B \cos \theta$) is the normal component of the external magnetic field [19].

Because of their directional response characteristic, two or three Hall effect detectors can be mounted in mutually perpendicular planes. From such multiple measurements, the intensity and direction of the magnetic field can be determined precisely, regardless of its orientation. In many cases, the direction of the magnetic field distortion in electromagnetic tests contains useful information concerning discontinuities and local property variations. Such local field distortions, when small in area compared to the coil, may not be detected by the larger coils because they integrate the effect of all flux lines enclosed within the circumference of the coils, regardless of their spatial direction.

Hall effect detectors, with uniform responses to various frequency components, provide signals that are linearly related to the instantaneous magnetic flux density values, in which all frequency components are read out with their relative magnitudes. This characteristic is a distinct advantage over detection coils which have a different response for each frequency component. However, according to Knoepfel [23], in order to successfully apply Hall effect detectors to pulsed fields, the pulse time must be much larger than the field diffusion time into the probe and the relaxation time for the scattering of the current carriers (electrons and holes in semiconductors) on which the Hall effect depends.
From the previous description, one can intuitively recognize the greater sensitivity of Hall effect detectors compared to detection coils. This greater sensitivity can be shown mathematically. Consider a conventional scanning system using coils for both signal induction and detection. As previously indicated, the defect response is proportional to the derivative of the magnetic flux as the detection coil passes over the flaw. Whether the same or separate coils are used, both the energy induced (as eddy-currents) and the energy detected (as a voltage signal) follow Faraday’s law of induction. Therefore, it is possible to write

\[ \varepsilon \propto - (\frac{d\phi}{dt}) \]  \hspace{1cm} (3-10)

where \( \varepsilon \) = energy, \( \phi \) = magnetic flux, and \( t \) = time [11]. The overall sensitivity of any eddy-current system depends on many variables. However, by looking at the contribution of just these two energy levels, one can see that both the induced and detected signals vary proportionally with excitation frequency when conventional coils are used for detection. Thus, the overall sensitivity \( s \) of a given conventional system can be expected to vary as the square of the signal frequency [11]:

\[ s \propto \varepsilon_{\text{induced}} \propto - (\frac{d\phi}{dt}) \]
\[ s \propto \varepsilon_{\text{detected}} \propto - (\frac{d\phi}{dt}) \]
\[ s \propto (\frac{d\phi}{dt})^2 \]

On the other hand, the Hall effect detector’s response to a defect is relatively frequency independent, and this wide bandwidth allows simultaneous coverage of different depths with each pulse. Using a Hall sensor, induced energies are frequency dependent but the Hall sensor’s received signal levels do not depend not on the rate of change of the field, but depend only on the magnetic flux density. Therefore,

\[ \varepsilon \propto K_h I_c B_n \]  \hspace{1cm} (3-11)

where \( K_h \) = Hall effect detector constant and \( I_c \) = constant control current to sensor [11]. Hence, for the detection of a deep defects (requiring very low-frequency), the sensitivity of the Hall effect detector will decrease only in proportion to the decrease in frequency, not the frequency squared.

Hall effect detectors may be more sensitive, but they also have some disadvantages. The most important drawback is that several effects introduce nonlinear deviations to the Hall voltage i.e., temperature, magneto-resistance, contact problems, etc. [23]. Hence, the voltage \( V_h \) appearing across the signal electrodes in the absence of a magnetic field is not likely to be zero as in the ideal case. The good point is that these deviations can be compensated by external correction circuits which reduce the signal to zero and provide temperature compensation [19].
3.4 Transient Response

The sensor voltage, as a function of time, represents the train of transient magnetic fields that are scattered back to the surface as a result of the square-wave current excitation. Thus, the total field transient scattered by a complex structure may be considered as a sum of transients each associated with a particular feature of the structure [21]. Since most of the gradient is caused by dispersion in the material and remains constant, it is often ignored and can be subtracted by signal processing.

Harrison [4] provides a brief but complete description of the sum of transients. This sum of transients is well represented by Figure 3-8. When the coil is in air, the magnetic field $H_s(t)$ measured by the sensor is directly proportional to the current. However, if the coil is placed on a non-ferrous conducting test object and not influenced by any flaws, the field $H_m(t)$ rises to the same steady value but with a different time dependence. $H_m(t)$ does not vary as rapidly as $H_s(t)$. This characteristic is due to the dissipation of energy by Joule heating in the halfspace. Therefore, the difference in fields $H_f(t) = H_m(t) - H_s(t)$ is always negative with respect to $H_s(t)$. $H_f(t)$ can be considered as the field scattered back from the specimen. If the coil is placed in the vicinity of a subsurface flaw, then the field changes by an amount $H_f(t)$ which is the field scattered by the flaw. $H_f(t)$ is negative with respect to $H_s(t)$ since the presence of a flaw will in general reduce the amount of energy dissipated in the test object. This reduction is due to the loss of material which causes a reduction of the cross-section area where eddy-currents flow and results in a reduction of power loss (FR).

![Figure 3-8](image)

Figure 3-8
Variation of the Magnetic Field during Transient Excitation from [4]
3.5 Data Processing

For the pulsed eddy-current technique, the shape of the transient measured at a single point provides a certain amount of information about the internal structure of a specimen. However, the transient shape cannot be uniquely related to the depth from which the transient was scattered. The output signal from the pulsed eddy-current technique contains convoluted information about the object and is unsuitable for direct imaging. The output signal depends on the type of scatterer but also on the geometry of the specimen, in particular its thickness. Therefore, signal processing is often used to address this problem. The objective of digital signal evaluation is to deliver statements for classifying or describing the defects present.

3.5.1 Balancing Process

As was previously discussed, the measured transient contains many separate components (also transients) from different parts of the structure being investigated. Many of these remain constant. In fact, the major parts of the total transient are due to the field in air and the scattered field due to the specimen [4]. The total transient can be subtracted in order to enhance the appearance of these small transients by a process referred to as a balancing process. It can be accomplished via two methods:

Method 1 (Reference Subtraction)

With the transducer positioned on a part of the specimen known to be unflawed, the observed transient is stored. Then, the stored signal is subtracted from all subsequent measurements; hence, as long as the transducer is moved over a similar region, a zero transient will be measured. If the transducer is moved over a flaw or other geometric feature, the out-of-balance transient can be associated with that feature [21].

Method 2 (Differentiation technique)

The circuit consists of a bridge circuit containing two probes as nearly identical as possible. For this case, one probe is placed on a standard metal specimen and the other on the unknown metal specimen to be studied [15,20]. With the bridge circuit balanced, the output is a zero response as long as both transducers are moved over similar regions.
The balanced transient will thus appear zero until the transducer is moved to a position where the geometry of the structure has changed or is affected by a flaw. By this means, the transients associated directly with individual features can be isolated and measured. The small transient signal can be amplified to the limit set by the resolution of the data [21]. This signature (Figure 3-9) can be used more effectively to discriminate the defects in relation with their depth. In fact, three features of the balanced transient are most often employed to quantify the defect, namely: peak amplitude, time to peak amplitude and time to zero crossing.

Peak Amplitude - The magnitude depends on the position and size of the defect or is proportional to the amount of metal loss.

Time to Peak Amplitude - With eddy-currents, there is very high attenuation and dispersion. Hence, the arrival time of this peak is related to the filtering of the magnetic field by the sample and to the position of the flaws. Note that there is not a linear relationship between distance of propagation and arrival time of the peak of the transient. Nonetheless, the trend is sufficiently dominant to make it a useful tool for analyzing the variation of a structure with depth [4].

Time to Zero Crossing - In theory, there is an infinite number of crossing points except that only two or three are visible experimentally before the amplitude becomes so small that the points can no longer be observed [15]. Horizontal shift of the crossing points shows a change in thickness of cladding. It also provides an indication of the location of the defect. Air gap, or simple plate separation, has the earliest time to zero crossing. This is because the total thickness of metal below the coil remains constant. The result is a lower inductance, and hence faster rise and decay times for the probe coil than what occurs when there is metal loss under the coil. Slightly later in time are the zero crossing points for metal loss in the bottom of the top layer, followed by thinning in the top of the bottom layer, and finally thinning in the bottom of the bottom layer [28].

Figure 3-9
Output Pulse Showing the Time in Milliseconds from [15]

3 - 13
The effect of the depth of a defect on the transient is shown in Figure 3-10. It is possible to observe a decrease in the magnitude of the transient and a change in the shape in that it becomes much broader. This is consistent with the passage of a pulse through a highly dissipative medium [4]. If these transients are normalized, the curves will be similar to those presented in Figure 3-11.

![Figure 3-10](image1)

**Figure 3-10**
Characteristic Transient Fields from a Constant Size Defect at Various Depths from [4]

![Figure 3-11](image2)

**Figure 3-11**
Transients Plotted in Normalized Form from [4]

There is a significant drawback to the balancing process. In order to identify the flaw transient, it is essential that the background parts of the transient remain constant throughout the duration of even the most extensive of measurements. Any changes to the background, such as lift-off, will be interpreted as changes to the flaw signal thus leading to inadequate results [21]. This restriction severely limits any "field" application of the pulsed eddy-current technique for corrosion detection in aircraft structures.
3.5.2 Inversion

As described earlier, the establishment of a pulsed eddy-current inspection technique is often based on only three features of the transient response i.e., peak amplitude, time to peak amplitude and zero crossing time. Therefore to determine the conductivity of a particular test object, the data must be processed in order to obtain the information being sought [29]. Since this process amounts to working with an effect to determine its cause, such algorithms are referred to as inversion schemes.

3.5.2.1 Forward Model

Johnson and Bowler [29] explain that in order to invert transient measurements, the probe signal is computed at discrete intervals in time and discrete intervals in the parameter space. Signal predictions for tabulated values of the required parameters are generated. These predictions are stored in a database and accessed by a parameter inversion scheme. This approach means that computer intensive calculations are performed only once to establish the database. During an inspection, the search of the database can therefore be carried out in such a way that it provides the sample parameters in real time. This research led to a method for the evaluation of either half-space conductivity and lift-off, or the evaluation of the dimensions of a four-layered stratified system of conductors where conductivity and lift-off are known. This last procedure is suited to conductivity measurement of metals with non-conductive coatings or thickness measurements of such coatings.

Methods of inverting measured signals for thickness measurements and conductivity profiling typically involve, in both cases, iterating with a forward model until the response from the model under the same excitation condition is as close to the measured signal as possible. These inversion methods are extremely time consuming due to the iterative approach. The complexity of such procedures and the computation resources that this technique requires have precluded its widespread acceptance in industry [30].

3.5.2.2 Look-Up Table

More recently, fast, feature-based methods for conductivity and thickness estimation have been reported. However, these methods involve manually constructing a comprehensive look-up table. The construction of the look-up table is a tedious process, and requires the selection of a reduced set of features to represent the signal.

Tai, Rose and Moulder [31] developed such a look-up table approach for determining the thickness and conductivity of surface layers from pulsed eddy-current data. There were three unknown parameters in the problem: the conductivity of the substrate metal, the conductivity of the layer, and the thickness of the layer. They were able to model quantitatively the pulsed
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eddy-current response and thus predict the thickness and conductivity of the layer without an artifact calibration standard.

Bieber et al. [10] established a pulsed eddy-current inspection technique based on the properties of the experimental curves shown in Figure 3-12. This Figure shows the amplitude versus the time to zero crossing for a range of flaw depths. The variation of the time to zero crossing is being explained by the change in inductance for each case. For example, the air gap has the earliest time to zero crossing. This feature is caused by the fact that the original thickness of the metal beneath the coil remains constant, which results in a lower inductance, hence, causing a faster rise and decay time for the probe coil compared to when there is some degree of metal loss under the coil. Therefore, the separation in time of flaws in different layers allows the determination of the location of corrosion based on time-gating. Taking advantage of this characteristic, they created a computer calibration model that allowed them to quantitatively determine metal loss and discriminate corrosion in a multi-layer metal aircraft structure. The main drawbacks with their approach are that the operation of this model is based on the acquisition of data from a calibration standard and lift-off must remain constant.

![Figure 3-12](image)

Inversion Chart from [10]

3.6 Imaging

Most advanced nondestructive inspection techniques utilize imaging as a means of providing a visual picture of the condition inside a test object. The operator usually has an expectation of image appearance, and regions that deviate from this expectation are normally considered suspect. Pulsed eddy-current imaging follows the same route i.e., the interpretation of the images
received depends to a great extent on prior knowledge of the specimen. The following subsections present different imaging techniques being used with pulsed eddy-currents.

3.6.1 Imaging by Inversion

Imaging with direct inversion yields a congruent image i.e., there is a one-to-one correspondence between the object and its corresponding image. Two examples of imaging by this technique were found: one is based on the characteristics of the transient response while the other is based on the relationship between the measured fields caused by the defects and the eddy-currents.

As indicated in section 3.5.2.2, Bieber et al. [10] proposed a model which enables one to determine the location of corrosion based on time-gating of the transient response. Using a calibration standard, they acquire images and record peak amplitude and zero crossing time for known defects. With there data, they generate calibration curves to determine quantitatively metal loss in the individual layers of the specimen. Figure 3-13 shows a plot of the calibration curves from a 1.5 mm lap-splice calibration standard. Once the calibration is carried out, a raw C-scan image of the test specimen is carried out. This image contains all the peak heights, from the entire spectrum of zero crossing times possible during the pulse duration. Using time gating, the image may be redisplayed plotting only those peak heights that have a zero crossing within a given time window. The software then assigns a color to each peak amplitude in the image to determine the amount of metal loss.

![Figure 3-13](image)

**Figure 3-13**

Calibration Curves from 1.57 mm Calibration Standard [10]
Zorgati et al. [32] have proposed a different method referred to as Diffraction Tomography Technique which could be implemented for pulsed eddy-current imaging. This method relies on the fact that variations of conductivity and/or permeability of homogeneous test objects define boundaries that indicate the presence of anomalies or defects. Specifically, local stress or corrosion may cause variation of permeability whereas cracks or notches modify the conductivity. Therefore, the fields scanned above a test object will behave as a function of the location and shape of the defect, and as a function of the frequency, location and other parameters of the external source.

Diffraction tomography imaging is a linearized solution for a nonlinear inverse problem such that the field data is back-propagated in a known background in order to generate some quantity that depends upon the unknown scatterer properties [32]. This definition includes a number of concepts that are worth looking into. First, the data used by this imaging technique is the time-domain fields sampled above the given test object due to a known source. Having this data, the next step is to find the relationship between the measured fields caused by the defects and the eddy-currents. This is modeled with integral equations (Lippmann-Schwinger-type) which involve the conversion of a diffusion-type equation satisfied by the diffusive field into a Helmholtz equation. The solution can be attained by numerical methods such as Method of Moments and Finite Element Modeling. The output is the tomographic image of the defect that allows evaluation of the material.

3.6.2 Indirect Imaging

Indirect images do not depend on the complex inversion processes and, consequently, are much faster to implement. Indirect images are generally derived by means of linear combinations of the parameters (i.e., peak height, peak arrival time and zero crossing time). The only criterion is that it must allow detection and characterization of flaws [4]. One fact to remember is that the image produced is not intended to be an exact replica of the object but rather aims to emphasize changes in a structure.

One parameter used for indirect imaging of pulsed eddy-current output signal is the time-of-flight. This approach is considered adequate although there is very high attenuation and dispersion which leads to a nonlinear relationship between distance of propagation and arrival time of the peak of the transient response. The reason is that the trend is sufficiently dominant to make it a useful tool for analyzing the variation of a structure with depth.

The time-of-flight numerical map can be formed by calculating the time at which the transient reaches its peak value. In practice, Harrison [4] found that this was not the best approach. The reason is that noise may adversely affect the transient response and the measured time may be inaccurate. Harrison found that moment about the origin in the time domain gives a more stable indication of the peak position.
Chapter 3  State-of-the-Art

The images produced are in effect a sequence of snapshots of the amplitude of the scattered field at the surface as it evolves in time. The earliest image contains information about the surface or near surface. The latest image contains information from only the deepest structure. The images in between contain convoluted information, but in general the deeper a feature the later its appearance in the sequence of images [4].

There are limitations to this technique. The method entails that the system has been balanced on a suitable reference point so that, as the transducer is moved around, the only transient observed is due to that specific feature. For a simple case like a plate specimen, it is easy to define a suitable reference point. However, in a real aircraft structure, finding a suitable reference point can be difficult since the structure may vary significantly from one position to another. As a result, the shape of the transient response will vary and it may be impossible to make any quantitative inferences about the shape of the combined transient or peak arrival time. Harrison [4] proposes to use a form of dynamic balancing that does not require an independent reference point as a solution to this problem.

3.7 Inspection Technique

Harrison [17] developed a technique for inspection of cracks under installed fasteners in aircraft structure. During the inspection, a probe containing a Hall effect sensor and a driving coil are rotated by a scanner held centered on a fastener or other point of interest. A repeating series of square-wave pulses energizes the probe as the Hall sensor and one pole of the probe core orbit the fastener. The instrument displays the outputs from each of the gated pulses arranged one after the other in the form of a continuous line that represents a complete scan around the circumference of the fastener hole. If there is no flaw and the scanner is perfectly centered, the signal amplitude is the same for each point and a straight horizontal line is generated. Any discontinuity in the eddy-current patterns generated from one pulse to the next will show as a bump or curve in the displayed line.

Lebrun et al. [20,33] developed a method for the nondestructive testing of a coating-spar blending in aluminum alloy (AU4G) with a titanium rivet, used in aerospace structures. The method is intended to detect and characterize cracks appearing beneath more than 5 mm of AU4G, without dismantling the structure. For the technique, a square pulse excitation current is used for signal induction and a magnetoresistive element is used to detect the resulting magnetic field. The goal of this research was to characterize the defects in accordance with their size and position. Their results showed that the depth of the flaw affects both the magnitude and the time location of the peak obtained. The size of the flaw mostly influences the magnitude of the signal. To achieve their aim, they had to implement signal processing to distinguish between size and location.
Tai, Rose and Moulder [31] established a pulsed eddy-current technique for determining the thickness and conductivity of conductive coatings on metal plates. Seven combinations of foil and substrate metals were studied including pure aluminum, copper and titanium foils over substrates of aluminum, titanium alloy and stainless steel. Prior to their research, Waidelich had measured the thickness of metal coatings using a pulsed eddy-current technique [15]. His method relied upon knowing the conductivity of the coating and substrate and using calibration specimens for quantitative measurements. This new technique does not require a calibration specimen. Instead, it uses a rapid inversion method based on the three features of the time-domain response (peak amplitude, time to peak amplitude and zero crossing time) and a lookup table approach for determining the thickness and conductivity of surface layers from pulsed eddy-current data.

Johnson and Bowler [34] investigated the feasibility of measuring the thickness and quality of surface treatments including the diffusion of aluminum into nickel parts and the case hardening of steel components. They established correlation between variation of the shape of the transient with each of the inspections considered. For example, in testing aluminized nickel ingots, a correlation was found between the peak height of the differential pulse signal and the depth of the aluminized layer. Their analysis stops there. They concluded by stating that it should be possible to estimate treatment depth using the pulsed eddy-current technique.

Finally, Burke et al. [35] have looked at ways to discriminate between metal loss and change in gap or coil lift-off. Their analysis is based on the fact that the reflected field intensity due to change in coil lift-off or interlayer gap decays more rapidly at long times than the change in the reflected field due to actual loss of metal. The reflected magnetic field intensity ($H_{r}^{B}$) due to eddy-current induction in the conductor system, previously referred to as $H_{z}(t)$ in section 3.4, is simply the result from the subtraction of the transient source magnetic field in air by the field measured via a Hall effect detector against a given test object. Their results are well summarized in Figure 3-14. At short times, the magnitude of the normalized change in reflected field intensity ($\Delta H_{z}^{B}/H_{r}^{B}$) initially increases for all cases. At later times, the response due to changes in gap or coil lift-off reaches a broad peak and then tends toward zero at $t \rightarrow \infty$. In contrast, the normalized response due to metal loss tends to a constant value at $t \rightarrow \infty$. 

3 - 20
The pulsed eddy-current technique is still confined to laboratory applications. This explains why the instrumentation used by PEC researchers is composed of an array of bulky laboratory equipments. Each researcher has a different set-up, however, they use the same basic equipment. The next chapter details the specific set-up used to acquire data for this thesis. In particular, it provides a short description of the functions associated with each instrument and the settings during the experimentation.
Chapter 4

EXPERIMENTAL SET-UP

4.1 Introduction

It is generally considered that an electromagnetic nondestructive test equipment performs six basic functions, namely excitation, modulation, signal preparation, signal analysis, signal display and materials handling [18]. By extension, an experimental set-up for pulsed eddy-current research must also perform these functions. Therefore, after an overview of the system's architecture, the individual components will be presented under sections representing each of the basic functions.

4.2 Architecture

The essence of the pulsed eddy-current test is that current pulses drive the test coil assembly whose output signals are analysed. The system's architecture is, up to a certain level, dictated by the transient response. In effect, variations in transient response due to defects are so small and the phenomenon occurs so rapidly that digital data processing is the only viable option. For the scan of a given surface, an enormous amount of digital data is generated. The analysis therefore requires a microcomputer's data handling capability. A microcomputer can also be used to carry other functions such as:

a. controlling most of the parameter settings for the instruments;
b. reading and analysing the outputs of the eddy-current instrument; and
c. sending outputs to external equipment.

The architecture selected to carry these functions is the star structure as shown in Figure 4-1. The central unit of the system's architecture is the computer. In collaboration with Tektrend International Inc., the computer assembled had a 214.6 MHz Pentium processor, 64 Mb RAM and 2 Gb Hard drive and the functions previously detailed were carried out through one of its applications, namely MPIS (Multi-Purpose Inspection System) version 2.01.

Each instrument is individually connected to the central control unit by its own bundle of control lines. The data are transmitted through the physical link using a communication protocol to ensure that they are correctly received without errors caused by interfering noise signals or malfunction of the circuits [36]. For the physical link between the oscilloscope and the
computer, the HPIB Interface Protocol was used. This particular protocol is a parallel control interface that allows an instrument to be a 'dumb' listener controlled by the host computer, but could also allow it to be an interactive talker/listener to allow control and data reporting.

Figure 4-1
Experimental Set-up

4.3 Excitation

As previously indicated, the computer is the central control unit of the set-up and it is via one of its applications, namely MPIS, that the excitation is digitally triggered. The triggering occurs at given spatial positions during the scan of the test sample. When the position is reached, MPIS sends a trigger to the pulse generator, Hewlett-Packard Model 214B, which provides the test coil assembly with the voltage controlled excitation signals. Other than pulse rate, all the pulse generator settings are controlled manually. One setting of particular interest is the pulse width. The selected width must be sufficient to allow the single coil transient response to reach its maximum, and subsequently decrease to zero. If this is not adequately set, valuable information about the test sample may be lost.
4.4 Modulation

The process which results in the change of the transducer output signal is called modulation. This function is carried out within the transducer/test object complex. In general, the test object can be considered the major contributor since it is the focus of the nondestructive test. For this thesis, two-layer plate assemblies were used as test specimens. The two-layer system has been used by other researchers such as Burke [35] to provide a simple but useful framework for investigating the effect on the transient reflected field of changes in layer thickness due to hidden corrosion in aircraft lap splice. To simulate different defect locations, the plates (shown in Figure 4-2) were placed in specific configurations and secured with nylon screws. Care was exercised in order to scan always the same region and avoid changes from other variables such as conductivity.

![Plate 1](image1.png) ![Plate 2](image2.png)
![Plate 3](image3.png) ![Plate 4](image4.png)

Figure 4-2
Visual Representation of the Plates Comprised in the Test Samples

Test sample #1 is an assembly composed of two 2024-T3 aluminum plates. This particular test specimen was used to study lift-off effects. It was composed of plates with the following characteristics (as specified by the manufacturer, National Research Council):

- **Plate 1 (serial 040-N1)**
  - Average plate thickness: 0.0418"

- **Plate 2 (serial 040-C3)**
  - Average plate thickness: 0.0419"
  - Material loss: 0.0134"
  - Remaining: 0.0285"
Test sample #2 is also an assembly composed of two 2024-T3 aluminum plates. Each plate has a defect and the assembly was made in such a way that the defect of plate 3 would be located at the top of the bottom plate while the defect of plate 4 would be located at the bottom of the top plate. For this assembly, there is no overlap of defects. The purpose of this second test sample was to confirm and validate the conclusions and observations made with test sample #1. It should be noted that the loss of material for this second sample is slightly less than for test sample #1. The specifications (as provided by the manufacturer, National Research Council) of the plates are:

| Plate 3 (serial 040-S1) | Average plate thickness: 0.0415"  
|                         | Material loss: 0.0099"  
|                         | Remaining: 0.0316"  
| Plate 4 (serial 040-S2) | Average plate thickness: 0.0421"  
|                         | Material loss: 0.0109"  
|                         | Remaining: 0.0312"  

These test samples are nonmagnetic; hence, linear conditions have been assumed. This assumption implies that the signal from a set of variables can be written as a linear sum of signals from individual isolated variables [37]. Therefore, to understand the effect a particular variable has on the over transient response, it is necessary to keep several test parameters constant, such as test sample conductivity (29.56 % IACS), thickness, and permeability. The parameters that were varied are listed below:

a. Probe Lift-Off - Measurements are made by scanning the test specimen with lift-off spacing of 0", 0.003", 0.006", 0.009" as defined by Zetec Calibration block.

b. Defect Location - Defect location was changed from the bottom of the top plate (BOT) to the top of the bottom plate (TOB) and finally to the bottom of the bottom plate (BOB).

For an inspection, the test object is a given and the main attributes of modulation are largely beyond control except for the choice of excitation signals and transducer design. The latter can be qualified as a modulating transducer since it requires an auxiliary energy source to convert energy from one domain into another. In other words, the transducer requires an electrical energy source to become operational. When a test object is brought up adjacent to the test coil, the coil excitation currents induce eddy-currents within the test object. It is then that modulation occurs. The modulation attributes are determined by the test coil assembly transmittance, which is affected by the current, field, and magnetic conditions existing in the test object and coupling system [18]. As a result, the transducer transforms the excitation signal into the response signal in a manner which is partially determined by the condition of that part of the test sample which lies in the field of the test coil.
Chapter 4  Experimental Set-up

The effect of modulation is not identical for all types of transducers. For this reason, three types of transducers were studied in this thesis. All coils within these transducers were right cylindrical with rectangular cross-section. Their dimensions are provided in Table 4-1. This table does not provide all of the available information related to the transducer with single coil for excitation and Hall effect detector as sensor. Detailed information pertaining to this particular transducer is presented in Chapter 5. It should also be noted that the information presented for the single coil and coil A of the driver-pickup probe is identical. The reason is because coil A was used as a single coil. The selection of a particular coil was possible because of the coil selector box. As shown in Figure 4-3, two switches allow 1) the selection of operation as driver-pickup probe or single probe and 2) the selection of an excitation coil.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Single Coil</th>
<th>Driver-Pickup Coils</th>
<th>Single Coil with Hall Effect Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coil A</td>
<td>Coil B</td>
</tr>
<tr>
<td>Coils inside diameter (mm)</td>
<td>6.6†</td>
<td>6.6†</td>
<td>1.59†</td>
</tr>
<tr>
<td>Coils outside diameter (mm)</td>
<td>13.9†</td>
<td>13.9†</td>
<td>6.35†</td>
</tr>
<tr>
<td>Coils length (mm)</td>
<td>0.685†</td>
<td>0.685†</td>
<td>0.660†</td>
</tr>
<tr>
<td>Number of turns</td>
<td>400†</td>
<td>400†</td>
<td>625†</td>
</tr>
<tr>
<td>Coils inductance (mH)</td>
<td>1.9850 ± 0.0005</td>
<td>1.9850 ± 0.0005</td>
<td>2.1820 ± 0.0005</td>
</tr>
<tr>
<td>DC resistance (Ω)</td>
<td>58.380 ± 0.005</td>
<td>58.380 ± 0.005</td>
<td>90.700 ± 0.005</td>
</tr>
<tr>
<td>Wire gauge (AWG)</td>
<td>41†</td>
<td>41†</td>
<td>45†</td>
</tr>
</tbody>
</table>

† Specifications provided by Air Vehicle Research Detachment, Ottawa

Table 4-1
Transducers Characteristics

4 - 5
Chapter 4  Experimental Set-up

4.5 Signal Preparation

The signal preparation portion of the experimental set-up consists of instruments which prepare the signal output of the test coil, or the signal output of the Hall effect detector, for the subsequent analysis function. The amount of signal modulation in most eddy-current applications is small and the signal must be amplified considerably to produce a useful level. Amplification is accomplished by a low-noise preamplifier. The particular instrument used for this research is a Princeton Applied Research Model 113. It is a general purpose instrument providing high gain and low noise amplification of signals from DC to 300 kHz. Adjustable high and low frequency roll-offs permit attenuation of those signals outside the range of interest. The preamplifier has two inputs which may be used either in the differential (A-B) or single-ended mode (A) to provide balanced or single-ended input. For the set-up, only the single-ended mode was utilized. The remainder of the settings used during experimentation can be found in Table 4-2 in section 4.8.

Once the signal is amplified, it goes to the oscilloscope. The digitizing oscilloscope continuously acquires and retains enough sample points to fill the pretrigger portion of the waveform record (the part of the waveform that is displayed before the triggering event) [38]. The main purpose of the oscilloscope is to perform the analogue-to-digital (A/D) conversion of the input signal. It uses what is referred to as High Resolution (Hi Res) acquisition mode. Hi Res is based on a
technique called interval averaging with decimation [39]. Basically the A/D converter runs continuously at its maximum sample rate. A high speed processor computes a real time average of all points acquired within a sample interval to create a point-averaged result. This acquisition mode enables 16-bit acquisition memory. The drawback of using the oscilloscope as A/D converter is that acquisition samples are limited to 15000. Concretely, this means that when 512 points are acquired for each record, less than 300 records can be obtained. If more than 300 records are taken on a scan line, the scan must temporarily stop to allow data to be downloaded to the computer hard drive before resuming its course.

Hi Res acquisition mode does not preclude aliasing to occur as the sampling rate is set via MPIS. Hence, there is a requirement to determine the adequate sampling rate for a given transient response. A higher sampling rate gives more data points per unit of time and therefore produces improved accuracy in representing the original signal. A rule of thumb is to have a sampling rate which is at least twice the highest frequency measured. Libby [18] refers to work carried out by Shannon who had shown that a band-limited signal having frequencies from 0 to W can be specified by 2TW points, where T is the zero frequency term. Thus, to fully describe a band-limited signal having a bandwidth W, it is sufficient to sample the signal at least 2W times/second, using equally spaced sampling intervals. In other words, when the sampling points are equally spaced, they should be 1/(2W) seconds apart or less. In our case, the bandwidth of the broadband transient response is limited by the preamplifier filters to 100 kHz. Therefore, the sampling interval should be 5 μs or less, i.e. a sampling frequency of 200 kHz. To be on the safe side, the sampling frequency selected was 500 kHz.

4.6 Signal Display

The signal display is the real link between the test equipment and its intended purpose, i.e. detection and identification of corrosion. The signal display software package used was ARIUS IV developed by Tektrend International Inc.. It is an advanced imaging and image enhancement software which provides some capabilities for data interpretation. ARIUS IV can image defects with a limited number of features such as maximum peak and time to the first peak, but also allows time gating and setting of any gate offsets. It uses the Windows operating systems and graphical user interface with some of its own interface features.
4.7 Materials Handling

The inspection of the entire test object is best accomplished with the help of a scanning system. For the experimental set-up, the test sample is stationary and a scanning system changes the position of the transducer to cover the surface of the test sample. The scanning system is a PC-based motion system which consists of hardware and software designed to control servo motors [40]. Servo-motors have the advantage of smoother low speed operation compared to stepper motors. However, they lack the positioning precision of their counterpart for very small movements. This lack of positioning precision is due to the fact that servo-motors use encoder feedback device and control loop algorithms to reach a desired position or velocity. The operation of the scanning system is controlled by commands from the central computer which are sent to the robot controller. Inserted in the controller is a bus motion board that generates control signals and receives feedback and I/O input signals. These control signals are passed through external amplifiers which act as a voltage to current amplifier for the servo-motor. Given a current, a servo-motor would turn indefinitely without stopping. Feedback devices are therefore required to return information about the motor's position, velocity and direction to the motion.

There are certain parameters that can be set when a scan is performed, specifically, the scanning and index axes, the dimension of the area to be scanned and the scanning speed. The latter is of particular interest for nondestructive inspection. Variations in scanning speed might cause fluctuations in the output signals. In these situations, the scanning rate must be held constant [18]. This situation was encountered when using the Hall effect detector as a sensing device. Specifically, because of the limitation in the number of points captured by the oscilloscope (15000 points), numerous stops would occur for a particular scan line. A constant speed was not an option for this set-up; however, to alleviate the problem, a very slow scanning speed was selected and it minimized the fluctuation in readings.
4.8 Instrumentation Settings

The following Table details the settings associated with the various instruments for the experimental set-up described in this chapter. There are three set of settings provided, one for each type of transducer used in this thesis.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Controls</th>
<th>Settings Single Coil</th>
<th>Settings Driver-Pickup Coils</th>
<th>Settings Single with Hall effect detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Generator</td>
<td>Pulse Position (ns) &quot;delayed&quot;</td>
<td>10.0 ± 2.5</td>
<td>10.0 ± 2.5</td>
<td>10.0 ± 2.5</td>
</tr>
<tr>
<td></td>
<td>Width (ms)</td>
<td>0.525 ± 0.025</td>
<td>5.25 ± 0.25</td>
<td>0.525 ± 0.025</td>
</tr>
<tr>
<td></td>
<td>Amplitude (V)</td>
<td>3.000 ± 0.125</td>
<td>3.000 ± 0.125</td>
<td>9.00 ± 0.25</td>
</tr>
<tr>
<td></td>
<td>Polarity</td>
<td>Positive</td>
<td>Positive</td>
<td>Positive</td>
</tr>
<tr>
<td>Preamplifier</td>
<td>Gain</td>
<td>100</td>
<td>500</td>
<td>50†</td>
</tr>
<tr>
<td></td>
<td>LF roll-off (Hz)</td>
<td>0.03</td>
<td>DC</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>HF roll-off (kHz)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Input</td>
<td>DC</td>
<td>DC</td>
<td>AC</td>
</tr>
<tr>
<td>Switch Box</td>
<td>Output Resistance (Ω)</td>
<td>1 ± 10%</td>
<td>1 ± 10%</td>
<td>1 ± 10%</td>
</tr>
<tr>
<td></td>
<td>Switch 1</td>
<td>Coil A</td>
<td>Coil A</td>
<td>Coil A</td>
</tr>
<tr>
<td></td>
<td>Switch 2</td>
<td>Single</td>
<td>Driver-Pickup</td>
<td>Single</td>
</tr>
<tr>
<td>MPIS</td>
<td>Robot Speed (mm/s)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Sampling Rate (kHz)</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Offset (points)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Length (points)</td>
<td>512</td>
<td>256</td>
<td>512</td>
</tr>
</tbody>
</table>

† Preamplifier settings for Hall effect detector output signal

Table 4-2
Settings for Pulsed Eddy-Current Data Acquisition
Chapter 5

TRANSDUCER DESIGN

5.1 Introduction

The construction of eddy-current transducers takes into account many parameters including the coil(s) (e.g. shape, cross-section, wire size, configuration), the type of sensor (e.g., coil(s), Hall effect detector, etc.), and sources. All of these parameters can be manipulated by the designer to produce a particular transducer, suitable for a specific application or range of applications [19].

Experimental design of an eddy-current transducer, or pulsed eddy-current transducer for that matter, is not a clear cut, definable procedure, but rather a multitude of methods and interactions. The basic design tools for these variations are based on the following principal parameters:

a. coil inductance
b. coil resistance
c. field distribution in space
d. coil response to relevant material property changes
e. lift-off characteristics
f. response to simulated discontinuity

However, these parameters may call for opposite design considerations. Hence, the design should be flexible and based on an iterative process. Some of these design tools were utilized in this thesis for manufacturing a transducer with a Hall effect detector which was done in collaboration with the Applied Magnetics Group at Queen’s University. Manufacturing this transducer was necessary since none was available at the RMC or other Canadian Forces research establishments.

5.2 Design Considerations

As a stepping stone in the design of the experimental transducer, the coil characteristics used are those provided by Captain Lepine, Air Vehicle Research Detachment. The coil dimensions are:

Coil’s inside diameter ($D_i$) = 6.6 mm  
Coil’s outside diameter ($D_o$) = 13.7 - 13.9 mm  
Coil’s length = 0.635 - 0.685 mm  
Number of turns = 400  
Wire diameter = 41 AWG  
$R_{dc} = 62.8 \, \Omega$  
$L (1 \, kHz) = 1.7 \, mH$

Figure 5-1  
Coil Dimensions
5.2.1 Coil's Inside Diameter (Dₐ)

The coil Dₐ selected is 6.6 mm. This dimension is somewhat restricting as a minimum of 5 mm is required for the installation of the Hall effect detector having the dimensions shown in figure 5-2.

![Diagram](image)

Figure 5-2
Hall Effect Detector Dimensions

5.2.2 Coil's Outside Diameter (Dₜ)

To determine the coil's outside diameter, it is necessary to select a wire gauge, the coil's length and the number of turns. The wire gauge selected was 40 AWG. The related specifications for this wire size can be found in Engineering Handbooks. In some of these, e.g. [41], the diameter provided is for the bare wire and does not include the insulation thickness. This may lead to miscalculation in the coil's outside diameter. Hence, Table 5-1 was compiled from [41, 42] and provides the dimensions of various wires with their respective resistance at 25°C. Where needed, the data in this Table were temperature corrected [19].
Since the number of turns was set to 400, the only remaining parameter to determine is the coil's length. This dimension directly influences the outer diameter for a given number of turns. The length chosen for the transducer design was 0.685 mm. With this last dimension, it is now possible to determine the outer diameter of the coil.

Reference [42] provides guidelines to account for embedding of wires. It states that from 5 to 10 percent (depending on the thickness of the insulation relative to the wire diameter) more layers can be wound in a given space due to the natural tendency of the wire of a layer to fall into the grooves between the wires of a lower layer. However, when computing the number of turns per layer, a deduction of 5 to 10 percent in the computed turns per layer must be made to allow for the fact that the wires will not lie exactly close to each other as assumed; a further deduction of one turn per layer must be made to allow for the space lost at the ends of a layer.

For 40 AWG, the wire diameter including the insulation is 0.09144 mm. Given the length of the coil to be 0.685 mm, there will be 7 turns per layer. Subtracting one turn per layer to allow for space lost at the ends during winding, the design will be such that there will be 6 turns per layer. Since the coil will have 400 turns, this will translate in 66 layers and 4 turns. With this information, it is possible to determine the coil's outside diameter ($D_o$). It is found by adding the coil's inside diameter to the result of the following relation [42]:

\[ \text{Thickness} = \text{No of layers} \times \text{wire diameters/layers} \times \text{wire diameter} \times \text{winding inefficiencies} \]  

(5-1)
Chapter 5  Transducer Design

For the design, $D_o$ will be:

$$D_o = 6.6 \text{ mm} + (67 \text{ layers} \times 2 \text{ diameter/layer} \times 0.09144 \text{ mm} \times 1.1) = 20.08 \text{ mm}$$

5.2.3 Inductance and Resistance

As previously indicated, the role of the test coil is very important in eddy-current testing. For single coils, it is by measuring the probe resistance and inductance that the "condition" of the test object can be determined. It is, however, necessary to know the characteristics of the probe in air. This value will help in determining if the manufactured coil operates according to its designed values.

The coil being designed is a short coil since the length to diameter ratio is less than 10 (i.e., $0.685 \text{ mm} / 6.6 \text{ mm} = 0.1$). For short coils, end effects will reduce the inductance because of lower flux at the coil ends. An approximate equation is available to calculate inductance [14]:

$$L_o = 4\pi\mu_r\bar{r}N^2(\ln \left(\frac{8\bar{r}}{K}\right) - 2) \times 10^{-10} \quad (5-2)$$

where

- $\mu_r =$ relative permeability of the core
- $\bar{r} =$ mean coil radius $= (D_o + D_i) / 4$ [mm]
- $N =$ number of turns
- $K = 0.112 \times (2 \times \text{length} + D_o + D_i)$ [mm]

Hence,

$$\bar{r} = \frac{(D_o + D_i)}{4}$$
$$= \frac{(20.08 + 6.6)}{4}$$
$$= 6.67 \text{ mm}$$

$$K = 0.112 \times (2 \times \text{length} + D_o + D_i)$$
$$= 0.112 \times (2 \times 0.685 + 20.08 + 6.6)$$
$$= 3.142 \text{ mm}$$

$$L_o = 4\pi(1.0)(6.67)(400)^2(\ln (\frac{8 \times 6.67}{3.142}) - 2) \times 10^{-10}$$
$$= 1.12 \text{ mH}$$

The calculation of the coil's resistance is quite simple once the length of wire required for the design is known. Effectively, if $D_i$, the coil's length and the number of turns is known, one can calculate the length of wire required to build the coil. The considerations that must be taken for calculations are the variation of the wire loop diameter with each layer, and also the winding
inefficiencies. With the help of a small program, the value of the coil's resistance can be easily determined. However, there is a simpler means to find it. It can simply be approximated by the following relation [42]:

\[
R = P_m \cdot N \cdot R_i
\]  

(5-3)

where \( P_m \) is the perimeter of the mean turn
\( N \) is the number of turns on the coil
\( R_i \) is the resistance of the wire per length

\[
P_m = \pi \left( 6.6 + 20.08 \right) / 2
= 41.91 \text{ mm}
= 41.91 \times 10^{-3} \text{ m}
\]

\[N = 400 \text{ turns}
\]

\[
R_i = 3510.50 \Omega / \text{km}
= 3.51050 \Omega / \text{m}
\]

\[
R = 41.91 \times 10^{-3} \times 400 \times 3.51050
= 58.85 \Omega
\]

5.2.4 Resonance Frequency

As detailed in Chapter 2, the coil/sample system can be expressed as a series electrical circuit. Building on this premise, it is possible to determine the resonance frequency. Specifically, for a series RLC circuit, the expression for the effective current flow caused by a sinusoidal excitation is given by [43]

\[
\tilde{I} = \frac{\tilde{V}}{R + j \left( \omega L - \frac{1}{\omega C} \right)}
\]  

(5-4)

At resonance,

\[
\omega_o L = \frac{1}{\omega_o C}
\]
Chapter 5  Transducer Design

$$\omega_o = \sqrt{\frac{1}{L C}}$$  \hspace{1cm} (5-5)

The value of resonance frequency for the experimental transducer can be calculated from equation (5-5) by substituting in the values of inductance and capacitance. The value of capacitance will be taken as being 50 nF as it is a proper order of magnitude for coaxial cable that will be used for the transducer (or probe assembly). Therefore,

$$\omega_o = \sqrt{\frac{1}{1.12 \ mH \times 50 \ nF}}$$

The result is $\omega_o = 133.63 \times 10^3 \text{ rad/sec}$ or $f_o = 21.27 \text{ kHz}$.

5.2.5 Frequency Bandwidth

For a series RLC circuit, the bandwidth is defined as the range of frequencies for which the power delivered to R is greater or equal to the power dissipated in the resonant circuit [43]. The two limit frequencies, on each side of $f_o$, are designated as the upper ($f_1$) and the lower ($f_2$) half-power frequencies. Hence,

at $f_o$ \hspace{1cm} $P_o = I_o^2 R$

at $f_1$ \hspace{1cm} $P_1 = \frac{1}{2}P_o$

at $f_2$ \hspace{1cm} $P_2 = \frac{1}{2}P_o$

Therefore,

$I_1^2 R_T = \frac{1}{2} I_o^2 R_T$ \hspace{1cm} and \hspace{1cm} $I_2^2 R_T = \frac{1}{2} I_o^2 R_T$

Note: $R_T$ stands for the total resistance in the circuit

These two relations can be rearranged to yield:

$$\frac{I_{1,2}}{I_o} = \frac{1}{\sqrt{2}} = \frac{V / Z_{1,2}}{V / Z_o}$$

$$\frac{1}{\sqrt{2}} = \frac{V / \sqrt{R_T^2 + X_{1,2}^2}}{V / \sqrt{R_T^2}}$$

5 - 6
If both sides of above relation are squared,

\[
\frac{1}{2} = \frac{R_T^2}{R_T^2 + X_{1,2}^2}
\]

The solution for this particular relation is \( X_{1,2} = \pm R_T \). Thus, at \( f_2 \), the circuit appears inductive (phase angle at -45°) while at \( f_1 \), the net reactance is capacitive and the current leads the voltage by 45°. In other words,

\[
X_{1,2} = \omega_{1,2} L - \frac{1}{\omega_{1,2} C} = \pm R_T
\]

Rewriting in another form,

\[
L C \omega_{1,2}^2 \pm R_T C \omega_{1,2} - 1 = 0
\]

The form of this equation is analogous to \( ax^2 + bx + c = 0 \) whose solution is:

\[
x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}
\]

Hence,

\[
\omega_{1,2} = \frac{\pm R_T C \pm \sqrt{R_T^2 C^2 + 4LC}}{2LC}
\]

Only one of these roots is physically possible. Therefore, the negative frequency can be discarded and

\[
\omega_{1,2} = \frac{\pm R_T C + \sqrt{R_T^2 C^2 + 4LC}}{2LC}
\]

(5-6)
Chapter 5 Transducer Design

It is possible to find the value of the bandwidth with equation (5-6) by subtracting $\omega_1$ from $\omega_2$. Thus,

$$\Delta \omega = \frac{R_T}{L} \quad (5-7)$$

By substituting the values of resistance, inductance and capacitance, it is possible to determine the lower and upper frequency as well as the bandwidth of the coil. The results are:

$$f_1 = 17.50 \text{ kHz} \quad f_2 = 25.86 \text{ kHz} \quad \text{Bandwidth} = 8.36 \text{ kHz}$$

5.2.6 Lift-off

Eddy-current test sensitivity to material properties is greatest when the eddy-current resistance losses are maximized. For inspection purposes, the maximum probe sensitivity is attained when the coil is in direct contact with the flat surface of a nonmagnetic test material. If lift-off is introduced, only a portion of the lines of force can reach the test material. The portion of the flux lines that do not contact the metal sheet constitute useless magnetic leakage flux because they do not produce an eddy-current reaction in the test material. As lift-off is increased, the magnitude of the test signal variation diminishes which leads to a decrease in the eddy-current test sensitivity. For any design, it is generally considered that an acceptable limit for probe lift-off distance is one tenth of the coil diameter [19]. Because of machining constraints, the lift-off of the experimental probe is 2.00 ± 0.25 mm.

5.3 Winding Process

The apparatus used for winding the coil is owned by the Applied Magnetics Group at Queen's University. It is an assembly driven by a sewing machine motor which is connected to a drill clutch mounted on an axle via pulleys and belt. This axle has a counter which keeps track of the number of turns wound. This set-up was found to be adequate for the job. The difficulties experienced with the set-up was that the winding speed was hard to control and the belt/pulley combination was not the best as the belt was too large for one of the pulley which led to more difficulties in controlling the winding rate. The solution adopted was to wind the coil with this apparatus, but control the winding speed manually.

The first observation made was that the coil exceeded the dimension of the coil holder. Initially, this was thought to be caused by winding inefficiencies, but was later found to be due to the insulation thickness which was not accounted in the initial design. The most common form of insulation for the smaller sizes (smaller than no.28) of magnet wire is enamel [42]. This material is thin, hard, tough and inert to many chemicals. It is also so elastic that the insulated wire may be stretched and bent without causing the enamel to crack or separate from the wire.
5.4 Testing / Results

Two coils were manufactured to provide the ability to carry out differential measurement (or dynamic balancing) in future research. For this thesis, only one of the manufactured coil was installed with a Hall effect detector and used to capture transient responses. In any case, it is considered important to validate the design for no other reason than to understand the characteristics of the coils better. This validation is achieved by taking various measurements with the set-up described in Annex A. Table 5-2 provides an overview of the results as well as a comparison between the theoretical and the experimental values associated with the coil.

<table>
<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Coil 1</th>
<th>Coil 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside Diameter (D₀)</td>
<td>6.6 mm</td>
<td>6.900 ± 0.005 mm</td>
<td>7.700 ± 0.005 mm</td>
</tr>
<tr>
<td>Length</td>
<td>0.685 mm</td>
<td>0.730 ± 0.005 mm</td>
<td>0.650 ± 0.005 mm</td>
</tr>
<tr>
<td>Lₘₚ</td>
<td>58.85 Ω</td>
<td>59.330 ± 0.005 Ω</td>
<td>58.540 ± 0.005 Ω</td>
</tr>
<tr>
<td>Resistance at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resonance (R)</td>
<td></td>
<td>66.90 ± 0.05 Ω</td>
<td>64.40 ± 0.05 Ω</td>
</tr>
<tr>
<td>Inductance (Lₘₚ)</td>
<td>1.12 mH</td>
<td>2.1360 ± 0.0005 mH</td>
<td>2.1320 ± 0.0005 mH</td>
</tr>
<tr>
<td>Capacitance (C)</td>
<td>50 nF †</td>
<td>57.250 ± 0.005 nF</td>
<td>53.290 ± 0.005 nF</td>
</tr>
<tr>
<td>Quality Factor (Q)</td>
<td>2.56</td>
<td>2.90 ± 0.05</td>
<td>3.10 ± 0.05</td>
</tr>
<tr>
<td>Resonance Frequency</td>
<td>21.27 kHz</td>
<td>14.3940 ± 0.0005 kHz</td>
<td>14.9310 ± 0.0005 kHz</td>
</tr>
<tr>
<td>(fₗₘₚ)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† ROM value for Coaxial Cable Capacitance

Table 5-2
Comparison between Theoretical Values and Experimental Measurements

5.4.1 Coil Dimension Analysis

At this point, the coil was designed without an assessment of its effectiveness at detecting defects located at various depths. As indicated by Van Drunen and Cecco [44] for surface probes, it is the coil diameter D₀ which largely controls penetration. They estimate that the magnetic field in a thick material under a surface probe penetrates to a depth of approximately D₀ / 4.
The theoretical coil diameter is 20.08 mm. This means that the magnetic field would penetrate to a depth of approximately 5.02 mm in a thick material. Considering that the test sample overall thickness is 2 mm, the penetration of the magnetic field in the test material is not an issue that will preclude detection of corrosion or loss of material.

Increasing the coil diameter to increase penetration has certain drawbacks. As diameter is increased, sensitivity to short defects decreases because the ratio of defect volume to inspected volume becomes smaller. Ultimately, there is a point where a further increase in coil diameter would result in significant surface and subsurface defects remaining undetected. This issue is clearly dependent on the minimum size defect to be found by a given inspection technique using a single coil for transducer. However, for the experimental transducer being designed, a Hall effect detector is used as sensing device. The use of the Hall effect detector will greatly improve sensitivity to small defects.

5.5 Hall Effect Detector

The Hall element is a magnetic field sensor and it includes a monolithic Hall cell, a linear amplifier, an emitter follower output and a voltage regulator as schematically shown in Figure 5-3. The sensed magnetic field can be either positive or negative. To avoid the requirement for plus and minus power supplies, a fixed offset is introduced into the differential amplifier [45]. The bias appears on the output when no magnetic field is present and is referred to as a null voltage. When a positive magnetic field is sensed, the output increases above the null voltage. Conversely, when a negative magnetic field is sensed, the output decreases below the null voltage, but remains positive. The output voltage is proportional to the magnetic field input.

![Functional Block Diagram](image-url)
For analog output Hall effect detectors, the transfer function expresses the relationship between a magnetic field input (gauss) and a voltage output. The transfer function for the Hall effect detector integrated in the transducer is shown in Figure 5-4.

![Figure 5-4](image-url)

**Figure 5-4**
Output Voltage as a Function of Magnetic Flux Density from [46]

The overall transfer function for a linear output sensor describes its output for a given input value. In Figure 5-4, the sensor’s input is on the abscissa and the output, on the ordinate. Since the transfer function is linear, it is described by its slope and the point where it crosses the Y-axis. This graphical representation of a linear transfer function can be stated as a mathematical equation where \( y \) represents the magnetic field input in gauss and \( x \) the output in volts:

\[
y = mx + b
\]

(5-8)

It is generally considered that the transfer function is characterized by sensitivity, null offset and span. From the previous description, the slope \( m \) is the sensitivity and the bias \( b \) is the null offset. The span defines the output range of the Hall effect detector. This parameter is necessary because the sensor will saturate outside this range. In order to include this parameter, equation 5-8 should be written as:

\[
y = mx + b \quad \text{for} \quad x_{\text{min}} < x < x_{\text{max}}
\]

(5-9)
Chapter 5  Transducer Design

Linearity is always an approximation. No device or circuit is absolutely linear. However, by limiting the input range to a region where the curve can be approximated by a straight line, linear transfer functions may be used.

5.5.1 Interfacing the Hall Effect Detector

When interfacing with analog output sensors, it is important to consider the effect of the load. The load must 1) provide a path to ground; and 2) limit the current through the output transistor to the rated output current for all operating conditions. Figure 5-5 illustrates a typical load configuration. The parallel combination of the pull-down resistor (R) and the load resistance (R_L) must be greater than the minimum load resistance which the sensor can drive. This resistance should be selected so that the current rating of the analog output sensor is not exceeded. For the transducer being designed, the current rating is 4 mA [46].

![Figure 5-5](image)

**Figure 5-5**
Hall Effect Detector Interfacing

To determine the value of the resistance (R), it is necessary to determine the output voltage. From Figure 5-4, one finds that the linearity of the output voltage is best when it ranges from +2.6 to +4.6 V. For design purpose, the output voltage was assumed to be 3.6 V. With this value, it is possible to determine the resistance as R_L. Specifically, the output voltage of the Hall effect detector goes to the preamplifier and this instrument has an input resistance of 100 MΩ. Solving for this simple parallel circuit, it is concluded that any resistance greater than 900 Ω would ensure an output current less than the rated maximum. The value selected for the set-up was 1500 Ω.
The other aspect that must be considered deals with input voltage and input current. The rated maximums are 12 V and 20 mA, respectively [46]. As seen from Figure 5-6, it is when the input voltage reaches 12 volts that the Hall effect detector attains the best sensitivity. The power supply used enabled the control of the voltage and the current. However, it was impossible to reach 12 volts without exceeding the rated maximum current. At this voltage, the output voltage exceeded the linear region. Rather than designing a circuit to control or limit the current in the Hall effect detector, it was decided to sacrifice the sensor sensitivity and select an input current of approximately 15 ± 2.5 mA. The settings selected for the pulsed eddy-current testing with the transducer using the Hall effect detector as sensor were:

- Operating Voltage ($V_{cc}$) 7.29 ± 0.005 V
- Output Voltage ($V_{out}$) 3.862 ± 0.0005 V
- Supply Current ($I_{cc}$) 15 ± 2.5 mA
- Resistance (R) 1.5 kΩ

Note: The field generated by the coil with a 9V square pulse excitation creates a field which increases the Hall effect detector output voltage by 100 mV. This being the case, the Hall effect detector operates in the linear region.
Chapter 5 Transducer Design

The last issue to be addressed deals with noise. The Hall effect detector specification [46] details that it yields a flat response up to 25 kHz. Frequencies above this level will introduce noise in the data. Using a high-pass filter to cut-off frequencies above 25 kHz is an option. However, it was not pursued because information pertaining to the test object conditions would be lost. This disadvantage outweighed any perceived benefit. Other than frequency, another source of noise is related to the transducer. When the coil is driven by a current, a small amount of heat is generated in the coil. The effect is obviously dependent on the thermal conductivity of the environment; nonetheless, it could result in a slight elevation of the transducer's temperature. The difference in heat loss between the transducer in air and in contact with a metallic specimen can change the temperature, and hence the sensitivity of the Hall effect detector. Specifically, the change in temperature leads to spurious variations in the transient signals which can limit the effectiveness of the method. This issue was not addressed, but is recognized as a possible source of noise.

5.6 Shielding Selection

The last element included in the transducer's design is a shield. It is installed around the perimeter of the transducer, leaving both ends uncovered. The shield's only purpose is to focus the field. The problem to be solved consists in determining whether the shield used for the transducer will be effective. The first issue to be addressed is the selection of the material used for shielding. The second issue is to determine the frequency (ies) of interest. With this information, it will be possible to assess the effectiveness of the shield.

5.6.1 Material

There is no known material that blocks magnetic fields. Magnetic shielding is essentially achieved by diverting the magnetic flux to the shielding material. For eddy-current applications, the shield's materials generally used have a high permeability and low conductivity [19]. However, other design considerations must also be taken into account. Specifically, it is advantageous to use a high permeability alloy with the crystalline anisotropy (K) and the magnetostriction (\(\lambda\)) equal to zero.

a. Positive K means the easy axes of magnetization are the cube edges, negative K means the easy axes are the cube body diagonals, and zero K means the material is isotropic, having no preferred easy (or hard) axes. Hence, the fact that \(K = 0\) means that in the absence of external "orientation" magnetic fields, the coercive force can be very low \((H_c < 1 \text{ Oe})\) and the permeability very high \((\mu > 1000)\) [47].

b. On the other hand, magnetostriction is the phenomenon in which a magnetic material changes its size depending on its state of magnetization. Thus, a magnetized specimen with positive magnetostriction is partially demagnetized by
Chapter 5  Transducer Design

the application of compressive stress. With negative magnetostriction, tensile stress is required to reduce the magnetization. Hence, the shield's material should have a magnetostrictive coefficient \( \lambda \) that passes through zero. This way, no change in the magnetization should occur due to tensile stresses in the shield caused by the thermal expansion (itself produced by the IR heating) of the copper coil.

The requirement of \( K = 0 \) and \( \lambda = 0 \) cannot be obtained in binary nickel-iron alloys (\( K = 0 \) for 75% nickel, \( \lambda_s = 0 \) for 81% nickel). To meet this requirement with the same composition, elements such as molybdenum, copper and chromium must be added [48]. Mumetal is one registered trade name for a high-permeability, magnetically "soft" alloy used for magnetic shielding which meets the \( K = \lambda = 0 \) condition. This type of shielding has desirable combinations of high initial permeability \( \mu_i \) and good ductility for forming into very thin strips. Hipernom, HyMu-80, Permalloy and other names refer to one of the two typical formulas for this alloy. Both include about 80% nickel and 15% iron, with the balance being copper, molybdenum or chromium, depending on the recipe being used.

5.6.2 Frequency and Effectiveness

Having selected the shield's material, the next problem to be solved is to determine whether the shielding used will be effective. First, it is necessary to find the highest frequency enabling the detection of a defect. This value can be found with the equation used to determine the skin depth, equation (2-21). Using this equation, it is found that the highest frequency that could detect the BOT defects is 250 kHz. For this frequency, and the corresponding shield's conductivity and relative permeability as found in [48], the shield can be considered a thin-metal (\( t/\delta << 1 \)) because the skin depth in the shield is 0.20 mm when its thickness (\( t \)) is \( 0.1625 \pm 0.0001 \) mm. At this high frequency, the shield would not be effective [48]. However, at low frequency, its effectiveness is greatly enhanced and it provides a focused field. The highest frequency calculated for the TOB defect is 128 kHz. For this frequency, the relative permeability of the shield is approximately 200. The skin depth is approximately 0.08 mm. This shield is not considered a thin-metal and absorption loss are more significant. Hence, the shield will focus the magnetic field inducing eddy-currents in the second plate.
Chapter 6

EXPERIMENTAL RESULTS AND DISCUSSION

6.1 Introduction

For conventional eddy-current techniques, a variation of coil-to-sample spacing results in a change in the coil's impedance. The effect is such that the scan of a test object with varying lift-off may lead to an inadequate assessment of material conditions. Hence, controlling probe lift-off is essential to attain reproducible test signals. The same applies to the pulsed eddy-current technique. However, based on the published research on pulsed eddy-current, the impact lift-off has on the transient response is barely documented by researchers. In fact, it is unclear whether it will be possible to determine positively the presence of a defect with variation in the lift-off distance. Also, the ability to determine the location of a defect independently of lift-off has not been addressed by researchers. These issues must be researched if the pulsed eddy-current technique is to become a mainstream application. To that end, experimental results were obtained with three types of transducers, namely a single coil probe, a driver-pickup probe, and a transducer using a Hall effect element as sensor. The transient responses obtained for each one are quite different and call for separate analysis. Hence, this chapter comprises three main sections, each dealing with the results for a particular type of transducer.

For each transducer, an analysis of the effects of lift-off on time domain transient responses from sample #1 is carried out using balanced transient responses. This representation makes it easier to visualize variations in the transient response due to the change of a given parameter and is also extensively used by other researchers. The first analysis carried out was designed to assess the ability of traditional features to characterize corrosion in the presence of lift-off. Then, time domain transient responses for various defect locations and lift-off distances are plotted into one graph. The intent is to highlight features that separate the material conditions under analysis. Conclusions drawn from the previous analysis is validated on the total transient responses of scans performed on sample #2.

6.2 Single Coil Transducer

The first type of transducer studied is the single coil. For this type of transducer, the maximum variation due to defects and lift-off is about two orders of magnitude smaller than the maximum amplitude. The use of single coil for pulsed eddy-current research is not very common. It is normally used for stationary measurements or measurements made on half-space conductors.
6.2.1 Analysis of Time Domain Response

The first analysis carried out was an analysis of the effect of lift-off on the time domain transient responses. Figure 6-1 shows a number of balanced transient responses associated with three different flaw locations and/or lift-off.

![Figure 6-1](image)

Figure 6-1
Composite Graph Showing the Effect of Lift-off on Balanced Transient Responses from Single Coil Transducer

The general shape of the balanced transient response, including the negative peak observed for most signals exhibited in Figure 6-1, is not a common feature described in literature dealing with pulsed eddy-currents. In fact, only one research [31] addresses negative peaks. It specifically dealt with the estimation of conductivity and thickness of a high conductivity material layered over a half-space substrate with a lower conductivity. The conclusions drawn from this research are not directly applicable to the sample and conditions associated with the research presented in this thesis.
As indicated in Chapter 3 (section 3.5), the expected signal shape comprises a positive peak followed by a zero crossing point. These two features are the cornerstone to the classification of defect locations. Nonetheless, the presence of a negative peak in data collected for a two-layer sample can be explained with the help of the impedance plane diagram. Starting with the negative slope observed at early times, this feature is applicable to changes in lift-off and to the presence of defects. In the first case, increasing the lift-off translates into an increase in normalized inductive reactance and a decrease in normalized resistance. The overall effect is an increase in the circuit’s time constant (L/R) i.e., a shallower ramp up. On the other hand, a decrease in sample thickness can be seen as an increase in sample resistance as expressed by equation (B-7). The impedance plane diagram confirms this conclusion, but also indicates that there would be an increase in inductance. Assuming this increase in inductance is more important than the increase in resistance, the overall effect would be a greater time constant for the equivalent circuit. In both cases, the circuit’s time constant increases. With the balancing process, this change in the time constant translates into a negative slope at early times. Hence, the reason for the presence of the negative slope can be partly justified with conventional eddy-current theory. As time goes on, the magnetic field penetrates more completely and the strength of the eddy-current reaches a maximum. This maximum is reached at different times for flawed and unflawed transient responses; this variation is likely due to the fact that flaws in the sample cause a higher resistance.

Figure 6-2
Lift-off Point of Intersection and its Ability to Positively Identify Defects Independently of Lift-off
To confirm the validity of the results obtained with the single coil transducer, a model was developed. The results are presented in Annex B. The model predicted the negative peak but also the lift-off point of intersection and the fact that all curves for material with defects would be below the subject lift-off point of intersection. Figure 6-2, which is an expanded view of Figure 6-1 at the lift-off point of intersection, clearly shows the separation between curves with lift-off and those with both lift-off and defects. The significance of this point is enormous. Since the lift-off value is almost zero at that point, it is possible to obtain an assessment of defects independently of lift-off.

To prove the point, a scan of sample # 2 was done with two different lift-off distances. The imaging of the scan results was done with the help of ARIUSTM using the total transient response rather than the reference balanced signal. It should yield the same results since the zero crossing on the reference balanced representation is simply a point where the transient response due to lift-off only and that of an unflawed sample with no lift-off have the same value. Therefore, for determining the presence of corrosion, a 4-μs gate was placed with an offset of 38 μs i.e., the time to lift-off point of intersection found from Figure 6-2. The scan results are shown in Figure 6-3. In this Figure, the red colored regions have the greatest amplitude and represent the lift-off. Alternatively, the yellow colored regions represent areas with loss of material. As expected, both scans show the presence of defects: the top portion represents a bottom of top plate defect and the bottom portion represents a top of bottom plate defect. These results confirm the validity of the lift-off point of intersection for the identification of loss of material.

![Figure 6-3](image)

Identification of Corroded Areas by Gating at Lift-off Point of Intersection
(Linear Color Scale: Red, 4.02 V; Yellow, 3.95 V)
Chapter 6  Experimental Results

The lift-off point of intersection does not provide any information about the defect location. To be able to determine defect location independently of lift-off, one must look at regions where the effect of lift-off is minimal or null. This condition is encountered for the tail region of the balanced transient signal. An inspection of this region, shown in Figure 6-4, reveals a layering of the signals for each defect location.

This observation can be explained by the fact that eddy-current decays to zero due to the electrical resistance of the sample. Since the same sample was used to collect all data, one could expect the same decay; however, this is not the case. The reason is that the plate thickness and defect locations will affect the resistance of the sample, or plate assembly. Specifically, the thinning of material causes an increased resistance to eddy-currents. Also, a constant size defect located at different locations in a two-plate assembly will cause a different resistance for each case. Going back to the equivalent series circuit of Chapter 2, a higher sample resistance would cause a decrease in current in the primary loop (i.e., the coil). The change of sample resistance explains the layering observed in the tail region of the balanced transient response, or alternatively in the transient response itself.

Figure 6-4
Tail Region of Transient Responses Showing Layering of Signals from Different Defect Locations
The verification of the validity of this observation is not very conclusive as shown by the scans carried out of sample #2 and presented in Figure 6-5. In this case, a 20-μs gate was selected with an offset of 1004 μs. From these Figures, it is almost impossible to discern the presence of the defect. This result can be explained by the fact that the variations looked at for this part of the transient response are three orders of magnitude smaller than the original signal captured. Noise is likely affecting the results tremendously. At this point, using the tail region of the single coil transient response is not considered a reliable means for the determination of corrosion location in a two-layer assembly.

![Figure 6-5](image_url)

Identification of Corrosion Location by Gating the Tail Region of Transient Response

(Exponential Color Scale: Red, 0.096 V; Blue, 0.072 V)
6.3 Driver-Pickup Transducer

The second type of transducer used in the context of this thesis is the driver-pickup transducer. The difference with the single coil is that excitation and sensing are carried out by two different coils having different characteristics. The analysis carried out for this transducer follows the same procedure as previously done for the single coil.

6.3.1 Analysis of Time Domain Response

The first two graphs (Figures 6-6 and 6-7) show balanced transient responses for various flaw locations but constant lift-off. The general shape of the balanced transient responses in these Figures correspond to what is found in literature. Specifically, a given size defect located in the first plate compared to the same size defect in the second plate has a greater peak amplitude and an earlier time to zero crossing. However, a comparison of both Figures reveals that lift-off strongly influences the magnitude of the transient response and the time to zero crossings. In effect, lift-off increases the amplitude and advances the occurrence of zero crossings. These variations can lead to misclassification of defects and/or false calls if lift-off is not considered in the data interpretation.

![Graph showing balanced transient responses](image)

Figure 6-6
Balanced Transient Responses for Various Defect Locations with No Lift-off
Chapter 6  Experimental Results

Figure 6-7
Balanced Transient Responses for Various Defect Locations with 0.006" Lift-off

To obtain a better appreciation of the influence of lift-off, the first verification carried out was to determine whether or not the presence of a defect could be positively identified via the traditional time to zero crossing method. To this end; transient responses for different defect locations and lift-off were plotted on a single graph. The results were that time to zero crossings for defects with various lift-off always occurred later in time than unflawed material affected by lift-off only. It is therefore possible to positively identify the loss of material due to corrosion from an examination of time to zero crossings. There is another means available to determine if there is material loss. A close examination of Figure 6-8 shows that the lift-off curves converge within a very short time region. In fact, it can almost be considered a single point that will also be referred to as the lift-off point of intersection. The location of this point is at 64 μs for the driver-pickup probe used in the experiment. All other curves representing defects with various lift-off also converge at this point, but the voltage value is greater. Hence, by determining the lift-off point of intersection, corrosion can be positively identified independently of lift-off by measuring the amplitude of the reference balanced signal at that point.
Figure 6-8
Composite Graph Showing the Effect of Lift-off on Balanced Transient Responses for Various Defect Locations

This conclusion is also applicable to the transient response since the only manipulation carried out was the subtraction of the reference signal. To validate the ability to positively identify corrosion location via the lift-off point of intersection, scans were made of sample #2. The first scan had no lift-off and the other had a 0.006" lift-off. With the help of ARIUSTM, a 2-μs gate was placed with an offset of 64 μs. The results, shown in Figure 6-9, clearly and accurately identify which areas have a loss of material independently of lift-off value. The gold colored region has the greatest amplitude and represents the defect area.
Having positively identified the presence of corrosion, the next step is to identify its location. The traditional means to determine defect location is the time to zero crossing. However, lift-off advances the zero crossing point and this means that it would occur over a range of time for the various defect locations. Experimental results obtained during this research work confirmed this and the following zero crossing ranges for the balanced transient responses shown in Figure 6-8 were found:

- Lift-off: 53 - 63 µs
- Bottom of Top defect: 75 - 95 µs
- Top of Bottom defect: 92 - 138 µs
- Bottom of Bottom defect: 96 - 146 µs

These results show an overlap between the various ranges. In effect, any transient response falling between 95 and 96 µs could be classified in any of the various defect locations. A better means of classifying a transient response to a particular defect location must be devised. As previously done for the single coil, one must look at the regions of the time domain response to determine portions which are not affected by lift-off. As for the single coil, the tail region of the response is also minimally affected by lift-off. Figure 6-10 provides a close-up view of that region and shows the same layering present in the single probe transient response.
Contrary to the verification done for the single probe, classifying the defect location from the information contained in the tail region of the signal seems possible with the driver-pickup transducer. The results of scans carried out of sample # 2 are presented in Figure 6-11. In this case, a 50-μs gate was selected with an offset of 462 μs. For both cases (i.e., with and without lift-off), it is possible to discern that the defects are located in two different layers. The red portion of the scan is the unflawed portion of the specimen. The bottom portion of the C-scans are top of bottom plate defects and the top portion of the C-scans are bottom of top plate defects. Both C-scans are not perfectly identical. The variation is likely due to noise since lift-off contribution is minimal. All considering, the tail region of the transient response yields some promise as a means to determine the location of a defect for driver-pickup transducers.

![Figure 6-10](image_url)

Figure 6-10
Tail Region of Transient Responses Showing Layering of Signals from Different Defect Locations
Chapter 6  Experimental Results

6.4 Transducer Using Hall Effect Detector as Sensor

The last transducer studied was the experimental transducer using a Hall effect detector. The first observation made when carrying out initial measurements was the fact that variations in scanning speed influenced the transient response, particularly its amplitude. This effect is likely caused by the lower frequency components of the transient response which propagate at slower rates through the material. Hence, variations in scanning speed precluded their inclusion in the measurements taken.

The limitation previously described applies only to the transducer with the Hall effect detector. The reason lies in the parameters being measured by the different types of sensors i.e., coil and Hall effect detector. For coils, the time rate of change of the magnetic flux is proportional to the test frequency. Consequently, the voltage induced in both the exciting coil and in pickup coil detectors is also proportional to the test frequency. Therefore, at very low test frequencies, the test signal amplitudes can be decreased to levels where signal-to-noise ratios are too low for reliable detection [19]. On the other hand, Hall effect detector signals are directly proportional to the actual magnitudes of the magnetic flux density and have uniform sensitivity over a wide frequency range. The variation of scanning speed is an undesirable variable that greatly impacts measurements made with a Hall effect detector. To minimize the effect, a very slow scanning speed of 1 mm/s was selected.
6.4.1 Analysis of Time Domain Response

The first analysis carried out was to focus on the effect of lift-off on the time domain transient responses. Figure 6-12 is a composite plot of balanced transient responses for various depth locations and lift-off distances. The general shape of these responses corresponds to what is found in literature. For each defect location, an increase in lift-off translates into an increased amplitude of the balanced transient response.

An interesting observation can be made from Figure 6-12 in that the output signal resulting from the leading edge of the square pulse is different than the output signal resulting from the trailing edge. The cause is likely related to the coupling between the coil and the Hall effect detector which produces a phenomenon of saturation or loss of sensitivity [20]. This phenomenon does not occur for the trailing edge of the square pulse and, as a result, the Hall effect detector measures a transient response which is representative only of the perturbation of eddy-current in the sample.
The location of defects is normally determined from the time to peak amplitude of the balanced transient response as was shown in Figure 6-13. The effect of lift-off on the balanced transient response is an increase in signal amplitude and an advance in time to peak amplitude. Therefore, a range of times to peak amplitude must be defined to allow determination of defect locations. The experimental results obtained during this research provided the following times to peak amplitude (associated with trailing edge of pulse) for the balanced transient responses shown in Figure 6-12:

- Lift-off: 538 – 568 μs
- Bottom of Top defect: 573 – 596 μs
- Top of Bottom defect: 627 – 656 μs
- Bottom of Bottom defect: 596 – 652 μs

These peaks are, in most cases, the second peak in a given edge (i.e., leading or trailing edge of the pulse) of the balanced transient response. Although some papers [4, 20] show the first peak, it is not a feature used by researchers to classify defects. By using the second trailing edge peak, a correct identification of defect location is possible; however, it should be pointed out that lift-off advances the peak location. At the limit, misclassification is likely to occur. An alternative method of separating defects from defect-free areas was proposed by Burke [35] as detailed in Chapter 3. Figures 6-13 through 6-16 were created using this method. In all cases, it was possible to determine the presence of defects (corrosion) independently of lift-off using the trailing edge portion of the signal i.e., 512 - 1000 μs.
Figure 6-13
Normalized Change in the Reflected Magnetic Field Due to Lift-off

Figure 6-14
Normalized Change in the Reflected Magnetic Field Due to Metal Loss at Bottom of Top Layer
Figure 6-15
Normalized Change in the Reflected Magnetic Field Due to Metal Loss at Top of Bottom Layer

The balanced transient response trailing edge also has a feature that allows determination of the
The balanced transient response trailing edge also has a feature that allows determination of the presence of defects. Specifically, lift-off signals and defect signals form two compact groupings as shown in Figure 6-17. This feature allows the determination of the presence of defects without the time to peak amplitude ranging required by the "conventional" method. The Figure also shows the characteristic layering of the defect signals associated with the location of the defects. These observations made with balanced transient responses are also applicable to transient responses since the only manipulation carried out was the subtraction of the reference signal. To confirm the validity of these observations, two scans were made of the verification sample. The first scan had no lift-off and the other had a 0.006" lift-off. With the help of ARIUS™, a 20-µs gate was placed with an offset of 800 µs. The results are presented in Figure 6-18. The C-scans clearly identify the areas with a loss of material. The red colored region has the greatest amplitude and represents the metal/lift-off area and the yellow colored region represents the flaw. The defect location is harder to ascertain from the C-scan. However, the B-scans identify a difference in amplitude for the top and bottom of the Figures that can be interpreted at defects located in different plates: the greatest horizontal amplitude corresponding to a bottom of top plate defect (1st plate); and the smaller peak at the bottom of the Figure corresponding to a defect in the top or bottom of bottom plate defect (2nd plate). These results are compatible with conclusions drawn from Figure 6-17.

It is important to look at the physical explanation of the two groupings and the layering. The effect of lift-off is limited to a 200-µs gate following the down pulse. In fact, the effect of lift-off can also be observed for the pulse (leading edge), but the noise blurs the exact effect of lift-off. Hence, for the down pulse, the effects of lift-off are limited to a certain time gate as is the case with the other transducer types. The possibility of detecting defects in the region unaffected by lift-off exists because the loss of material causes an increased resistance to eddy-currents. Hence, the induced field will be reduced compared to the field induced for an unflawed sample. This premise is also valid to determine the location of a defect in a plate assembly. After all, a loss of material corresponds to an increased resistance to eddy-currents, and eddy-current density decreases with depth. Therefore, one should expect the second grouping to be layered by defect locations as was the case for the other two types of transducers.
Figure 6-17
Tail Region of Transient Responses Showing Separation Between Lift-off only and Defects with Various Lift-off as well as Layering of Signals from Different Defect Locations
Figure 6-18
Identification of Corrosion and Corrosion Location by Gating the Tail Region of Transient Response
(Logarithmic Color Scale: Pink/Red, 0.24 V; Green/Yellow, 0.13 V)
6.5 Relative Ability of Transducers to Achieve the Thesis' Objectives

As stated in Chapter 4, section 4.4, the effect of modulation is not identical for all types of transducers. The experimental results of this thesis confirm this statement. The results also demonstrate that certain transducers achieved the objectives set for this thesis better than others. Table 6-1 provides a quick comparison of the overall results.

<table>
<thead>
<tr>
<th>Transducer Type</th>
<th>Positive Identification of Corrosion Location Independently of Lift-Off</th>
<th>Positive Identification of Corrosion Location Independently of Lift-Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Coil Transducer</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Driver-Pickup Transducer</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Transducer with Hall Effect Detector</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 6-1
Ability of the Transducers to Meet the Thesis' Objectives

For all of the different transducers, it is possible to determine the presence of corrosion independently of lift-off. When coils are used as sensor, the presence of corrosion can be determined via the lift-off point of intersection. On the other hand, the tail region of the transient response can be used in the case where Hall effect detectors are used as sensors.

The positive identification of corrosion location independently of lift-off is another matter. Not all of the transducers were capable to achieve this objective. In all cases, the characteristic used is the fact that the tail region of the transient response show a distinct layering that can be used for the determination of the corrosion location. However, this feature is not totally reliable. For coils, this particular region of the transient response is characterised by a low signal-to-noise ratio. This characteristic can preclude the determination of the corrosion location as was observed for the single coil transducer. Notwithstanding this result, it was found that good distinction between defect locations could be achieved with the driver-pickup transducer. The transducer using the Hall effect detector as sensor also enabled the determination of the corrosion location. Its capability was not clearly illustrated by the C-scan. However, the B-scan imaging
provided the indication of the relative amplitude of the signal for the bottom of top and top of bottom defects.

The Hall effect detector is possibly the best sensor for the determination of the defect location. Although the imaging may not be convincing, this conclusion is drawn on the fact that the signal measured are one order of magnitude greater than those of the single coil and driver-pickup transducer. Noise is therefore less of a factor for this type of sensor.
7.1 Conclusions

The pulsed eddy-current (PEC) technique holds the potential of becoming the primary means of detecting corrosion in multi-layer structures. Its broadband excitation and transient response enable the nondestructive inspection of such structures in a matter of seconds. However, it is still considered an experimental technique because there are some stumbling blocks that must be overcome before it finds acceptance as a field application. In particular, it is necessary to be able to interpret the transient response and distinguish between lift-off, defect locations and defect size when these effects occur simultaneously.

Time domain features have been extensively used to determine test object conditions. However, lift-off complicates the analysis of pulsed eddy-current transient responses. The traditional means used to determine the presence, the amount and the location of corrosion is affected by lift-off. Specifically, lift-off increases the balanced transient response peak amplitude, advances its location, and advances its time to zero crossing (where applicable). The overall effects are such that defect size and location cannot be adequately determined by these traditional features. For this reason, researchers recommend to keep a constant lift-off during inspection. However, in cases where lift-off varies slightly, one must know the effect of this variation on the inspection results or alternatively, develop means to eliminate lift-off contributions.

This thesis focused on the effects of lift-off. The objectives were to (1) assess the possibility of detecting the presence of corrosion independently of lift-off, and (2) determine corrosion location independently of lift-off. This first objective is possible with the use of traditional features. Specifically, it can be done by gating out lift-off zero crossings or alternatively, gating out lift-off maximum peak regions (depending on the type of transducer). However, there is an easier method. The loss of material due to corrosion can be assessed independently of lift-off by focusing on the regions of the time domain response where lift-off contributions are minimal when not zero. When coils are used as sensors, the lift-off point of intersection was found to be an excellent means of positively identifying corrosion independently of lift-off. For Hall effect detectors, the tail region of the transient response can be used for the same purpose.

Some degree of success was also achieved for the second objective i.e., determining the location of defects independently of lift-off. Experimental results show that portions of the time domain transient response not influenced by lift-off can be used for that purpose. In particular, the tail of the leading edge and trailing edge transient response exhibit a distinctive layering which could be useful in determining defect locations. However, the variation is so minimal that noise can
Conclusions and Recommendations

Thus far, most researchers in pulsed eddy-currents have not considered lift-off effects in their studies. However, lift-off is a fact of life and it will be encountered during field inspections. For example, in aircraft lap-splice inspection, lift-off might be caused by uneven paint thicknesses, uneven rivets, or simply pillowing between rivets. This thesis effectively bridged a gap. It demonstrated that lift-off affects the features traditionally used to determine the presence of corrosion and its location, but more importantly, it demonstrated the ability to determine the presence and location of corrosion independently of lift-off. This achievement gives a better prospect for field use of the pulsed eddy-current technique.

7.2 Recommendations

Research on pulsed eddy-currents should continue to be actively pursued at the RMC. This thesis looked at the effect of lift-off combined with various defect locations. Other parameters must also be looked at if this technique is to ultimately become a field application. Parameters such as varying gap, defect size, and plate thicknesses must be combined, and ways to demodulate their contribution must be studied in future research.

Future PEC research might lead to the conclusion that lift-off effects mask too much information and that not enough features are available to classify all parameters or conditions completely. If this is the case, it might be ultimately necessary to use means to try and completely eliminate the effect of lift-off. Alleviating the effect of lift-off could be done by using a transducer with differential configuration. Two sensing devices placed side-by-side should provide high sensitivity to localized variations but should also tend to cancel out the effect of lift-off, gradual material variations, or ambient temperature changes. This research would break new ground as no known research on pulsed eddy-current has been done with this type of transducer. On the other hand, PEC research might yield other conclusions. For example, pattern recognition might be a better means for the assessment of the test object conditions. Exploratory research done at the RMC in this field, using features from power and phase domains, yielded very promising results. Further research in this area would be beneficial as it would provide valuable knowledge to this field and enhance the understanding of the PEC transient response.

Research is also necessary to find a good means of generalizing the transient response being analyzed. Currently, changes in test conditions directly affect the shape of the transient response e.g., a change in voltage directly affects the amplitude of the transient response. The solution to this particular problem may lie in normalization i.e., dividing the transient response by the transient response of the transducer in air.
Data fusion, transducer design, and modeling are also issues that will, in due time, be addressed by PEC researchers. In fact, this "fringe" technique has a lot of potential and provides various research opportunities. More importantly, it has the potential to address a very real problem experienced by aircraft fleets around the world. In fact, PEC presents itself as a likely solution for the detection and quantitative assessment of corrosion in multi-layer structures. Developing the PEC technique to its full potential will possibly alleviate many airworthiness concerns associated with corrosion in aircraft structures.
Annex A

EXPERIMENTAL DETERMINATION OF COIL CHARACTERISTICS

A.1 Resonance Frequency and Bandwidth

To find the frequency range of the experimental coil, the circuit shown in Figure A-1 was constructed.

![Circuit diagram](image)

Figure A-1
Circuit to determine the frequency range

Via this circuit, it is possible to determine the ratio of $V_o/V_i$ for various frequencies. The highest value corresponds to the case where the circuit is at resonance. The half-power points can be easily determined by taking the root mean square of the peak value. Tables A-1 and A-2 present the data captured (i.e., $V_o/V_i$) and Figures A-2 and A-3 show the same data plotted. The latter representation clearly shows the frequency range (or bandwidth) of the experimental coils. Bandwidths of 4.65 to 56.7 kHz were found for coil 1 and 4.70 to 56.9 kHz for coil 2.
### Table A-1
Voltage Ratio at Various Frequencies for Coil 1

<table>
<thead>
<tr>
<th>Freq (kHz)</th>
<th>( V_i ) (V)</th>
<th>( V_o ) (mV)</th>
<th>( V_o / V_i ) (x10^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.883</td>
<td>0.87</td>
<td>0.87</td>
<td>185.74</td>
</tr>
<tr>
<td>4.597</td>
<td>1.07</td>
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<td>217.48</td>
</tr>
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<td>4.648</td>
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<td>1.08</td>
<td>219.42</td>
</tr>
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<td>4.741</td>
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</tr>
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<td>1.18</td>
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<td>255.20</td>
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<td>60.857</td>
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<td>1.57</td>
<td>210.88</td>
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</table>

\[
313.51 / \sqrt{2} = 221.69
\]

### Table A-2
Voltage Ratio at Various Frequencies for Coil 2

<table>
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<tr>
<th>Freq (kHz)</th>
<th>( V_i ) (V)</th>
<th>( V_o ) (mV)</th>
<th>( V_o / V_i ) (x10^3)</th>
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<td>4.163</td>
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</tr>
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<td>4.550</td>
<td>4.851</td>
<td>1.08</td>
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</tr>
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<tr>
<td>58.187</td>
<td>7.440</td>
<td>1.67</td>
<td>224.46</td>
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</table>

\[
317.11 / \sqrt{2} = 224.23
\]

Table A-1
Voltage Ratio at Various Frequencies for Coil 1

Table A-2
Voltage Ratio at Various Frequencies for Coil 2
Annex A  Experimental Determinination of Coil Characteristics

Figure A-2  Frequency Range for Experimental Coil 1

Figure A-3  Frequency Range for Experimental Coil 2
Annex A  Experimental Determination of Coil Characteristics

A.2 Determination of Resistance and Inductance

The coil’s resistance and inductance can be easily found with an Impedance Analyser. The particular instrument used was an HP model 4192A LF Impedance Analyser. It allows measurement of a wide range of impedance parameters including those of interest, namely coil resistance and inductance. The procedure to obtain the values is simple, but prerequisite data (i.e., resonance frequency) is necessary to find the particular coil characteristics. Hence, once the resonance frequency is set, values corresponding to resistance, inductance and quality factor can be read directly from the instrumentation. The data are presented in Table 5-2.
Annex B

MODELING THE TRANSIENT RESPONSE

B.1 Introduction

The typical arrangements of exciting coils and test materials used in eddy-current tests can be considered analogous to that of two-winding transformers with air cores. The transducer contains a test coil which, when placed on or close to a sample, can be considered as the primary winding of a transformer. The variation in the current caused by the voltage pulse creates a field which induces eddy-currents in the test sample which acts as a single secondary winding. Therefore, the test coil and test sample can be modeled as a transformer with multi-turn primary (coil) and single turn secondary (sample).

B.2 Transformer Theory

An electrical transformer can be described as two circuits coupled inductively, in which a change of current in one winding induces an electromotive force or voltage in a second winding (Figure B-1). If a time varying electric current is caused to flow through the coil known as the primary winding, a voltage will be induced in the other winding (secondary winding).

![Ideal Air Core Transformer Circuit](image)

Figure B-1
Ideal Air Core Transformer Circuit

The voltages induced in the secondary windings of the transformer are proportional to the time rate of change for flux linkage with the secondary windings. The flux linkage, in turn, results from magnetic field variations created by current variations in the primary windings. If coil 1 is excited by current from an external source, and so serves as the primary winding, the voltage induced in coil 2 is given by Faraday's law of induction:
Annex B  Modeling the Transient Response

\[ V_2 = M_{12} \frac{dI_1}{dt} = N_2 \frac{d\phi_{12}}{dt} \]

Alternatively, if coil 2 had been excited by current from an external source, a voltage would be induced in coil 1 as

\[ V_1 = M_{21} \frac{dI_2}{dt} = N_1 \frac{d\phi_{21}}{dt} \]

When the exciting coil flux fails to couple with the test material, a voltage of self-inductance is induced in the magnetizing coil. This component of test coil voltage carries no information concerning the properties of the test material, although it is responsive to the spacing between the test coil and the adjacent surface of the test material. Hence, a practical air core transformer involves two coil windings with resistances \( R_1 \) and \( R_2 \), and self-inductances (due to the leakage fields) \( L_1 \) and \( L_2 \) as shown in Figure B-2. Under these conditions, the total voltage that appears across the terminals of the windings is given by the sum of (1) the voltages induced by mutual inductance effects, (2) the voltage induced by self-inductance effects, and (3) the voltages resulting from flow of current through winding resistances. Figure B-2 provides a representation of the flux leakage concept. This Figure shows two coils in each loop instead of one in order to delineate clearly between mutual inductance and self-inductance.

\[ V_1 = M_{21} \frac{dI_2}{dt} + L_1 \frac{dI_1}{dt} + I_1 R_1 \]
\[ V_2 = M_{12} \frac{dI_1}{dt} + L_2 \frac{dI_2}{dt} + I_2 R_2 \]

Figure B-2
Practical Air Core Transformer Circuit

Under these conditions, the total voltages across the terminals of coil 1 and coil 2 can be written as:
B.3 Development of the Two-plate Model

For a two-plate model, the principles elaborated in the previous section are still applicable. The only difference is that the circuit comprises two transformers rather than one. The circuit can be represented as:

![Figure B-3](image)

Air Core Transformer Circuit for Single Coil and Two-plate sample

It is possible to write the loop equations. Equating sources to sinks yields:

\[ V_1 - L_1 \frac{d}{dt} i_1 - M \frac{d}{dt} i_2 = i_1 R_p \]  \hspace{1cm} (B-1)

\[ - M \frac{d}{dt} i_1 - L_2 \frac{d}{dt} i_2 - L_3 \frac{d}{dt} i_2 + M' \frac{d}{dt} i_3 = i_2 R_s \]  \hspace{1cm} (B-2)

\[ M' \frac{d}{dt} i_2 - L_4 \frac{d}{dt} i_3 = i_3 R_i \]  \hspace{1cm} (B-3)

It is possible to replace \( \frac{di}{dt} \) by \( \frac{\Delta i}{\Delta t} \) given that time intervals are small enough. Using backward difference, the three previous equations (B-1 through B-3) become
Annex B  Modeling the Transient Response

Equation (B-1)

\[ V_1 - \frac{L_1}{\Delta t} (i_{11} - i_{10}) - \frac{M}{\Delta t} (i_{21} - i_{20}) = i_{11} R_p \]

\[ i_{11} \left( R_p + \frac{L_1}{\Delta t} + \frac{M}{\Delta t} \right) + i_{21} \left( \frac{M}{\Delta t} \right) = V_1 + L_1 \frac{i_{10}}{\Delta t} + M \frac{i_{20}}{\Delta t} \quad \text{(B-4)} \]

Equation (B-2)

\[ -\frac{M}{\Delta t} (i_{11} - i_{10}) - \frac{L_2}{\Delta t} (i_{21} - i_{20}) - \frac{L_3}{\Delta t} (i_{21} - i_{20}) + \frac{M'}{\Delta t} (i_{31} - i_{30}) = i_{21} R_s \]

\[ i_{11} \left( \frac{M}{\Delta t} \right) + i_{21} \left( \frac{L_2}{\Delta t} + \frac{L_3}{\Delta t} + R_s \right) + i_{31} \left( -\frac{M'}{\Delta t} \right) = M \frac{i_{10}}{\Delta t} + (L_2 + L_3) \frac{i_{20}}{\Delta t} - M' \frac{i_{30}}{\Delta t} \quad \text{(B-5)} \]

Equation (B-3)

\[ \frac{M'}{\Delta t} (i_{21} - i_{20}) - \frac{L_4}{\Delta t} (i_{31} - i_{30}) = i_{31} R_t \]

\[ i_{21} \left( -\frac{M'}{\Delta t} \right) + i_{31} \left( \frac{L_4}{\Delta t} + R_t \right) = -M' \frac{i_{20}}{\Delta t} + L_4 \frac{i_{30}}{\Delta t} \quad \text{(B-6)} \]

The system of equations that must be solved is the following:

\[
\begin{bmatrix}
R_p + \frac{L_1}{\Delta t} + \frac{M}{\Delta t} & \frac{M}{\Delta t} & 0 \\
\frac{M}{\Delta t} & \frac{L_2}{\Delta t} + \frac{L_3}{\Delta t} + R_s & -\frac{M'}{\Delta t} \\
0 & -\frac{M'}{\Delta t} & \frac{L_4}{\Delta t} + R_t
\end{bmatrix}
\begin{bmatrix}
i_{11} \\
i_{21} \\
i_{31}
\end{bmatrix}
= \begin{bmatrix}
V_1 + L_1 \frac{i_{10}}{\Delta t} + M \frac{i_{20}}{\Delta t} \\
M' \frac{i_{10}}{\Delta t} + (L_2 + L_3) \frac{i_{20}}{\Delta t} - M' \frac{i_{30}}{\Delta t} \\
-M' \frac{i_{20}}{\Delta t} + L_4 \frac{i_{30}}{\Delta t}
\end{bmatrix}
\]

To solve this set of equations, it is first necessary to determine the values of the variables. The following will describe the way the values of the various variables are derived with accompanying assumptions where applicable.
Annex B  Modeling the Transient Response

$R_p$ and $L_1$ are the resistance and inductance of the coil and the theoretical value can be calculated as detailed in Chapter 5. $R_s$ and $R_t$ are the resistance of the given associated with the plates composing the sample. It is assumed that resistance of each plate in the assembly can be derived from the following equation [14]:

$$R_s = \frac{\rho l}{A} = \frac{\rho \pi D}{tw}$$  \hspace{1cm} (B-7)

where $\rho$ = electrical resistivity

l = eddy-current flow distance

A = cross-sectional area to current flow

D = probe diameter

w = coil width or length

t = plate thickness

Equation (B-7) is an approximation that essentially neglects the diffusion process. It is also possible to express this relation using the copper resistivity and %IACS. In doing so, equation (B-7) becomes:

$$R_s = \frac{\left(\frac{\rho_{cu}}{\%IACS}\right) \pi D}{tw}$$  \hspace{1cm} (B-8)

where $\rho_{cu} = 0.01724 \ \mu \Omega \cdot \text{cm}$

%IACS = conductivity value from 1 to 100

The mutual inductance ($M$) and the self-inductance ($L_2$) can be determined theoretically. Just as the self-inductance of a coil depends upon the number of turns, core material, wire size and other parameters, the mutual inductance between two coils depends upon their geometric configuration (proximity and orientation), permeability and individual inductance. The tightness of coupling between the two windings is defined by the coefficient of coupling, $k$. An ideal transformer has perfect coupling i.e., $k = 1$. It means that all of the magnetic flux from the primary coil is linked with the test sample. For eddy-current applications, all of the magnetic flux is not linked with the test sample. In this case, the coefficient of coupling can be determined by the following relation:

$$k = \frac{M}{\sqrt{L_1 L_2}}$$  \hspace{1cm} (B-9)
In the case where the primary and secondary coils are of the same dimension but are wound with a different number of turns, the relation (B-9) can be expressed as a function of the turns ratio [49]:

\[ k = \frac{N_1}{N_2} \sqrt{\frac{L_2}{L_1}} \]  

(B-10)

From equation (B-10), it is possible to determine the inductance of the secondary coil (L₂) if the coefficient of coupling is known. Once L₂ has been determined, the value of the mutual inductance (M) can be calculated.

The only variables that still need to be estimated are L₃, L₄ and M'. In fact, only one of these three variables needs to be derived. Specifically, if L₃ can be calculated, L₄ and M' can be derived in the same fashion that L₂ and M were previously derived i.e., the values will be determined by using a coupling factor coefficient, which accounts for the gap distance between the plates. The derivation of the value of L₃ is based on the calculated value of L₂. The first equation to be used is the relation defining the inductance of a coil:

\[ L = \frac{N \phi}{I} \]  

(B-11)

where \( \phi \) is the flux produced by the current I. This relation shows the inductance dependence on the flux. Building on this dependence, it is possible to use the relation derived for semi-infinite conductor which describes the exponential decrease in eddy-current density with depth

\[ \frac{J_x}{J_o} \propto e^{-x/\delta} \propto \frac{\phi_x}{\phi_o} \]  

(B-12)

Combining equations (B-11) and (B-12) yields:

\[ L_3 = L_2(e^{-t/\delta}) \]  

(B-13)
B.4 Results

To test the model, the single probe and the test sample characteristics were fed to the model. A comparison between the model's output and experimental results was carried out to determine the validity of the model and is shown in Figure B-4. A difference between the model and experimental results is present just below the knee of the transient response. This variation is caused by the fact that the experimental excitation voltage is not instantly going from zero to a given value as assumed in the model. The pulse generator generates an excitation pulse characterized by a quick rise time (\( \approx 50 \) ns), an overshoot (approximately twice the setting) and a region where the excitation voltage is almost flat (in reality, it is sawtoothed). By mapping the excitation voltage and feeding this information to the model, closer results would be achieved.

Figure B-4
Comparison of Theoretical and Experimental Transient Responses for Single Probe
The comparison between the model and experimental results is facilitated by using reference balanced transient responses. This approach was taken for Figure B-5. It shows the comparison of signals associated with changes in lift-off. At early times, the model adequately simulates the experimental response. An increase in lift-off increases the amplitude of the negative peak, but has no effect on the lift-off point of intersection.

![Graph showing comparison of theoretical and experimental balanced transient responses for varying lift-off](image)

Figure B-5
Comparison of Theoretical and Experimental Balanced Transient Responses for Varying Lift-off

Another feature observed experimentally is the fact that balanced transient responses with varying lift-off intersect each other below the lift-off point of intersection, thus providing a means to detect corrosion independently of lift-off. The model confirms the experimental observation as can be seen in Figure B-6.
The model has a deficiency for times after the lift-off point of intersection. This deficiency can be observed in Figure B-7. There might be a number of possible causes explaining this situation. The more plausible explanation is that one of the assumptions taken does not reflect adequately the physical phenomenon. In particular, equation B-12 may be the culprit. It was used to derive the values of inductances between the plates. This equation is adequate for a semi-infinite conductor, but may lead to inadequate prediction for a two-plate assembly. Compounded to this is the fact that lift-off may also affect the plate's resistance more than the model predicts it. As a result, the model does not predict the long time response adequately. Notwithstanding this deficiency in describing the long time transient response, the model gives the possibility of determining the lift-off point of intersection, and it also confirms some of the results obtained experimentally.
Figure B-7
Deficiency in Modeling Long Time Response
B.6 Computer Code

C*****************************************************************************
C PULSED EDDY CURRENT MODELING
C*****************************************************************************
C Author: Sylvain Giguere
C Use: Prediction of lift-off crossing point
C Date: 2 February 1999
C
C Abstract: The possibility of identifying corrosion independently of
C lift-off has been shown experimentally. It relies on the
C lift-off crossing point. The following program is a model
C based on transformer type circuit. It models two plates
C with excitation and detection carried out with a single
C coil. This model allows the simulation of defect at
C various location by identifying plate thickness and, where
C applicable, the change in coupling between plates.
C
C Language: WATFOR-77 September 90
C*****************************************************************************
C*****************************************************************************
C DECLARATION
C*****************************************************************************
C
DOUBLE PRECISION RP,L1,L2,L3,L4,RS,RT,V
DOUBLE PRECISION CC(3),TIME,DLTAT,M1,M2
INTEGER J,M,IFLAG,ZZ
DOUBLE PRECISION B(3,3),C(3),X(3)
REAL R,DETA

C*****************************************************************************
C INITIALIZATION
C*****************************************************************************
C Opening the file for the output data
C
OPEN(90,FILE='REP')
REWIND(90)

C Setting the dimension of the matrix and vectors
C
M = 3

C Initializing a counter used to reduce the number of point in the
C transient response
C
ZZ = 0
Annex B  Modeling the Transient Response

Zeroing variables to allow initial running of subroutines

\[
\begin{align*}
CC(1) &= 0 \\
CC(2) &= 0 \\
CC(3) &= 0 \\
TIME &= 0 \\
DO &\quad 7 I = 1, M \\
&\quad DO 6 J = 1, M \\
&\quad \quad B(I,J) = 0 \\
&\quad C(I) = 0 \\
&\quad 6 \quad CONTINUE \\
&\quad 7 \quad CONTINUE
\end{align*}
\]

Outputting the starting point values

\[
\begin{align*}
\text{CALL OUTPUT(TIME, CC(1))}
\end{align*}
\]

Inputting variables defining the model and conditions (e.g. coil dimensions, plate thickness, lift-off, plate separation and others)

\[
\begin{align*}
\text{CALL INPUT(V,RP,RS,RT,L1,L2,L3,L4,M1,M2,DLTAT)}
\end{align*}
\]

\section*{PROCESSING}

\[
\begin{align*}
\text{DO 10 J = 1,6000} \\
\text{Calculating the vector and matrix coefficients} \\
\text{CALL MATRIX(V,CC,RP,RS,RT,L1,L2,L3,L4,M1,M2,DLTAT,B,C)} \\
\text{Performing gaussian elimination to solve the matrix} \\
\text{CALL LASSOL (M,B,C,M,X,R,DETA,IFLAG)} \\
\text{Updating vector CC with the output from subroutine LASSOL} \\
CC(1) &= X(1) \\
CC(2) &= X(2) \\
CC(3) &= X(3)
\end{align*}
\]

Updating the time counter

\[
\begin{align*}
\text{TIME} &= \text{TIME} + \text{DLTAT}
\end{align*}
\]
Reducing the number of data points sent to the output file

```
IF (J .EQ. 1 OR J .EQ. ZZ*10) THEN
    CALL OUTPUT (TIME, CC(1))
    ZZ = ZZ+1
ENDIF
10 CONTINUE

STOP
END
```

```
SUBROUTINE INPUT(V,RP,RS,RT,L1,L2,L3,L4,M,M2,DLTAT)

Abstract: INPUT concentrates all input into one subroutine making it easier to modify in the event coil and assembly characteristics are changed. The subroutine also calculates a number of variables derived from the input and passes them to the main program.

DECLARATION

DOUBLE PRECISION K2,V,RP,DLTAT,M,M2,RS,RT,T1,T2,SD
DOUBLE PRECISION N,L1,L2,L3,L4,COND1,COND2,RHOCU,D,W,PI
```

Coil information (number of turns, resistance, inductance, diameter, width)

```
N = 400
RP = 58.38
L1 = 1.985E-3
D = 13.85
W = 3.625
```

Plate information (conductivity, thickness, coupling factor between plates i.e. gap)

```
PRINT*, 'THE 1st PLATE CONDUCTIVITY IN %IACS (RANGE: 1-100)' READ*, COND1
```
Annex B  Modeling the Transient Response

PRINT*, ' THE 1st PLATE THICKNESS?'
READ*, T1
PRINT*, ' THE 2nd PLATE CONDUCTIVITY IN %IACS (RANGE: 1-100)'
READ*, COND2
PRINT*, ' THE 2nd PLATE THICKNESS?'
READ*, T2
PRINT*, ' EFFICIENCY OF SECOND TRANSFORMER I.E. GAP'
READ*, K2

C  Inspect parameters (excitation voltage and coupling factor
C i.e. lift-off)
C
V = 3
PRINT*, ' THE COUPLING FACTOR K?'
READ*, K

C  Manipulating the input (electrical resistivity of copper, Pi,
C plate resistances, time increment for model calculations,
C standard depth of eddy current penetration and inductances)
C
RHOCU = 0.1724E-6
PI = 3.141592654
RS = ((RHOCU / (COND1/100)) * PI * D)/(T1*W)
RT = ((RHOCU / (COND2/100)) * PI * D)/(T2*W)
DLTAT = 1E-7
SD = 500 * SQRT(0.1724 / ((COND1/100) * 1000))
L2 = ((K / N)* SQRT(L1))**2
L3 = L2 * EXP (-T1/SD)
L4 = L3
M = ((K**2) * L1) / N
M2 = ((K2**2) * L3)

C
RETURN
END
C
SUBROUTINE MATRIX(V,CC,RP,RS,RT,L1,L2,L3,L4,M2,DLTAT,B,C)

Abstract: MATRIX calculates the coefficient associated with the 3 equations representing the pulsed eddy current model for a two-plate inspection with single coil.

PROCESSING

Calculating matrix vector and vector coefficients

B(1,1) = RP + L1/DLTAT + M/DLTAT
B(1,2) = M/DLTAT
B(1,3) = 0
B(2,1) = M/DLTAT
B(2,2) = L2/DLTAT + L3/DLTAT + RS
B(2,3) = -M2/DLTAT
B(3,1) = 0
B(3,2) = -M2/DLTAT
B(3,3) = L4/DLTAT + RT
C(1) = V + L1*(CC(1)/DLTAT) + M*(CC(2)/DLTAT)
C(2) = M*(CC(1)/DLTAT)+(L2+L3)*(CC(2)/DLTAT)-M2*(CC(3)/DLTAT)
C(3) = -M2*(CC(2)/DLTAT) + L4*(CC(3)/DLTAT)

RETURN
END
SUBROUTINE LASSOL (N,A,M,X,R,DETA,IFLAG)

Abstract: LASSOL solves a system of N linear equations and
N unknowns, AX=B, using gaussian elimination with
partial pivoting and row equilibration.

DECLARATION

DOUBLE PRECISION A(M,M), B(M), X(M)
DIMENSION AB(16,17)
DOUBLE PRECISION SUMR, DBLE
REAL TEMP, R, DETA
INTEGER SC, N, IFLAG

PROCESSING

NP1=N+1
NM1=N-1
FACT=1.0
DO 3 I=1,N
   ROWMAX=0.0
   DO 1 J=1,N
      ROWMAX=AMAX1(ROWMAX,ABS(REAL(A(I,J))))
      IF (ROWMAX.EQ.0.0) GO TO 14
      SCALE =1.0/ROWMAX
      FACT=FACT*ROWMAX
   DO 2 J=1,N
      AB(I,J)=A(I,J)*SCALE
   AB(I,NP1)=B(I)*SCALE
3   CONTINUE

Begin basic elimination loop. Rows of AB are physically
interchanged in order to bring element of largest magnitude
into the pivotal position. Each row interchange is equivalent
to multiplying the original matrix determinant by (-1). Therefore,
the final sign of the determinant will be adjusted using the
sign correction factor, "SC", which is changed at every row
substitution.
Annex B  Modeling the Transient Response

SC=1
DO 9 K=1,NM1
C
BIG=0.0
DO 4 I=K,N
C
TEMPB=ABS(AB(I,K))
IF (BIG.GE.TEMPB) GO TO 4
BIG = TEMPB
IDXPIV = I
4 CONTINUE
IF (BIG.EQ.0.0) GO TO 14
IF (IDXPIV.EQ.K) GO TO 6
C
Pivot is in row IDXPIV. Interchange row INXPIV with row K.
C
DO 5 I=K,NP1
TEMP1=AB(K,I)
AB(K,I)= AB(IDXPIV,I)
AB(IDXPIV,I)=TEMP1
5 SC=SC*(-1)
6 KP1=K+1
C
Eliminate X(K) from equations K+1,K+2...K+N.
C
DO 8 I=KP1,N
QUOT = AB(I,K)/AB(K,K)
C
DO 7 J=KP1,NP1
AB(I,J)=AB(I,J)- QUOT*AB(K,J)
7 CONTINUE
8 CONTINUE
9 CONTINUE
C
Begin calculation of solution X using back substitution
C
IF (AB(N,N).EQ.0.0) GO TO 14
X(N)= AB(N,NP1)/AB(N,N)
DO 11 IB=2,N
C
I=NP1-IB
IP1=I+1
SUM=0.0
DO 10 J=IP1,N
SUM= SUM + AB(I,J)*X(J)
10 CONTINUE
X(I)= (AB(I,NP1) -SUM)/AB(I,I)
11 CONTINUE
Annex B  Modeling the Transient Response

C Calculate maximum residual R.
C
R=0.0
DO 13 I=1,N
   SUMR=0.0
   DO 12 J=1,N
      SUMR=SUMR + DBLE(A(I,J))*DBLE(X(J))
   12 CONTINUE
   R= AMAX1(R,ABS(SNGL(SUMR-DBLE(B(I)))))
13 CONTINUE
C Calculate the value of the determinant
C
DETA=1.0
DO 121 I=1,N
121 DETA=DETA*AB(I,I)
   DETA =DETA*FACT*SC
   TEMP=ABS(DETA)
C
IFLAG=1
IF (TEMP.LT.0.001) IFLAG=3
RETURN
14 IFLAG=2
C
RETURN
END
C
SUBROUTINE OUTPUT (TIME, II)

Abstract: OUTPUT sends the model results to a file titled "REP". It must be noted that any signal amplification done is accounted for in this subroutine.

DECLARATION

DOUBLE PRECISION TIME, II, TEMPS, AMPS

PROCESSING

TEMPS = TIME * 1E6
AMPS = 100*II
WRITE(90,*) TEMPS, AMPS

RETURN
END