Imaging of Cancer in Tissues Using an Electromagnetic Probe

Thesis

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Abstract

Cancer is diagnosed in over 1 million new patients every year (Frangioni A. M., 2003). It is often treated with surgical resection of tumors, but cancer is an invasive disease marked by the mutations of cells that continually reproduce and invade, or metastasize to, other organs (National Cancer Institute, U.S. National Institutes of Health, 2009). For a curative surgery to be successful the margins must be clear without cancer cells present in the unresected tissue. Currently, this analysis is done by pathological analysis of small portions of the tissue under a microscope and well after the surgery. Such information, if available to the surgeon while the patient is still in the OR would provide valuable real-time information and impact decision making such as whether or not more tissue needs to be removed.

This thesis describes the use of an electromagnetic (EM) probe to distinguish between cancerous tissue and healthy tissue and to enable imaging surgically excised tissue for quantification of margins. The electromagnetic properties of cancerous and healthy tissues are shown to be different and distinguishable by monitoring changes in mutual inductance between a pair or coils caused by the formation of eddy currents in the tissues. The output voltage and phase of the receiver are monitored using a dual channel lock-in amplifier with the driver coil excited by a 99 kHz, 7 VPP, sawtooth input.
Point-wise voltage measurements are made with the EM probe on surgically excised tissue samples showing that the EM properties of cancer and healthy tissue are indeed different and differentiable. Also, supporting experiments conducted on copper wire loops to show that the voltage and phase of the EM probe signal is affected by eddy current domain size. The EM probe is most sensitive when the eddy current loops are of the same size as the probe’s diameter. It is also observed that the phase response is considerably more sensitive than the voltage response. A numerical model is developed to predict the probe’s response to different excitations as well as to different eddy current loop domain sizes. The model agrees well with experiments for sinusoidal excitations, however, the responses for a sawtooth excitation are severely under-predicted. This is likely due to either frequency dependent impedances or the excitation of the coil near resonance by a harmonic of the sawtooth excitation.

This thesis culminates in using the EM probe to develop a new method for imaging surgically excised tissue. A passive, non-electromagnetically interacting device is developed to allow the probe to traverse convex shaped and flat surfaces. The new imaging technique is used to image paraffin phantoms. The positions of embedded copper artifacts within the phantoms are successfully imaged, with all objects smaller than the effective probe diameter appearing to be of a size on the order of the probe diameter. The new imaging technique shows great promise for quantifying surgical margins in real-time, impacting the decisions of surgical oncologists in the OR and enhancing the curative outcomes of surgical removal of cancer.
Dedication

Dedicated to my family, friends and each person this work may someday help
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List of Abbreviations

AC ................................................................. Alternating Current

AWG ............................................................. American Wire Gauge

CT ............................................................... Computer Tomography

CAT ............................................................. Computer Aided Tomography

DC ............................................................... Direct Current

EM .............................................................. Electromagnetic

EMF ............................................................. Electromotive Force

FDG ............................................................. Fluorodeoxyglucose

MAbs .......................................................... Monoclonal Antibodies

MRI ............................................................. Magnetic Resonance Imager (ing)

NPs .............................................................. Nanoparticles

OR ............................................................... Operating Room

PC ............................................................... Personal Computer

PET ............................................................. Positron Emission Tomography
RIGS………………………………………………………………………Radioimmunoguided Surgery
Chapter 1: Introduction

There are more than 1 million non-skin cancers diagnosed in the United States annually (Frangioni, 2003). Of these 45% are not cured and only 5% are cured by chemotherapy and/or radiation treatments (Frangioni A. M., 2003). Surgery, however, cures approximately 50% of these cancers (Frangioni, 2003). Surgery has the potential to become an exceedingly successful treatment of non-skin cancers. The state-of-the-art utilizes pre-operative diagnostic imaging, such as CT, PET, and PET/CT to identify cancer. However, scientific and diagnostic instrumentation are unavailable for use in the operating room (OR), forcing surgeons to rely solely on their own skill and experience and using post-operative analysis only to find out how successful they were in extracting the diseased tissue. A common analysis tool available to surgeons in the OR are frozen sections wherein small pieces of surgically excised tissue are sent for pathological analysis while the patient is still in the OR (Martin & Thurston, 1996). Unfortunately, by the nature of this analysis outcomes are at best inconclusive since only small portions of the tissue, hundreds of microns in size, are examined for assessing surgical margins (de Montpreville, Dulmet, & Nashashibi, 1998).

Preoperative scans, generally performed with a CT or PET scanner, inform the surgeon of the locations of suspicious tissue. However, there are drawbacks associated with these diagnostics. In the case of CT scanning, which only displays density
differences, artifacts often appear in the scans, increasing the difficulty of proper
diagnosis and decreasing the specificity of the scans. These artifacts are generally caused
by patient movement in respiration or bowel movements (Rosenbaum, Lind, Antoch, &
Bockisch, 2006).

In PET scans, fluorodeoxyglucose (FDG), similar to glucose and labeled with the
radioisotope $^{18}$F, is used as a tracer of glucose metabolism in the body (Chang, et al.,
2006). Essentially, FDG-PET compares background glucose consumption to elevated
glucose consumption in the tumor since tumors are expected to have a higher metabolic
rate compared to healthy tissue. Since FDG is not cancer specific, false positives often
occur when the glucose consumption of an area of interest in elevated. This happens
routinely when there is active inflammation or infection (Chang, et al., 2006). In many
cases, the oncologist can determine from other clues if the active area is a malignancy.
Conversely, false negatives occur when a malignancy has a metabolic rate similar to that
of the rest of the body. False negatives can also occur when the tumor size is small
compared to the 1-cm resolution of typical PET systems as well (Chang, et al., 2006).

Diseased lymph nodes are thought to play a role in the recurrence and metastasis of
cancer, although the exact mechanisms of metastasis remain elusive. Locating lymph
nodes, let alone diseased lymph nodes, during cancer surgery is also problematic because
typically the only way to find them is by feel or sight. These limitations in the diagnosis
of cancer demand that the surgeon not only be very skilled but that the excised tissue is
analyzed for margin analysis. Margin analysis is the inspection of a tissue resection for
cancerous tissue near the cut edge. If there is cancerous tissue present then there is likely to be cancer left behind in the patient, thus increasing their chances for recurrence. Margin analysis is currently done by a pathologist who examines small portions of the surgically excised tissue, from near the cut edge, under a microscope. The combination of this subjective approach to disease detection and margin analysis, and the limitations of preoperative imaging are some of the reasons why cancer recurs after curative surgery and patients eventually succumb to the disease. There is clearly a need for selective removal of diseased tissue with real time analysis in the OR.

This body of work will address a new technique that may be used to complement current diagnosis techniques with real-time or near real-time information about cancer margins in the OR. Presented in this thesis is a technique that is applied as a method of imaging excised tissue samples; however, it has the potential to be used as a handheld surgical probe as well. The hypothesis guiding this work is that the ability of a material to magnetize under the influence of an externally applied time-varying magnetic field is fundamentally different and distinguishable between cancerous tissue and healthy tissue. It is believed that eddy currents are induced in the tissue and they affect the characteristics, i.e. induced voltage and phase, differently for healthy and diseased tissues.

Even weak conductors, such as living tissue, exhibit magnetization when subjected to the magnetic field of a time-varying current. A way to measure this magnetization is by observing the change in mutual inductance between two coils, one of which is driven
by a periodically time varying current. It is important to distinguish between these EM measurements and magnetic resonance measurements. Magnetic resonance, like that in an MRI, magnetizes the sample or patient globally, utilizing the alignment of hydrogen nuclei spin states. In contrast, the EM method described in this thesis relies on temporary, local magnetization due to the creation of eddy currents within a partially conducting medium and does not use the nuclei spin states of the hydrogen atom molecules. The eddy currents then generate their own magnetic fields which interact with the applied magnetic field, thereby altering it. Changes in mutual inductance are then quantified based on how the input field is altered (Rangamathan & Rangarajan, 1982).

The interactions between the applied magnetic field and the sample are detected by the detector (receiver) coil of an EM probe consisting of two concentrically wound copper coils. The applied magnetic field is produced in one coil (the driver) with a periodically time varying current. The induced voltage in the second coil (the receiver) is then monitored by a lock-in amplifier which tracks the magnitude of the second coil’s voltage at a particular phase. The simple circuit is initially nulled with nothing placed in front of the coil pair, with the phase on the lock-in amplifier adjusted so that its output is zero. Then when a magnetic or conductive material is brought near the coils, the output will give a non-zero voltage magnitude at the phase used to null the device. This happens because the mutual inductance between the coils is altered by the presence of the partially conducting material either via eddy currents or via magnetic viscous relaxation (Steinmetz, 1916).
The content of this thesis is organized as follows, first, measurements are made on samples of excised tissue to show differences between healthy and diseased tissue. It is imperative to start with tissue in order to validate the hypothesis that the magnetic characteristics of healthy and diseased tissue are inherently different. Next, the EM probe is used to develop a relationship between eddy current domain size and the change in magnitude and phase of the receiver coil using supporting experiments on loops of conducting wire. Following that, a simple AC circuit model is developed to predict and explain the phase shift and magnitude change for a given wire loop (eddy current domain) diameter. Finally, a passive mechanism is designed to allow the probe to traverse a given geometry automatically. This scanning produces images of phantoms, eventually enabling the possibility of imaging surgically excised tissue.

Beyond the scope of this work, the principal goals of this project are to produce 2-D and 3-D images of surgically excised tissue for the quantification of surgical margins. This should also aid the surgeon in real-time decision making in the OR related to whether or not additional tissue needs to be removed. Another goal is to design a sufficiently robust probe that can be used by a surgeon as a hand-held device. It is anticipated that the selectivity of the EM technique may be further improved by using monoclonal antibodies, which are beyond the scope of this work. Diagnostic redundancy is a key to the success of curative surgery. CT and PET provide pre-operative diagnostic images. A hand-held probe will allow the surgeon to know in real time if cancer that they cannot see or feel is present. A real-time imager for margin analysis will allow the surgeon to know if the resection is likely curative before closing the patient. Finally,
pathology will give their final report to help determine the patient’s further care and the success of the surgery.

This thesis is organized as follows. The following chapter provides background on cancer, preoperative imaging, current intraoperative techniques, and other EM techniques. The experimental setup and apparatus, as well as the experimental procedures are described in detail in Chapter 3. The experimental results, in addition to the results of a numerical model are presented and discussed in Chapter 4. Chapter 5 provides a summary and conclusions from the work presented. Finally, Chapter 6 addresses the recommendations and plans for future work.
Chapter 2: Background

2.1 Cancer

Cancer is a term that describes any cellular mutation in which cells divide without control and are able to invade other tissues (National Cancer Institute, U.S. National Institutes of Health, 2009). There are several different types of cancer because cancer can originate from nearly any cell type in the body. Carcinomas are the most common type of cancer and develop from cells on the surface of any internal or external body surfaces (National Cancer Institute, 2006). Sarcomas arise from cells in supporting tissues like bones, cartilage, fat, and muscle (National Cancer Institute, 2006). Lymphomas arise from tissues of the body’s immune system and lymph nodes (National Cancer Institute, 2006). Leukemias are caused by immature blood cells that grow in bone marrow then accumulate in the blood stream (National Cancer Institute, 2006).
In addition to the categories of cancer, cancers are typically named for the Latin names of the parts of the body. Figure 2.2 describes some of the most prevalent prefixes for cancer names, some of which will be discussed in this work.
In this thesis, the focus will be on malignant tumor producing carcinomas. It is important to note that not all tumors are cancerous, just as not all cancers produce tumors. The difference between a cancerous tumor and a benign tumor is the cells of a benign tumor are not invasive and therefore do not spread to other organs and tissues. However, cells in a benign tumor are diseased and often continue to grow with time, though they do...
not have the potential to spread. The spreading through the bloodstream, or metastasis of tumors, is what truly defines cancer (National Cancer Institute, U.S. National Institutes of Health, 2009).

2.2 Cancer Detection and Diagnosis

2.2.1 Preoperative Imaging

In most cases, patients suspected to have cancer, especially those with suspected metastases, are imaged by CT, PET, a combination PET/CT, or occasionally MRI. CT scanners utilize x-ray radiation to generate a 3-D image from 2-D x-ray projections. The image is generated by projecting the x-ray transmission through the subject then rotating the projection either 360° or 180°, depending on the scanner type. CT scanners as they are today were developed in the 1970s, first by engineer Sir Godfrey Hounsfield, at EMI Central Research Laboratories in the UK, where significant portions of the Beatles music profits were put into the scanner’s research and development (Rogers, 2001). Independently, Allan McLeod Cormack of Tufts University developed the analysis necessary to produce images from the raw transmission data. Together, they shared the Nobel Prize in Medicine in 1979. Typical problems in CT scans are the production of artifacts caused by a patient’s voluntary or involuntary motion during the exam.

PET scans are performed on patients who ingest, inject, or inhale a radionuclide tracer that will selectively accumulate in the area to be imaged. In oncological PET scans, FDG is commonly used. FDG is a conjugation of $^{18}$F, a radioisotope of fluorine, and D-glucose, a type of sugar; it accumulates in parts of the body where the cells have a
higher metabolic uptake of glucose, but it is not cancer specific (Chang, et al., 2006). The PET scanners then detect the emissions arising from the radionuclide. Typically, cancerous tissues show up clearly, however cancers with lower metabolic uptakes (e.g. signet ring cell cancers) are often lost in the body’s background signal. Potential for images of benign lesions or inflammation showing up as cancer is also a problem associated with PET imaging, however, most skilled technicians can determine the differences between benign lesions and cancer (Chang, et al., 2006).

MRI scans are used less frequently to image cancer; however they are becoming more common especially when used in conjunction with CT scans. MRI allows for very detailed images of soft tissues as well as very detailed contrast in areas like the prostate, pelvis, head and neck (Bayouth, 2009). MRI does not utilize radionuclides or x-ray radiation, however it does use contrast agents, some of which like gadolinium can be toxic in appreciable amounts. In fact, approximately 30% of MRI scans perform use a gadolinium tracer (Caravan, Ellison, McMurry, & Lauffer, 1999). Instead, the patient is initially magnetized, that is, the spin states of individual hydrogen nuclei align. The individual relaxations of the hydrogen nuclei from their aligned spin states create the MRI image. Some drawbacks of MRI are a lack of anatomical detail that make patient positioning difficult if a CT or PET scan of the same area is requested.

### 2.3 Other Cancer Detection Methods

It is crucial for surgical oncologists to have the most information available about their patient’s cancer before surgery, however, information gathered during and after
surgery is just as important. In this section, a few preoperative, intraoperative, and postoperative techniques that have been used will be described. The method discussed in this thesis will first be used as an intraoperative and postoperative imager, with the potential to become an intraoperative, hand-held probe.

Intraoperative detection is essential for positive surgical outcomes. Currently, the most common methods of intraoperative detection are the surgeon’s senses of sight and touch (Martin & Thurston, 1996). Also, preoperative imaging and diagnosis is useful and successful in detecting the principal tumors, but can often not successfully predict the metastatic spread (Martin & Thurston, 1996).

An intraoperative technique for cancer detection has been developed in the past. Radioimmunoguided Surgery (RIGS) uses cancer specific monoclonal antibodies (MAbs) conjugated with radioisotope tracers to produce radioactive “hot” spots where cancer is present (Bertsch, Burak Jr., Young, Arnold, & Martin, 1995) (Martin & Thurston, 1996). Essentially, RIGS succeeds by using a gamma detecting probe to detect the radioactive hot spots generated by MAbs with conjugated radionuclides (Martin & Thurston, 1996). This has allowed surgeons to find cancer otherwise undetectable by traditional techniques. Unfortunately, although gamma probes are commercially available (e.g. Neoprobe Corp.), RIGS has not progressed beyond clinical trials.

MAbs used in RIGS development and research are B72.3 and CC49, and both were labeled with iodine 125 (Bertsch, Burak Jr., Young, Arnold, & Martin, 1995). The general RIGS procedure is to inject the patient prior to surgery with the iodine 125
conjugated MAbs, allowing time for the labeled antibody to clear the system, leaving only the radioactive elements attached to cancerous or diseased tissue. The gamma probe is then used during surgery to locate the tissues emitting gamma radiation, which are then removed, if possible. This method has worked very successfully (Bertsch, Burak Jr., Young, Arnold, & Martin, 1995). There are problems associated with it, however. For instance, both the patient and the healthcare workers can be exposed to potentially harmful doses of accumulated radiation exposure. This is particularly problematic for the healthcare workers, who may work with several patients being treated with the RIGS system per week. Unlike CT or X-ray scans, there is little shielding for the workers themselves when performing hours long operations.

MAbs are highly specific antibodies that recognize antigens produced by a tumor. When MAbs recognize the tumor’s antigen, they attach specifically to that antigen. This makes MAbs useful for their ability to deliver anticancer drugs, toxins, or radionuclides selectively to cancerous tissue, leaving healthy tissue unaffected. MAbs are relevant to this thesis because there are opportunities for improving the selectivity of the EM probe for cancer detection through the conjugation of non-toxic particles that would affect the EM signal favorably.

MAbs conjugated with other materials and substances are beginning to be extensively investigated. Other techniques in which they are used include optical techniques using fluorescent dyes (Frangioni, 2003) or gold nanoparticles (NPs) (El-Sayed, Huang, & El-Sayed, 2005) (Sokolov, et al., 2003). In these studies, researchers
use visible or near-infrared light to excite the dyes or NPs. Unfortunately, there are many drawbacks to these techniques, including scattering from the tissue around the tumor, causing the specificity to be imprecise. Also, depth sensitivity is limited due to the penetration depths of the excitation source, generally a laser. The use of NP excitation has never been brought to clinical trial, and the use of near-infrared light excitation of fluorescent dyes has had only limited testing at the clinical stage with applications to breast sentinel lymph node mapping (Troyan, et al., 2009).

Electrical impedance methods have been used extensively to detect malignant breast tumor. These tumors have also been imaged using electrical impedance tomography (Zou & Guo, 2003). Electrical impedance technology utilizes electrodes to measure the impedance of a section of tissue by applying a small voltage to one site on the body and monitoring the voltage at a second location. This technique has been done with both skin surface and embedded electrodes. The most disadvantageous aspect of this technique is that it only yields information about the path of least impedance. The concept of least impedance in the body can be likened to a lightning strike, where the path of the bolt is always the easiest path to ground. The only information that can be extracted is the information about the path of the current follows, like the bolt. Tissue is generally heterogeneous, especially cancerous tissue, so this restriction can be burdensome, especially when the user is imaging with this technique. Information about areas with higher impedances is lost.
2.4 Electromagnetic Measurements

In this work, the primary focus is detecting small changes in the electromagnetic properties of healthy and diseased tissues by looking at changes in mutual inductance due to eddy current interactions within a sample. These eddy current interactions are defined by the current loop domain size of the eddy current, which is characterized by the magnetic properties of the material. Using mutual inductance to determine the magnetic susceptibility of a substance is widely used in the geological sciences. For instance, categorization of sedimentary samples is monitored by magnetic susceptance. Specific properties of the sediment, such as the presence of greigite, or a contaminant can be detected with the method (Roberts, 1995) (Versteeg, Morris, & Rukavina, 1995). Interestingly, similar methods have been applied to quantify the salt content of seawater, as well as the impurity ratio in semiconductors (Gencer & Tek, 1999).

Likewise, monitoring eddy current domain size is typical in the field on non-destructive testing. For example, this method is commonly used by engineers to determine flaws (embedded cracks or voids) in non-destructive tests of pressure vessels, pipes and welds (Collaboration for Nondestructive Testing).

Methods similar to those presented in this thesis have been applied in the medical field as well. However, these measurements have been primarily focused on the measurements of conductivity or resistivity rather than mutual inductance (Gencer & Tek, 1999). In these measurements, a transmitter coil induces an electric field in two separate receiver coils in the proximity of the sample to be measured with a low
frequency sinusoidal current (Gencer & Tek, 1999). The magnitude of the induced electromotive force, EMF, is monitored, and interpreted as changes in sample conductivity (Gencer & Tek, 1999).

The method discussed in the literature that is most similar to the EM method discussed in this thesis is Magnetic Induction Tomography (MIT), also known as Mutual Inductance Tomography (Korjenevsky, Cherepenin, & Sapetsky, 2000). Essentially, MIT monitors differences in electrical impedance of the sample, by monitoring a phase shift between a single driver coil and a single receiver coil within a circular array of driver and receiver coils (Korjenevsky, Cherepenin, & Sapetsky, 2000). The drivers are turned on separately from one another in succession, and then a filtered back projection technique is employed to produce an image.

There are several key differences between MIT and the EM method discussed in this thesis. First, in the EM technique described in this work there is a single driver and single receiver, and the phase shift between the receiver’s null state with no sample present and that when the sample is present, is monitored. Secondly, all imaging with the EM probe is done with lateral scanning, rather than antenna-like projection with filter-back project post analysis. This is because the EM probe is principally designed to detect cancer with applications for imaging as a secondary goal. This allows EM scanning to have improved spatial resolution and specificity. Thirdly, in MIT the driver coils are driven with 20 MHz sinusoids, which is in stark contrast to the 99 kHz sinusoids and sawtooth excitations employed in the present work. Finally, MIT assumes there is very
low coupling between the driver coils and the detector (receiver) coils, whereas in the system developed in this thesis, the coupling between the driver and receiver is significant (Korjenevsky, Cherepenin, & Sapetsky, 2000).

To summarize, the EM imaging strategy explored in this thesis employs an EM probe consisting of a pair of concentrically wound, inductively coupled coils. The coils are driven at a relatively low frequency (99 kHz) and the phase and voltage outputs are monitored with a dual-channel lock-in amplifier, allowing information about both to be gathered relative to a null condition. The EM probe shows promise not only in intraoperative cancer detection but also in intraoperative margin analysis of excised tissue. The methods, results, conclusions, and plans for future work are discussed in detail in the subsequent chapters of this work.
Chapter 3: Experimental Apparatus and Procedure

The experiments described in this thesis are conducted on a single basic setup with several small modifications to accommodate a variety of experiments. Each component of the system is necessary for the investigation of the magnetic properties of both the samples and the instrument itself. This chapter contains two sections which will discuss the experimental apparatus and procedure.

3.1 Experimental Apparatus

There are several different subsystem components used to observe and investigate the magnetic properties of different samples using an EM probe. The apparatus in each subsystem and its purpose will be discussed. There are three independent subsystems in this investigation, the EM probe, the driving and processing elements of the EM probe, and the samples analyzed with the probe.

3.1.1 The Electromagnetic (EM) Probe

The EM probe used in each of these experiments is named A6 for its sequence in the design and construction process. A6 is a concentrically wound dual coil system. The inner coil, or driver coil, allows for the driving signal input, which produces a time varying magnetic field. This magnetic field in turn induces a voltage in the outer coil, or the receiver coil. In a closed circuit, this induced voltage results in a current flow.
device operates because when the EM probe is brought into the proximity of a conducting material, the induced voltage in the receiver changes, which is then measured.

The EM probe is made from 32 American Wire Gauge (AWG) insulated copper wire. The inner coil has approximately 132 turns, in two layers. The outer coil has approximately 302 turns, in 6 layers. To estimate the number of turns in each coil, first measure the direct current (DC) resistance and measure the inner and outer diameters of the coil, then take the average. Then, using the effective diameter, that is, the mean of the outer diameter and the average diameter for the receiver coil, and the mean of the inner diameter and the average diameter for the driver and the DC resistance per foot of the 18 AWG copper wire, 164ohm/1000ft, calculate the resistance per turn of coil. The total number of turns is then the coil resistance divided by the estimated resistance per turn. It should also be noted that the inner coil is neatly and tightly wound with each turn parallel and immediately adjacent to the previous turn, whereas the outer coil is slightly scatter-wound. This is due to the difficulty of keeping each layer of turns tightly packed, though it is not highly scatter-wound.

To manufacture the EM probe, an EMCO Compact 5 CNC Computer Numerically Controlled CNC Machine was used to turn the coils (Motor # N1078415). The procedure begins by inverting 27/64 drill bit, so the smooth round shaft is out, in the horizontal lathe fitting on the CNC machine. Next, a single layer of copper wire is wound on the surface of the drill bit. It is imperative that this layer is tightly packed, but not scatter-wound. This is the release coil, which is fastened into place using a layer of
Clear Gloss 01, Sally Hansen Hard as Nails Color nail polish (Coty, Inc.). When it is dry, the release coil should be taped off at the desired coil length, in this case the EM probe is 0.511 inches long. Now, being careful to keep the turns tightly packed, two layers of turns are created for the driver coil, one pass to the right and one pass to the left. When turning coils, the CNC machine is set to a BC1 gear pattern and speed 16% per minute, which corresponds to approximately 50 revolutions per minute. The driver coil is then finished with the nail polish to secure it and allowed to dry. Being careful not to unravel the driver coil, or tangle the wire leads, the receiver coil is turned with the same CNC machine settings. This time 6 passes are made with attention to making each turn as parallel as possible, but likely with some scatter windings. Again, the receiver coil is fastened using the clear nail polish. To remove the EM probe from the drill bit, carefully unwrap the release coil, until the probe slides off the drill bit easily. The EM probe’s average outer diameter of 0.532 inches and its inner diameter is 0.44 inches. See Figure 3.1.

The self inductance and resistance of the driver and receiver coils were measured using an Extech Instruments LCR Meter (Model 380193). The driver coil was measured to have a self-inductance of 69.6 µH and a resistance of 2.54 Ω. The receiver coil was measured to have a self-inductance of 475.5 µH and a resistance of 6.36 Ω. It should be noted that the capacitances were measured with the LCR meter as well, but the results were immediately considered dubious. The driver coil capacitance was measured at 362.9 µF and the receiver coil capacitance was measured at 53.17 µF. These capacitances are believed to unrealistically high due to a capacitive buildup in the coil.
that was not being accounted for. For instance, when measuring the capacitance on the driver coil, the receiver coil is left as an open circuit. When the driver coil then induces a voltage in the receiver coil no resulting current can flow in the open circuit, resulting in a capacitive buildup. The same occurs within the driver when the LCR meter is measuring capacitance on the receiver.

In some of the experiments reported here, an EM probe A2, similar to A6, was used to perform measurements. The characteristics of A2 are similar to that of A6 and are described in detail in “An Electromagnetic Method of Cancer Detection”, by Jennifer McFerran (McFerran, 2009). The two probes were specifically designed to be exactly alike, however, the process of producing the coils allows for subtle differences in their EM properties.

Figure 3.1: Diagram of the EM probe. The probe consists of two concentric coils made from 32AWG insulated copper wire.
3.1.2 Driving and Data Collection System

In order to use the EM probe to detect differences in EM properties of a sample, it is necessary to setup a system to drive and collect the data. A Hewlett Packard 33120A 15 MHz function/arbitrary waveform generator is used to drive a 7Vpp, 99kHz, sawtooth waveform through an 830 Ω ballast resistor and the driver coil. Connected as shown in Figure 3.2, a Stanford Research Systems, SR530 Dual Phase Lock-in Amplifier is used to independently measure the amplitude and the phase of the signal from the receiver coil. The lock-in amplifier uses the reference signal from the function generator to measure the phase shift of the receiver coil. The lock-in amplifier is useful for this application because it is designed to accurately measure small signals even when the noise may be up to one-thousand times larger (Stanford Research Systems, 2001). In the cases of excised tissue measurements a Stanford Research Systems, SR510 Single Phase Lock-in Amplifier is used to measure the amplitude of the signal from the receiver coil at a fixed phase.

The DC output from the dual lock-in is sent to an Agilent 54622A, 100MHz, Oscilloscope. The convention of lock-in output 1 to oscilloscope channel 1 and lock-in output 2 to oscilloscope channel 2 was followed. Using an RS-232 data cable, the scope output is transferred to a PC using Agilent Scope Control Software Version 2.0.0. This software allows for the scope data to be transferred to a text file, excel file, or saved as an image, that can be saved and analyzed.
Figure 3.2: Experimental Setup for Data Acquisition
3.1.3 Raster Design

One of the goals of this work is to utilize the EM probe to develop an imaging technique. To achieve this, a passive design to allow the probe to traverse a sample or phantom is designed. The motion of the probe is controlled either by a Velmex VP9000 Controller or by a MAXNC CL2 Milling Machine. The MAXNC stage is used for measurements of the surgically excised tissue and the rectangular phantoms, while the Velmex stage is used to measurements on the round phantoms and the wire loops. The Velmex VP9000 Controller uses the Velmex VP9000 Series Controller Ver. 99.1.B
software. The stages utilized are Unislide © by Velmex, Inc, 6 in wide, 5 in travel stages. The x-axis is a MB6012K1J-S8 stage and the z-axis is a MA6012K1-S8-0. Whereas the MAXNC CL2 is a self contained 4-axis system controlled using MAXNC system software in a DOS computing environment on a Gateway 2000 P5-90 Pentium computer. For the purposes of this design setup, the fourth axis, the rotational axis, is unnecessary and hence it is removed. See Figure 3.4 for a dimensioned representation of the MAXNC setup without the rotational axis.
Figure 3.4: MAXNC Setup (McFerran, 2009)

Despite the ability to move the probe it is necessary to devise a means to allow the probe to traverse an unknown terrain without damaging the probe, altering its output signal, or damaging the sample, while still maintaining knowledge of the probe tip
location. To not affect the output signal of the receiver coil, there must be no bulk metal parts near the probe. If there is bulk metal in the proximity of the probe the eddy currents that build in the metal will induce a proportionally larger current in the receiver than the sample, thus swamping out the information about the sample. The best way to address this problem is to use materials that do not support the formation of these eddy currents, such as most types of plastic.
Figure 3.5: The rastering apparatus assembled with the EM Probe. A) Rainbow Magic Spring Mini, B) LEGO Part # 4295445, C) BD 5 mL Syringe, D) LEGO Part# 4361493, E) LEGO Wheels, F) EM Probe
The raster design consists of several components each serving a unique function. An image of the overall design is shown in Figure 3.5. It is important that the probe be at an angle with respect to the sample in order to minimize contact area with the sample. Doing this yields a more point-wise measurement, increasing spatial accuracy. This is done using LEGO Parts #4793454 and #4290883 from the LEGO City Police Helicopter #7741 toy set. This piece is shown in Figure 3.6A.

The probe needs to traverse an unknown, yet gently sloping terrain. In the case of tissue samples, the terrain is also soft, so it is necessary to have wheels in order to keep the probe from experiencing a large lateral force. The wheels used, are modified LEGO wheels from the Thunder Race #8119 set. The wheels were modified by cutting the connective center piece so the wheels could be inverted close to each other when mounted on the device. This cut is displayed in Figure 3.6B. To address concerns of varying sample elevation, a BD 5mL Syringe with a Luer-Lok™ Tip, with the rubber tip removed is used. When the rubber tip is removed the plunger is allowed to move freely up and down the syringe shaft without bending. This allows the probe to easily traverse a downgrade in the sample, while maintaining full contact with the sample’s surface. The last issue to be addressed is the possible rotation of the probe about its axis as it traverses a sample. A 1.5in diameter, hexagonal, Magic Spring Mini is used as a very loose spring to prevent any twisting around the axis of the syringe. The Magic Spring is also ideal because it doesn’t interfere with the syringe’s ability to allow the probe to raise and lower freely.
Other components are used to easily assemble and attach the probe to the raster device. First, the probe assembly is attached to LEGO Part #4295445 from the LEGO City Police Helicopter #7741 toy set using electrical tape. Then LEGO Part #4361493 and LEGO Part #4379843 are taped together around the syringe to create a press fit, and taped around the outside with electrical tape to hold into place. This assembly then fits easily into LEGO Part# 4295445, and can then be secured with electrical tape. Next, a piece of threaded nylon, 0.625mm in diameter, is fastened to the top of the syringe using a quick-set epoxy. The threaded nylon is used to fixture the raster setup to the precision stage, using two plexiglass threaded nuts. The Magic Spring is attached to the lower nut, over the threaded nylon, syringe plunger assembly, and attached at the top of the syringe shell, using electrical tape.
3.2 Experimental Procedure

The following section outlines the procedures taken to collect data during the course of this study. The section also includes the setup, shut-down, and post-processing procedures typically used for each experiment.

3.2.1 Measurements on Human Surgically Excised Tissue

Measurements of amplitude at a fixed phase are conducted using the EM probe A2 using the SR510 Single Phase Lock-In Amplifier. The experimental arrangement
consists of the A2 probe mounted 20° from the vertical and connected as shown in Figure 3.2. The driving function is a 7Vpp, 99 kHz, Sawtooth, the lock-in amplifier settings are detailed in Table 3.1, and the scope is set to 2V/div and 10sec/div.

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Table 3.1: Lock-in Amplifier Settings for the current loop experiments
Measurements are gathered by placing the tissue sample directly beneath the probe, such that the edge angled downward is directly above the area to be examined. Using the MAXNC system, the probe is brought down until it makes full contact with the tissue. At this point, the stage is zeroed to establish an origin. When this zero is recorded, the stage is brought 10mm above the surface of the tissue. At this distance, the probe is not sensitive to the presence of the tissue. Then an oscilloscope sweep is started simultaneously with the start of a MAXNC program that brings the probe into contact with the tissue three successive times. The program begins by moving to zero at 2.08 mm/sec, pausing for 5 seconds, moving to 10 mm, pausing for 5 seconds, then repeating two more times. The code used to program the MAXNC is given in the appendix. The data is then read from the oscilloscope to the computer using the Agilent scope reading software, saved and processed in MATLAB.

To process the scope trace data, the voltage drop for each touch is recorded, the high, low and average of these touches calculated, and finally plotted with error bars representing the variation between each time the probe makes contact with the sample. This process is repeated for various locations on a given tissue sample, depending on geometry, suspected tumor location, and any other known markers such as tissue cauterization or scar tissue.

All of the tissue samples examined in this thesis have been covered by the “Clinical Trial of The Ohio State University Comprehensive Cancer Center,” protocol approved by The Ohio State University Human Subjects Review Board. The patients
covered under this protocol have each signed a written consent that has been approved by
the Human Subjects Review Board.

3.2.2 EM Probe Response to Controlled Eddy Current Domain Sizes

Measurements of amplitude and phase shift by the EM probe A6 are made for
specific eddy current domain sizes by producing copper loops and experimenting with
various sizes (diameters) of these loops. Even though the conductivity of copper wire is
substantially different from tissue, these measurements will help reveal the dependence of
the probe characteristics on the domain size (i.e. diameters) of eddy currents. To produce
the loops Fisherbrand ® 18AWG Bare Copper Wire, PN 155451B, are shaped into loop
diameters of 3.65mm, 4.8mm, 5.8mm, 7.28mm, 12.85mm, 21.68mm, and 35.28mm. The
loops are closed with a small amount of Alphametals Inc. 60/40 Rosin Core tin-lead
solder, #21604 to make a circular conducting path.

The experiment is setup with the A6 probe along the z axis, perpendicular to the
stage’s xy plane, and connected as shown in Figure 3.2. The driving function is a 7Vpp,
99 kHz, sawtooth, the lock-in amplifier settings are detailed in Table 3.2, and the scope is
not necessary for this experiment.
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Table 3.2: Lock-in Amplifier Settings for Loop Experiments

The first wire loop is placed directly beneath the probe, such that the center axis of the ring is along the same line as the center axis of the probe. Using the precision Velmex stage system, the probe is brought down until it covers the ring completely, and is flush with the plexiglass stage. At this point, the stage is zeroed to define an origin. Next, the probe is raised along the z-axis, 12.5 mm. Now, using the “Rel” key on the lock-in amplifier, both the magnitude, $R$, and the phase, $\phi$, are zeroed. The offset of the magnitude, $R_{\text{offset}}$, and the reference phase, $\theta_{\text{ref}}$, are recorded. Then, the stage is programmed to return to the zero set point, where the magnitude shift and phase shift are
read off the digital outputs 1 and 2, respectively. This process is repeated for each loop as well as with no loop present.

Magnitudes and phase shifts are recorded as differences between when the probe makes near contact with the loops and when it is far away from the loops. The phase is simply recorded off the digital output. In the case of the voltage magnitude, the offset, as well as an amplification conversion factor need to be taken into consideration. The conversion factor scales as ±10V at full scale of the sensitivity. So for 500mV sensitivity, the conversion factor is 50mV/V. The magnitude of the voltage is determined from Equation 3.1.

\[
R = \frac{R_{\text{offset}}}{\text{ConversionFactor}} - \frac{R_{\text{shift}}}{\text{ConversionFactor}} \quad 3.1
\]

3.2.3 Preparation of Phantoms

In many instances, it is not possible to perform experiments on actual tissue specimens. In these instances, it is necessary to construct specimens that simulate or mimic some characteristics of real tissues. These are known as phantoms. It is necessary to prepare samples that can provide varied features with a known configuration in order
to assess the specificity and sensitivity of the raster device that uses the EM probe A6. This was accomplished using a combination of paraffin wax and 18 AWG bare copper wire. It has been shown in the literature that paraffin wax is a common phantom for the human body (Srinivasan, Kumar, & Singh, 2002) (Nikawa, Chino, & Okada, 1992) (Chacko & Singh, 2000). The paraffin is Homedics Body Basics Para Spa Hypoallergenic Paraffin Wax Pearls, CPPARWAX-A, with no dyes or scents, and the wire is Fisherbrand © 18 AWG Bare Copper Wire, PN 155451B.

The phantoms used for the following experiments are prepared as follows. First a 75 mm by 150 mm by 6.25 mm mold is lined with aluminum foil. The aluminum foil must be well formed to the mold with as little wrinkling as possible. Next, various lengths of wire, and/or various diameter loops of wire are cut and arranged in a desired pattern in the bottom of the mold.

Next, a 500mL beaker is filled approximately half way with paraffin wax pearls, and put on a hotplate set to medium heat. The wax should be allowed to melt completely, unit it is very clear and without any solids. Finally, the wax should be gently poured into the molds, always pouring around the copper wires or loops, so that they stay where they were originally placed. The wax is then allowed to fully cool and set at room temperature, then, using the foil, the phantom is lifted out of the mold, and the foil peeled back. The last step is to accurately measure the phantom and each feature within it. Examples of these phantoms, referred to as the Rectangular Phantoms, are shown in Figure 3.7.
Figure 3.7: Rectangular paraffin phantoms, (a) Paraffin phantom with straight copper wire pieces, (b) Paraffin phantom with different diameter copper rings, (c) Paraffin phantom with a single copper ring larger than the diameter of the EM probe.
A second type of paraffin wax phantom was also developed to test the scanner’s ability to traverse an unknown topography. In this case, the same procedure as in the case of the rectangular phantoms is followed, except the mold does not need to be lined in aluminum foil. The mold in this case is the underside of an ordinary soda can. The curvature of the underside allows the paraffin to be easily removed without damaging the sample. Also in this case, either a single length of bare copper wire, or single loop is used. These phantoms are shown in Figure 3.8, and are referred to as the Round Phantoms. These are used to roughly mimic the topography of breasts removed in mastectomies.
Figure 3.8: Round paraffin phantoms, A) Round paraffin phantom with single copper loop, B) Round paraffin phantom with single copper wire length.

3.2.4 Imaging the Phantoms

Measurements of amplitude and phase shift by the EM probe A6 are made by raster scanning the probe across a phantom in order to create an image. In this case, the probe’s motion is controlled by the MAXNC stage for the rectangular phantoms and the Velmex stage for the round phantoms. The raster device is attached to the probe. The
probe’s tip is at an angle of approximately 20° from the vertical, as depicted in Figure 3.5. For the case of the rectangular phantoms, the driving function is a 7Vpp, 99 kHz, Sawtooth, the lock-in amplifier settings are detailed in Table 3.3, and the scope is set to 200mV/div for the phase output, 100mV/div for the magnitude output, and 5sec/div.

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Table 3.3: Lock-in Amplifier settings for rectangular phantom experiments.
The purpose of this experiment is to show that the A6 probe can be used as an imaging device. Therefore, the phantom is taped off with electrical tape to ensure a repeatable origin and to set the axes of the image. Next, the probe tip, i.e. the part of the probe angled towards the phantom surface, is centered on the origin of the phantom. The z-axis is brought down close enough to the phantom to partially depress the syringe/mini spring assembly. Also, care should be taken that the wheels are making even contact with the phantom surface, so that they will roll evenly across the phantom.

Once the probe is in place, the stage is zeroed such that this is the defined origin. Now, using the “Rel” keys on the lock-in amplifier, both the magnitude, $R$, and the phase, $\phi$, are zeroed. The offset of the magnitude, $R_{\text{offset}}$, and the reference phase, $\theta_{\text{ref}}$, are recorded. The stage is then programmed to move 87.5 mm in the x direction, at a rate of 2.08mm/s. In the case of the MAXNC, the uncertainty of the location of the probe tip is approximately 2 mm, since the rate is a parameterized function that must be tuned by stopwatch, and therefore has a human error uncertainty of about 1 second.

At the same time the stage begins to move, the oscilloscope begins a single line sweep. When this sweep is completed, the voltage information pertaining to phase and magnitude is collected and saved on a PC as a text file by using an RS-232 cable and the Agilent Scope Control Application software. The A6 probe is then brought to its zero location along the x-axis and is stepped along the y-axis in increments of 2.5 mm. Again, the Rel keys are used to zero the magnitude and phase, and the process is repeated until the probe has stepped the width of the phantom in the y-direction.
Once this data is collected, it is processed in MATLAB 7.1 and 3-D surface plots are generated. Each of these plots is interpolated linearly between data points. The data then can be compared to the known dimensions of the phantoms.

For the round phantoms, a single scan through the center of the phantom is performed. This is similar to a single sweep of the rectangular phantom. In the case of the round phantoms, the probe is set up as shown in Figure 3.9. This experiment investigates both the specificity of the probe with non-uniform terrain and the robustness of the raster design to handle the phantom curvature.
Figure 3.9: Positioning of the probe and raster device on the round phantoms.
Chapter 4: Results and Discussion

In this chapter, experimental measurements are reported along with a discussion of these results. In the next section, point-wise measurements on surgically excised tissues from human subjects are reported. Section 4.2 describes the results obtained on the supporting experiments on wire loops of different diameters as well as a discussion of the development of a numerical model. Finally, Section 4.3 presents the results of scanning the probe over phantoms previously described in Section 3.2.3 and Section 3.2.4 to obtain images. The potential to apply this new imaging strategy for visualizing surgically excised tissue for the purpose of quantifying margins is also discussed.

4.1 Surgically Excised Tissue

Tissue samples obtained from different human subjects with different cancers were subjected to point-wise measurements with the EM probe. This was done to ensure that cancerous tissue could be distinguished from healthy tissue. Measurements on two cases are described. The first is a lymphoma case where an infected lymph node was surgically removed from the thigh of the patient, along with a small section of healthy tissue (see Figure 4.1). The second is a signet ring cell metastatic ovarian cancer found implanted in the abdominal wall, omentum, and small bowel. The particular sample probed in this
work was an implanted mass in the abdominal wall. Results from each of these cases are described in detail next.

Figure 4.1: Surgically Excised Tissue Samples, Lymphoma Case

One point location was chosen as representative on each sample. Then, the probe was brought into contact with the diseased tissue following the procedure described in Chapter 3. This was repeated three times, alternating between the diseased and the healthy sample, for a total of eighteen data points.
The results from the lymphoma case are presented in Figure 4.2. Note that in some cases the error bars are smaller than the size of the data marker. There is a striking difference of nearly 3 Volts between the voltage recorded on the healthy tissue and the cancerous tissue, at a fixed phase of 34°. Lymphoma is a very specific cancer type, in which the margin lines of the cancer are clear. That is, the cancer is present in the lymph node but not likely to be found in the tissue around it. It can be seen that the EM probe is capable of distinguishing between cancer and healthy tissue without ambiguity.
Figure 4.2: Results for a diseased lymph node versus healthy tissue samples from the EM probe.

Figure 4.3 shows a micro PET/CT scan of a tissue specimen of an implanted mass excised from the abdominal wall of the patient in the signet ring cell case. The bright red regions indicate enhanced uptake of FDG signifying the presence of cancer. The schematic shown in Figure 4.4 displays the same surgically removed mass along with the locations where measurements were taken with the EM probe at a fixed phase. Measured
voltages corresponding to the locations on the specimen shown in Figure 4.5 are indicated in Figure 4.4. The region labeled as “2” contains a near-surface tumor, whereas regions “3” and “4” contain embedded tumors, and region “1” appears “healthy”. As can be seen from Fig. 4.5, the embedded tumors yield voltages (at a fixed phase) that correspond to the presence of cancer.

It is important to point out that signet ring cell cancers are rarely noticeable on clinical PET scanners because the metabolic rates of signet ring cell masses closely resemble those of the surrounding healthy tissue. Consequently, it is very difficult if not impossible to detect the presence of signet ring cell cancers. The reason that this cancer is discernible in the PET scan is because the image displayed in Figure 4.3 is obtained ex-vivo, after the tissue has been removed from the body. This removal of background signal from the body enables the cancer to be imaged in the surgically excised mass. In contrast, no such issues are expected to arise with the use of the EM probe either ex-vivo as can be seen in Fig. 4.5 or in-vivo intraoperatively. Also, it should be noted that at location 4 a tumor mass was felt by the surgeon that did not show up well on the PET/CT, however, it was seen by the EM Probe. The failure of the PET/CT to identify this mass is likely a lack of vasculature in the tumor that prevented elevated levels of FDG uptake.
Figure 4.3: Micro PET/CT image of signet ring cell cancer case, annotated with the points where the EM probe was used to analyze the same piece of tissue.
Figure 4.4: Diagram of signet ring cell case with EM probe measurement sites. Information known by the surgeon at the time of resection is also indicated.
Margin analysis is the study of how close to the edge of an incision cancer is present. If the cancer is too close to the edge of the resected tissue, the patient is more likely to suffer a recurrence since cancer cells are likely present outside the margins of the removed tissue. Clear margins can indicate that all of the cancer in a particular site has been removed, and can significantly help a patient’s prognosis, as well as help define a treatment plan (Chang, et al., 2009). The micro PET/CT image in Figure 4.3, may be taken as an example of a poor margin. The bright red section indicates the presence of cancerous tissue. The problem is that this image is not generally available to the surgeon.
in the OR. In most cases the patient receives a post-operative scan in which the results are not available until long after the patient exits the OR and is recovering from surgery. This means that the surgeon has no indication of the poor margin in the operating room, where they can attempt to resect more tissue. The intraoperative detection and ex-vivo imaging described in this thesis, may offer surgeons a way of having this image in the operating room while there is still time to resect more diseased tissue.

Another significant conclusion that can be drawn from the signet ring cell case is that the EM probe has a great potential not only for detecting cancer, but for imaging it. The fact that the average voltage drop at locations 2 and 3 were between 1.5 and 2 volts less than that of site 1, and approximately 4 volts more than that of site 4, shows that the probe is sensitive to its proximity to the cancer. Site 4 was the site of an embedded tumor that was felt by the surgeon, but not detected well by PET/CT, whereas, site 2 was a surface tumor, and site 3 was an embedded tumor.

As can be seen from the lymphoma and the signet ring cell cases, there are distinct and distinguishable differences between cancerous tissue and healthy tissue. However, the actual voltages are quite different between the two samples. This difference points to inherent variations among tissue types within the body. What is important to remember, is that this can be advantageous for imaging and detection with the EM probe, because cancer yields a distinctly different voltage drop than healthy tissue directly in its proximity, despite variations in tissues.
4.2 Supporting Experiments and Modeling

In this section, results from EM probe measurements on closed current loops are described. Although the wire loops have a substantially different electrical conductivity compared to biological tissue, these measurements serve to improve our understanding of the probe response and detection. In addition, these measurements provide information related to the variation of the probe signal with varying domain size of the eddy currents. Also described in this section is a numerical model used to attempt to understand the probe characteristics.

4.2.1 EM Probe Response to Controlled Eddy Current Domain Sizes

The EM probe’s response to controlled eddy current domain sizes has been separately examined (McFerran, 2009). Specifically, experiments conducted include the EM probe’s response to changes in domain size, location relative to the probe, driving frequency, and conductivity of the sample. Each of these experiments was performed using a sinusoidal input. From McFerran’s work, it has been shown that eddy current domain size influences the phase shift of the induced voltage in the receiver coil relative to the voltage of the driver coil much more than magnitude of the voltage. It was found that eddy currents of dimension 1 mm or smaller, corresponding to the thickness of the wires used, are not responsible for the observed EM probe signal but currents on the order of the diameter of the wire loops contribute to the observed signal. McFerran’s work also shows that the conductivity of the sample is an important consideration. It was found that as conductivity increases, the phase shift decreases.
The eddy current domain size experiments described here are repeated in a manner similar to that reported by McFerran, using a 99 kHz sawtooth waveform, in order to determine if the trends with eddy current domain size are consistent with the waveform used to analyze tissue samples. The experimental procedure has been outlined in the Experimental Apparatus and Procedure chapter. Results from the sinusoidal input, Figure 4.6, can then be compared to the sawtooth input, Figure 4.7. Please note, that the experimental error bars are on the same order of magnitude as the data markers.
Figure 4.6: Response of the EM probe to changes in eddy current domain size for a sinusoidal input. This experiment is performed by restricting the eddy currents loops to the diameters of copper wire loops.
Figure 4.7: Response of the EM probe to changes in eddy current domain size for a sawtooth input. This experiment is performed by restricting the eddy currents loops to the diameters of copper wire loops.

It can be seen from Figures 4.6 and 4.7 that both the sinusoidal and sawtooth responses follow a similar trend. The peak to peak voltage is smallest when the eddy current loop diameter is closest to that of the EM probe. Conversely, the phase shift is greatest when the eddy current loop diameter is closest to that of the EM probe. Also, the smaller the loop diameter, and by definition the eddy current loop, the phase shift and
peak to peak voltage output approach the case when there is no loop present (D=0). Likewise, as the loops become larger than the probe diameter, and the eddy current loops get larger, the phase and peak to peak voltage approach the no loop case. However, the slope is more gradual. This is because when the probe induces eddy currents in larger rings, those eddy current loops are stronger, so they interact more with the EM probe. However, as the loops exceed the diameter of the probe, the magnetic interactions between the probe and wire loop weaken because the wire loop interacts with weaker magnetic field lines from the probe. This indicates that eddy currents on the same order as the probe diameter have the largest effect on the probe signal.

Another important characteristic of the results that further display that the trends between the sinusoidal function and sawtooth function are consistent is that the sawtooth results for both magnitude and phase are simple multiplicative factors of those from the sinusoidal input. The phase shifts registered by the lock-in amplifier for the sawtooth is close to 50 times that for the sinusoidal input. Likewise, the peak to peak magnitudes for the sawtooth are approximately 6.4 times those for the sinusoid. These modified results are shown in Figures 4.8. and 4.9.
Figure 4.8: Comparison of experimental sawtooth phase response to a modified sinusoidal response.
The behavior of the lock-in amplifier was verified as follows. For the 7.28 mm wire loop, with a sawtooth reference and AC trigger, a 10 degree phase shift was measured. When the square wave was used as a reference the same 10 degree phase shift was observed for all three lock-in amplifier trigger settings, AC, positive pulse, and negative pulse. This verifies that the increased phase response of the current loops on the EM probe is not an artifact of the lock-in amplifier.
This is further verified by the magnitude data, which is also shown to differ by a constant multiplicative factor. This data was validated by measuring peak to peak voltage on an oscilloscope, so the reference signal as well as the lock-in amplifier, are not possible sources or error. It’s important to note that the multiplicative factors are not the same, nor are they necessarily expected to be the same. For example, according to McFerran, phase and magnitude responses differ greatly with respect to different sample types (McFerran, 2009).

4.2.2 Numerical Model

It is not only important to show the variations in magnitude and phase for different eddy current domain sizes experimentally, but it is imperative to attempt to understand and predict the response of the EM probe for a given sample. This understanding can help optimize the EM probe and its design for use in cancer detection.

McFerran has developed an analytical model for a sinusoidal input (McFerran, 2009). The results of this model showed excellent agreement with experiments for the case of sinusoidal excitation. In the analytical model, values for the mutual inductances were calculated from the vector potential, and then applied to the EM probe. In this section, a numerical model is developed for sawtooth excitation of the EM probe driver coil. Mutual and self inductances, as well as the wire loop AC resistances are taken from McFerran’s work (McFerran, 2009).
To predict the response of the EM probe to a sawtooth input, a circuit model approach was used. Figure 4.10 shows a diagram of the EM probe and current loop system. Beginning from the left, $V_o$ is the input voltage into the driver coil of the probe, a 7Vpp, 99 kHz, sawtooth. $R_b$ is the ballast resistor on the driver side. It is an 830 $\Omega$ precision resistor that serves as a voltage regulator for the circuit before the lock-in amplifier. $R_d$ and $L_d$ are the resistance and self-inductance of the driver coil, respectively. $C_d$ is a capacitive term on the driver side used to model capacitive effects between turns of the coil in the drive. Similarly, $R_l$ and $L_l$ represent the resistance and self-inductance of the current loop, and $R_r$ and $L_r$ are the resistance and self-inductance of
the receiver coil. Like $C_d$, $C_r$ accounts for capacitive effects within the receiver coil. Both $C_d$ and $C_r$ are parameters in this model.

The oscilloscope is included in order to consider the effects of a parallel capacitance on the receiver coil; it includes a high impedance resistor and a parallel capacitance which can be combined with the value of $C_r$. This is reasonable, because both the oscilloscope and the lock-in amplifier are high impedance measurement systems that are present during all experiments. The arrows labeled with an I, correspond to the different values of current in the model.

Figure 4.11: Circuit model representation of EM probe and current loop with the mutual inductances labeled. For the mutual inductances, the first indice represents the forcing entity and the second indice represents the induced entity. For instance, $M_{dr}$, is the mutual inductance caused by the driver, imposed on the receiver.
The first step in designing the circuit model is to determine the governing equations of the circuit representation. This is accomplished using Kirchhoff’s Voltage Law, and Kirchhoff’s current law. The resulting equations are:

\[ C_d \frac{dV_{cd}}{dt} = I_1 - I_d = -\frac{V_{cd} + V_0}{R_b} - I_d \]  
4.1

\[ C_r \frac{dV_{cd}}{dt} = I_r - I_2 = I_r - \frac{V_r}{R_s} \]  
4.2

\[ V_{cd} = R_d I_d + L_d \frac{dI_d}{dt} + M_{ld} \frac{dI_l}{dt} + M_{rd} \frac{dI_r}{dt} \]  
4.3

\[ R_l I_l + L_l \frac{dI_l}{dt} = -M_{dl} \frac{dI_d}{dt} - M_{rl} \frac{dI_r}{dt} \]  
4.4

\[ -V_{cr} = R_r I_r + L_r \frac{dI_r}{dt} + M_{dr} \frac{dI_d}{dt} + M_{tr} \frac{dI_l}{dt} \]  
4.5
Next, the governing equations are solved such that each equation is left in terms on only one first order differential equation. For instance, Equation 4.5 is left only in terms of the derivative of $I_r$. Each equation is then programmed into MATLAB, utilizing the numerical solver, ode15s. Ode15s was chosen because the system is stiff and small changes in parameters cause the system to become unstable. The stiffness of the system also validates the calculated values from the analytical model by Jennifer McFerran because the range of possible values of the parameters, such as the inductances, were limited for a numerical solution to still exist. Calculated values obtained from McFerran are listed in Table 4.1. Also, it should be noted that the values for the mutual inductance from the receiver to the loop, as well as the mutual inductance from the loop to the driver are assumed to be zero. Though, physically this is not likely to be the case, it is a simplifying aspect of the numerical model.
As mentioned earlier, the capacitances in the driver and in the receiver are unknown. In order to estimate these values, experimental scope traces were taken across the driver coil and the receiver coil when there was no sample present. $C_d$ and $C_r$ were then parameterized until the time domain outputs of the numerical model for the driver and receiver coils matched well. Examples are found in Figures 4.12 and 4.13 for fitting to a sinusoidal waveform input function. Figures 4.14 and 4.15 illustrate the varying of capacitances when using a sawtooth waveform input function. If the capacitance is set too small, the oscillations are generally greater than those observed in the experimental data. If the capacitance is too high, as in Figure 4.13, there are too few oscillations in the signal. Generally, the capacitance of the driver affects the driver signal predominantly. However, due to mutual inductance, the driver signal affects the receiver, so that the

<table>
<thead>
<tr>
<th>Current Loop Diameter</th>
<th>mm</th>
<th>0.00E+00</th>
<th>3.65E+00</th>
<th>4.80E+00</th>
<th>5.80E+00</th>
<th>7.28E+00</th>
<th>1.29E+01</th>
<th>2.17E+01</th>
<th>3.53E+01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop Resistance</td>
<td>ohm</td>
<td>0.00E+00</td>
<td>1.63E-04</td>
<td>2.76E-04</td>
<td>3.73E-04</td>
<td>5.18E-04</td>
<td>1.06E-03</td>
<td>1.93E-03</td>
<td>3.26E-03</td>
</tr>
<tr>
<td>Loop Inductance</td>
<td>Henry</td>
<td>0.00E+00</td>
<td>1.25E-09</td>
<td>2.76E-09</td>
<td>4.29E-09</td>
<td>6.83E-09</td>
<td>1.83E-08</td>
<td>3.98E-08</td>
<td>7.78E-08</td>
</tr>
<tr>
<td>Mutual Inductance Driver to Loop</td>
<td>Henry</td>
<td>0.00E+00</td>
<td>8.62E-09</td>
<td>2.47E-08</td>
<td>4.53E-08</td>
<td>8.71E-08</td>
<td>3.55E-07</td>
<td>4.02E-07</td>
<td>3.03E-07</td>
</tr>
<tr>
<td>Mutual Inductance Loop to Receiver</td>
<td>Henry</td>
<td>0.00E+00</td>
<td>5.98E-08</td>
<td>1.23E-07</td>
<td>1.96E-07</td>
<td>3.34E-07</td>
<td>1.17E-06</td>
<td>1.53E-06</td>
<td>1.16E-06</td>
</tr>
<tr>
<td>Mutual Inductance Driver to Receiver</td>
<td>Henry</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
</tr>
<tr>
<td>Mutual Inductance Receiver to Driver</td>
<td>Henry</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
<td>1.53E-04</td>
</tr>
</tbody>
</table>

Table 4.1: Mutual Inductances, Self-Inductances and loop resistances used in the numerical model. Values are obtained from McFerran.
combination of \( C_d \) and \( C_r \) is just as important as getting either \( C_d \) or \( C_r \), if both the receiver signal and driver signal are being matched to the experimental data.

Being able to reproduce the waveforms of the driver and receiver with no sample present by only changing the unknown parameters, \( C_d \) and \( C_r \), is a sign that the model is likely correct. This suggests that the governing equations describe the system appropriately. The validity of the values for the parasitic capacitances in the driver and receiver is further confirmed by the reproduction of the experimental traces using the numerical model to produce time traces of the driver and receiver outputs when using both a sinusoidal input and sawtooth input for values of a 0.3 nF capacitance on the driver and a 0.25 nF capacitance on the receiver.
Figure 4.12: Time domain prediction of the driver and receiver coils' response to a 7Vpp, 99 kHz, sinusoidal input, with poor values for the driver and receiver's capacitance chosen. The capacitance of the driver is 1nF, and the receiver’s capacitance is 1nF in this simulation.
Figure 4.13: Time domain prediction of the driver and receiver coils' response to a 7Vpp, 99 kHz, sinusoid with good values for the driver and receiver's capacitance chosen. The capacitance of the driver is 0.3nF and the receiver’s capacitance is 0.25nF in this simulation.
Figure 4.14: Time domain prediction of the driver and receiver coils' response to a 7Vpp, 99 kHz, sawtooth input, with poor values for the driver and receiver's capacitance chosen. The capacitance of the driver is 1nF, and the receiver’s capacitance is 1nF in this simulation.
Figure 4.15: Time domain prediction of the driver and receiver coils' response to a 7Vpp, 99 kHz, sawtooth with good values for the driver and receiver's capacitance chosen. The capacitance of the driver is 0.3nF and the receiver's capacitance is 0.25nF in this simulation.

As a check for validity with the analytical model and experiments, the numerical model was first run for a sine wave input. Those results are displayed in Figures 4.16 and 4.17. This shows that the numerical model is in excellent agreement with the experimental data and the analytical model for a sinusoidal input, especially in the phase response. In the magnitude response, each data point is approximately 40 mV from the experimentally measured peak to peak value. This is likely due to the fact that the capacitances chosen do not perfectly model the receiver output, as can be seen in Figure
4.15. The other differences between the numerical model and analytical model can be accounted for the fact the numerical model uses a circuit model approach to the problem.

Figure 4.16: Comparison phase shift output of the numerical model to experimental data for the EM probe, and the analytical solution developed by Jennifer McFerran for a 7VPP, 99 kHz, sinusoidal input.
Figure 4.17: Comparison of the magnitude output of the numerical model to the experimental data for the EM probe and the analytical solution developed by Jennifer McFerran for a 7VPP, 99 kHz, sinusoidal input.

It is shown that the numerical model cannot accurately predict the phase shift seen experimentally with a sawtooth function. Again, the trend is similar; however, the phase shift magnitudes are more similar to what was seen experimentally for a sinusoid. The magnitude is predicted well; however it is offset from the experimental data by approximately 200mV in the sawtooth waveform case. Again, this is due to the inability
to model the receiver output accurately with the values of parasitic capacitance. Figures 4.18 and 4.19, give the numerical model output compared with experimental data for a sawtooth waveform. Figure 4.20 shows a comparison of the phase shifts for the numerical model between using a sinusoidal driving function and a sawtooth driving function.

Figure 4.18: Comparison phase shift output of the numerical model to experimental data for the EM probe for a7VPP, 99 kHz, sawtooth input.
Figure 4.19: Comparison of the magnitude output of the numerical model to experimental data for the EM probe for a 7VPP, 99 kHz, sawtooth input.
Figure 4.20: Comparison of the phase output of the numerical model when a sawtooth driving function is used versus a sinusoidal driving function of the same amplitude and frequency, 7VPP, 99 kHz.
Figure 4.21: Comparison of the magnitude output of the numerical model when a sawtooth driving function is used versus a sinusoidal driving function of the same amplitude and frequency, 7Vpp, 99 kHz.

The fact that the forcing function has such little effect on the calculated phase shifts and contrary to what is observed experimentally for a sawtooth excitation, is enigmatic. It is suspected that the possible reason for this discrepancy is that electrical properties such as the coil impedances could be frequency dependant. The lock-in amplifier only considers one frequency, the dominant frequency of the reference signal, 99 kHz. The
coil, on the other hand, sees the infinite series of frequencies that comprise a sawtooth wave form, with the 99 kHz frequency being the lowest. Currently, each of the frequency dependant impedances, including resistance, is calculated only for the 99 kHz harmonic in the analytical model. This is why when a sinusoidal function is used to predict the EM probe’s output the agreement between calculation and experiments is quite good. For a sinusoid, the EM probe only sees a 99 kHz harmonic, as does the lock-in amplifier.

The calculated small changes in phase shifts for the sawtooth waveform and the sinusoid can also point to frequency dependent impedances. The change in a waveform modifies the phase shifts slightly and modifies the peak to peak voltages drastically. The peak to peak voltages calculated are comparable to those observed experimentally for both a sinusoidal input and a sawtooth input to the driving coil. Since the magnitude of the sawtooth voltage output is comparable to the experimentally measured value, it is suspected that the waveform shape plays a more dominant role in the magnitude data, whereas the range of frequencies with a dominant frequency at 99 kHz is what controls the phase shifts. Both this hypothesis and altering the numerical model to include frequency dependent impedances will be examined in a future body of work.

In addition to frequency dependent impedances, another possible culprit for the drastic amplification of the phase shifts when the sawtooth is imposed is that the sawtooth contains frequencies at or near the resonance of the EM probe. When operating at resonance, it is suspected that the EM probe will increase in sensitivity substantially. The reason the forcing function is not initially set to the resonant frequency is that the
lock-in amplifier cannot handle frequencies beyond 100 kHz, and it was shown that the resonant frequency of the EM probe is approximately 403 kHz. This was determined by doing a frequency sweep of the coil and observing when resonance occurs on an oscilloscope.

Figure 4.22: Experimental resonant frequency of the EM probe
Finally, the most promising explanation for the dramatic phase shifts seen when using a sawtooth input may be the effect of magnetic viscosity, also known as magnetic diffusion. Magnetic viscosity is associated with the action of a time varying magnetic field penetrating a sample through a type of diffusion. It is described by a characteristic time constant that is determined by the type of sample, the frequency of the changing magnetic field, and the time rate of change of the magnetic field. Eddy currents cannot develop in a sample until the magnetic field has diffused into the sample to the skin depth or if the sample is sufficiently thin, the whole sample.

In the low frequency limit, Maxwell’s equations may be combined to yield a diffusion equation for the magnetic induction, B:

\[
\frac{\partial \vec{B}}{\partial t} = \frac{1}{\sigma \mu} \nabla^2 \vec{B}
\]

where \( \sigma \) is the electrical conductivity and \( \mu \) is the magnetic permeability of the material exposed to the B field.
The quantity $D_m = \frac{l}{\sigma \mu}$ is the known as the coefficient of magnetic diffusivity, which has units of length squared over time. Thus, $D_m = \frac{l}{\sigma \mu} \approx \frac{l^2}{\tau_D}$ and the characteristic time for magnetic diffusion, $\tau_D$, can then be obtained:

$$\tau_D \approx l^2 \sigma \mu$$

$$l^2 \approx \frac{C}{(\omega \mu \sigma)^k}$$

where $l$ is a characteristic length on the order of the skin depth, and $C$ and $k$ are constants.

For copper, the characteristic time for diffusion is estimated to be between 1 and 10 microseconds. This is in contrast to the fall time of the sawtooth waveform, which produces the strongest eddy currents in the material, and takes only 100 nanoseconds. This suggests that the characteristic time it takes for eddy currents to develop in the sample is longer than the time it takes for the externally applied magnetic field to change drastically, thus introducing a significant phase shift. The reason this phase shift is not observed with a sinusoidal forcing driving signal, is that the magnetic field changes more gradually with time, changing over the course of 10 µs, so the formation of the eddy
currents is on the same time scale as the variation of the magnetic field, yielding smaller phase shifts.

This hypothesis is also supported by experimental measurements investigating the effects of varying conductivity of the samples, and the driving frequency (McFerran, 2009). The predicted phase shift can be found by Equation 4.9. Combining Equations 4.7, 4.8, and 4.9, the phase shift in terms of the sample conductivity and the driving frequency is determined, as is reflected in Equation 4.10.

\[
\Delta \phi \approx \tau_D \omega \\
\Delta \phi \approx \frac{C}{(\omega \sigma \mu)^{k-1}}
\]

This suggests that for values of the constant, \( k \), greater than 1, when the sample conductivity and/or the driving frequency are decreased, the phase shift will increase. This is reflected in the experimental measurements shown in Figure 4.23, where \( k \) is determined to be 1.67. This order of magnitude analysis shows that the introduction of the effects of magnetic viscosity into the numerical model may likely substantially increase the predicted phase shifts for a sawtooth excitation, yielding better agreement with experimentally measured values. Magnetic diffusion is a key piece of physics that needs to be incorporated into future analysis.
Figure 4.23: Experimental phase shifts resulting from the variation of wire loop conductivity and driving frequency (McFerran, 2009).

4.3 Imaging with the EM Probe

4.3.1 Scanning over a curved surface – precursor to imaging

To apply the EM probe for use as a postoperative detector and imager for surgical resections of cancer and assessing margins, the probe must be able to traverse a curved
surface without incurring damage or damaging the sample being analyzed. The raster
device described in Chapter 3 was specifically designed for this purpose. To explore the
potential of this design, the round phantoms were imaged as described in Chapter 3.

In order to accurately determine the position of embedded objects within the
phantoms, or simulated tumors, the projection of what the EM probe “sees” must be
estimated. Although the probe is set at a 20 degree angle from the vertical to ensure a
single point of contact with the specimen at any time, the magnetic field lines extend into
the surface of the specimen and thus, interact with it by inducing eddy currents at
different depths. It is assumed that the distance between the edge of the EM probe tilted
upward and the specimen is sufficiently large that the magnetic field lines cannot reach
beyond the back edge of the probe. With this assumption, simple geometry gives the
effective diameter of the probe as 12.5 mm, versus the 13.3 mm of the actual diameter of
the probe. Figure 4.24 shows the geometry of the probe, with a diagram of how the field
lines may appear in this configuration.
Both the phase and magnitude for the two different phantoms are shown in Figures 4.25, 4.26, 4.27, and 4.28. It is clear from these results that the raster device holds promise both as an imaging scheme and as a detector. In every case, the position of the ring or wire length was reproduced well. The figures showing phase output show much stronger signals over noise compared to the voltage maps and this will allow for improved imaging and detection.
Figure 4.25: Phase results of single line scan over the round phantom with an embedded copper ring. The physical location of the ring is marked, as well as the position of the front edge of the probe when the projected edge of the probe is no longer over the ring.
Figure 4.26: Magnitude results of single line scan over the round phantom with an embedded copper ring. The physical location of the ring is marked, as well as the position of the front edge of the probe when the projected edge of the probe is no longer over the ring.
Figure 4.27: Phase results of single line scan over the round phantom with an embedded copper length of wire. The physical location of the wire length is marked, as well as the position of the front edge of the probe when the projected edge of the probe is no longer over the ring.
Figure 4.28: Phase results of single line scan over the round phantom with an embedded copper length of wire. The physical location of the wire length is marked, as well as the position of the front edge of the probe when the projected edge of the probe is no longer over the ring.

An interesting feature of the round phantom with the ring is that the center of the ring is not captured. This is to be expected because the induced magnetic field in the wire loop is strongest at the center of the loop; therefore the signal should be strongest there. Another fact evident in these images is that all objects smaller than the effective diameter of the probe appear to approximately have the effective size of the probe. This
suggests that future probe designs, should have smaller effective diameters in order to achieve greater spatial resolution.

It is also important to understand the errors in position. Since the Velmex stage was used for the round phantoms, the error in the position of the probe tip at any given time was approximately 0.25 mm. This is reflected in how well the edges of the phantom artifacts are reproduced in the scans. A physical problem that was encountered during these experiments is that the raster device could not climb an upward slope of a paraffin wax phantom. This is believed to be problematic for two main reasons. One, paraffin is hard and slippery, therefore the contact friction of the raster device was not high enough to enable the EM probe to successfully traverse the upward incline. Also, the curvature of the phantom itself is very large, unlike what is expected from excised tissue samples. Two, the raster device is somewhat heavy since the EM probe is composed of several layers of copper wire and nail polish adhesive and the raster structure is composed of several different plastics. This likely contributed to the system’s inability to lift itself over the upward incline.

To remedy this problem, the probe was started at the edge of the paraffin, with the raster wheels near the peak of the phantom, as described in Chapter 3. On the downgrade of the round phantom, the raster device performed as designed. The probe remained in contact with the surface of the phantom, gently lowering as needed, defined by the curvature. Since the navigation of the raster device was so successful on the downward slope it is easier to simply set the origin of the phantom at the zenith of the contoured
sample. Then several scans can be performed, each starting at the origin and negotiating only the downgrade of the sample. However, it would be best if future work would incorporate redesigning the raster device to allow for better navigation of varied terrain.

4.3.2 Imaging with the EM probe

Imaging with the EM probe is necessary for applications to postoperative detection. If the surgeon can have more information about the success of the surgery before it is over, then more surgeries will be successful and more lives could be saved. To initially examine the EM probe’s ability to image, a set of three different rectangular phantoms are used. These phantoms are described in detail in Chapter 3.

Each rectangular phantom was developed to examine different issues that may arise when imaging tissue. The first phantom has a single large wire loop to explore how well the probe can resolve a structure larger than its diameter. The second phantom contains three smaller copper wire loops and is designed to determine if the different loops can be resolved when in close proximity to each other. Finally, the third rectangular phantom has three straight copper wire lengths. Its purpose is to observe the quality of the image when both the magnitude and phase shifts are considerably smaller. It should be noted that the error in position along the long axis of these images is ±2mm. This is because there is a 1 sec uncertainty in the MAXNC feed rate, and the scanning rate is 2.08 mm/sec. This problem can only be addressed by using a more precise stage, such as the Velmex system, but with a third stage added for the third degree of freedom.
Figure 4.29: Diagram of the rectangular, paraffin phantom with one large copper loop. The axes used to scan the image from are marked and the coordinates are labeled.
Figure 4.30: Phase output of the rectangular, paraffin phantom with one larger copper loop. Step size along the short edge is 2.5 mm. The phantom was scanned along the long edge at a rate of 2.08 mm/sec. The feature locations from Figure 4.29 have been marked for comparison.
Figure 4.31: Magnitude output of the rectangular, paraffin phantom with one larger copper loop. Step size along the short edge is 2.5 mm. The phantom was scanned along the long edge at a rate of 2.08 mm/sec. The feature locations from Figure 4.29 have been marked for comparison.

It can be seen from Figures 4.30 and 4.31 that the EM probe can resolve something larger than its diameter; however, the edges are less distinct than the center of the ring in both the phase and magnitude images. This is likely because the intensity of the magnetic field produced by the eddy currents in the loop is greatest at the center. This effect will be less apparent in the case of tissues, because there the eddy currents are not as restricted as they are in the case of the wire loop. Moreover, Figures 4.30 and 4.31 clearly establish that the phase information yields much less ambiguous images than the images constructed from the magnitude of the induced voltages in the receiver coil.
These results further emphasize the fact that phase changes more significantly with smaller changes in sample attributes, i.e. changes in eddy current size, or conductivity, compared to changes in the magnitude. Finally, the error in the detection of the ring along the vertical axis is explained by the coarseness of the scan along that axis, i.e in increments of 2.5 mm. It is further explained by the diameter of the probe, which is 13.3mm. If the probe is centered about the scanning line, then the probe can gather information from nearly 7 mm on either side of the probe. Those interactions, however, are quite weak, but within 2-3mm, the information is likely to be conveyed. For instance, a scan with the probe centered at 7.5 mm can detect the edge of the ring, which is located at 10mm.
Figure 4.32: Diagram of the rectangular, paraffin phantom with three small copper loops. The axes used to scan the image from are marked and the coordinates are labeled.
Figure 4.33: Phase output of the rectangular, paraffin phantom with three small copper loops. Step size along the short edge is 2.5 mm. The phantom was scanned along the long edge at a rate of 2.08 mm/sec. The feature locations from Figure 4.32 have been marked for comparison.
Figure 4.34: Magnitude output of the rectangular, paraffin phantom with three small copper loops. Step size along the short edge is 2.5 mm. The phantom was scanned along the long edge at a rate of 2.08 mm/sec. The feature locations from Figure 4.32 have been marked for comparison.

In the case of the rectangular paraffin phantom with the three small copper rings, the locations of the rings were reproduced in both images that used the phase measurements and voltage magnitudes, respectively. Notably, the smallest ring placed near another larger ring, could not be distinguished from the larger ring. The images show them touching when in fact they are not. This is likely due to the 2mm error associated with scanning, in combination with the coarse steps in the vertical direction. Also very noticeable in both the phase and voltage magnitude images for this phantom, is that the rings appear to be the same diameter as the probe. This is evident both along the scanning axis and the stepping axis. This further suggests the need for a smaller probe, which will increase the spatial resolution of the detector and imager. Finally, since the
copper wire loops used in this phantom give rise to some of the largest voltage magnitudes and phase shifts, both the magnitude and phase are effective for detection in this phantom. This may not be true for imaging biological tissues.

Figure 4.35: Diagram of the rectangular, paraffin phantom with three straight lengths of copper wire. The axes used to scan the image from are marked and the coordinates are labeled.
Figure 4.36: Phase output of the rectangular, paraffin phantom with three straight lengths of copper wire. Step size along the short edge is 2.5 mm. The phantom was scanned along the long edge at a rate of 2.08 mm/sec. The feature locations from Figure 4.35 have been marked for comparison.
Figure 4.37: Magnitude output of the rectangular, paraffin phantom with three straight lengths of copper wire. Step size along the short edge is 2.5 mm. The phantom was scanned along the long edge at a rate of 2.08 mm/sec. The feature locations from Figure 4.35 have been marked for comparison.

In the case of the third rectangular paraffin phantom with the three straight copper wires, the quality of both the phase and magnitude measurements decreased considerably. This is expected because now the eddy current loops are on the order of the thickness of the wire, less than a millimeter, versus several millimeters. Again, the position of the wires was correctly reproduced with the problem of the wire width, only 1 mm, appearing to be on the order of the effective diameter of the probe, 12.5 mm. The image of this phantom based on the magnitude of the voltage induced in the receiver coil only ranges about 15 mV, whereas the phase-based image has phases that range approximately 2.5
degrees, corresponding to a 125mV range, per the lock-in amplifier’s conversion scale. Therefore, it is easier to resolve changes in phase in the presence of noise rather than magnitude, proving it is a more powerful means of producing images.
Chapter 5: Summary and Conclusions

The use of an EM probe for the purpose of detecting and imaging tissue with embedded cancerous tumors has been examined in this work. It has been shown that the EM probe can differentiate cancerous tissue from healthy tissue and that the method shows promise for intraoperative detection of cancer. The EM probe utilizes phase sensitive detection through the use of a lock-in amplifier. The motion of the probe is controlled by a precision stage. The forcing function to the probe is a 7 Vpp, 99 kHz, sawtooth waveform. The success of the distinction of cancer from healthy tissue was demonstrated in ex-vivo measurements in two clinical cases, one a lymphoma, and the other a signet ring cell ovarian cancer found metastasized in the abdomen. In both cases, point-wise measurements of the excised tissue were made and cancer was differentiated from healthy tissue.

With the successful detection of cancer in surgically excised tissue, an attempt was made to better understand the source of the signal produced by the probe. This work was based on the work of McFerran (McFerran, 2009). In this thesis, the effect of eddy current domain size on the phase and magnitude of the receiver voltage using a 7 Vpp, 99 kHz, sawtooth waveform was explored. It has been shown that eddy current domain size has an influential effect on the phase and magnitude outputs of the EM probe. It has also been shown that eddy currents on the same order as the probe diameter have the largest
effect on the observed signal. Finally, it has been shown that phase is more sensitive to changes in eddy current domain size than the magnitude of the induced voltage in the receiver.

To further interpret and to predict the effect of domain size on phase and magnitude measurements from an EM probe, a numerical model has been developed. The numerical model utilizes a circuit representation of the EM probe and a single eddy current loop. The model considers the effects of parasitic capacitances, self-inductances, mutual inductances, and resistances of the driver coil, receiver coil, and the eddy current loop. The model agrees well with experimental data when a sinusoidal waveform forcing function is used in the driver coil. The predicted phase and magnitude outputs closely match the experimental data. However, when a sawtooth waveform is used for the driver voltage, the numerical model under predicts the phase by a factor of 50. The magnitude of the voltage induced in the receiver calculated by the numerical model is predicted well, within errors associated with parameterization of the parasitic capacitances. It is concluded that the sources of the error in phase for a sawtooth driver input may be the frequency dependent electrical properties that are not considered in the model. Another deficiency in the model is the assumption on the importance of mutual inductance from the loop to the driver, as well as from the receiver to the loop. In the numerical model these effects were considered to be nonexistent. Finally, the physics associated with magnetic viscosity needs to be explored further. It has been shown that it is probable that the relativity long characteristic time for the externally applied magnetic field to penetrate
a metallic sample and induce eddy currents may be responsible for the large phase shifts observed in the case of sawtooth excitation.

With the knowledge that it is just as important to monitor phase as it is voltage, a device to raster the EM probe without affecting its functionality has been developed for the purpose of imaging biological tissue extracted during cancer surgery. The raster device is composed of non-conducting parts, namely plastics, and it has been found to allow the probe to remain in contact with an unknown terrain exceptionally well on a downward slope, though not for an upward slope. Nevertheless, the strategies described in this thesis allow the EM probe to be used immediately on a sample by setting the origin as the zenith of the sample and scanning along the downgrades. In the long term, it is recommended that a redesign of the raster device be undertaken in the future.

Images based upon the magnitude of the induced voltage in the receiver coil of the EM probe and the phase, were obtained for three paraffin, rectangular, phantoms. These phantoms were used to examine three different situations: how the EM probe images a loop larger than its diameter, how the probe can distinguish between two loops in close proximity to one another, and finally, how well the EM probe images a phantom which produced low signal. It has been shown with these phantoms, that phase-based imaging is a more sensitive technique compared to imaging using voltage magnitudes. It has also been shown that the spatial resolution of the images may be increased by decreasing EM probe’s diameter. There is a balance that must be struck, however, because the probe is most affected by eddy current loops on the same order as its
diameter. This indicates that quantifying the eddy current domain size within cancerous tissue will be valuable. Experiments on the phantoms also show that any object smaller than the probe’s effective diameter, will be imaged as though it were approximately as large as the probe’s effective diameter. Also, any object that is larger than the probe’s diameter runs the risk of poor imaging at the edges. This effect will be less apparent in the tissue cases, because there the eddy currents are allowed to develop freely in the geometry.

The imaging of phantoms can be directly applied to surgically excised tissue samples. The EM probe’s ability to detect small changes in the specimen’s electromagnetic characteristics, as well as to reproduce the location of the variation of these changes with known uncertainties will allow for the successful imaging of tissue. For instance, in the signet ring cell case, the probe detected variations in signal based on its proximity to cancer, in this case, it is believed that the EM probe can and will produce an image of the locations containing cancer. This will be an invaluable tool for surgeons in quantifying surgical margins and provide priceless peace of mind for patients and their families.
Chapter 6: Recommendations for Future Work

The investigation into the use of an EM probe for the detection and imaging of cancer is far from concluded in this thesis. It is proposed that this work be continued to its fruition at clinical trials and as standard medical practice in the hopes that it will improve the field of surgical oncology and ultimately save patients’ lives. To accomplish these goals a number of short term and long term recommendations are suggested.

Categorization of phase and voltage magnitudes in tissue samples from different parts of the body may be useful. This information may provide valuable information about the variations within the body with different tissue types, as well as help researchers develop a model that accurately predicts the response to a certain tissue type. It is also imperative to conduct measurements on various types of cancer. It is suspected that the heterogeneity of tumors or increased capillary splitting in their vicinity causes the signal in the EM probe. The biology of tissues needs to be studied especially with regard to the exact mechanisms that result in eddy current formation and the circulation of charges in tissue when subjected to a time-varying magnetic field.

It is imperative that the probe characteristics and signal be understood in greater depth. It has been shown experimentally that the sawtooth waveform increases the phase and magnitude of induced voltages. The numerical model developed in this thesis was
unable to reproduce or explain the large phase shifts observed experimentally in the case of the wire loops for sawtooth excitation. It is possible that the phase response could not be predicted correctly because of the exclusion of frequency dependent impedances and inductances in the model. If the frequency dependent impedances cause the drastic phase shifts, it will be instructive to look at other waveforms, both numerically and experimentally, such as a square wave. The square wave includes many frequency harmonics analogous to the sawtooth wave and will excite the coil at multiple frequencies as well. It is also possible that the numerical model failed to predict the large phase shifts seen experimentally because the effects of magnetic viscosity were not taken into consideration. In future work it is crucial that these effects be quantified and incorporated into the numerical model.

Once the EM probe is better understood, issues involving imaging should be addressed. First, the raster device should be redesigned to accommodate better navigation of unknown terrain. A passive design is best, but feedback control might be the best option. A possibility would be to incorporate optical sensors that provide feedback to the stage enabling vertical height adjustment. Also, the probe should be optimized. The tradeoff between sensitivity and spatial resolution needs to be investigated. This should be done first by a combination of numerical and analytical model predictions then verified experimentally.

Finally, extension to 3-D imaging should be explored. It is well known that depth of penetration is a frequency dependent property. It is recommended that the driving
frequency be exploited to gather information about subsurface artifacts, such as embedded tumors. This can be modeled numerically, addressed experimentally with phantoms, and then explored with excised tissue samples. 3-D imaging will be a valuable tool for an imager and detector of excised tissue samples.
References


Appendix

A. MAXNC Program code

Steps for the user:

1) Turn MAXNC on and start program by typing MAX in the dos MACNC environment
2) Follow on screen instructions, i.e. Turn on the CAPS lock, hit H for home switches
3) Press 5 for Jog Commands
4) Jog in the X, Y, and Z axes to the desired origin, i.e. zero point location
5) Press M for menu
6) Press 6 for the zero commands
7) Press 0 for all zero
8) Press 3 to get to MDI mode
9) Type G0Z0.4 to move the MAXNC 0.4 inches in the positive Z direction
10) Hit Enter twice to return to main menu
11) Either press 1 and load MOUSE.DAT or press 4 and edit the current program with the following commands:

G1Z0.0F5
G4P5000
G1Z0.4F5
G1Z0.0F5
G4P5000
G1Z0.4F5
G1Z0.0F5
G4P5000
G1Z0.4F5
M30

12) Hit M for the main menu, press 2 for run
13) If necessary spacebar will interrupt the program
14) Repeat process as needed.
B. MATLAB Scripts:

Excised Tissue: Lymphoma

Data reduced in Excel format for entry into MATLAB .m file

Matlab Script for plotting the Lymphoma results:
%excised_plotter.m
%Plots the results for the excised tissue case: Lymphoma 12-12-2009
%Uses reduced data from the lymphoma12-12-09.xls file

clear all; close all; clc;

% Healthy
trial=[2 3 4];

avg_h=[1.1452 1.01666667 0.9375];
high_h=[1.25 1.05 0.96875];
low_h=[1.0915 0.96875 0.90625];
e_high_h=high_h-avg_h;
e_low_h=avg_h-low_h;

figure(1)
errorbar(trial,avg_h,e_low_h,e_high_h,'ko', 'MarkerFaceColor','k', 'MarkerEdgeColor','k');
xlabel('Trial');
ylabel('Average voltage drop, V');
title('Healthy Sample: Lymphoma 12-12-2008')
legend('Healthy Sample')
axis([1 5 0 3])
set(gca,'xtick',[2 3 4])

% Tumor
avg_t=[2.95833333 3.11458333 2.82291667];
high_t=[2.96875 3.15625 2.875];
low_t=[2.9375 3.09375 2.78125];
e_high_t=high_t-avg_t;
e_low_t=avg_t-low_t;

figure(2)
errorbar(trial,avg_t,e_low_t,e_high_t,'rs', 'MarkerFaceColor','r', 'MarkerEdgeColor','r');
xlabel('Trial');
ylabel('Average voltage drop, V');
title('Cancerous Sample: Lymphoma 907762962')
legend(['Cancerous Sample'])
axis([1 5 1 4])
set(gca,'xtick',[2 3 4])

figure(3)
errorbar(trial,avg_h,e_low_h,e_high_h,'ko', 'MarkerFaceColor','k', 'MarkerEdgeColor','k');
hold on
errorbar(trial,avg_t,e_low_t,e_high_t,'rs', 'MarkerFaceColor','r', 'MarkerEdgeColor','r');
xlabel('Trial');
ylabel('Average voltage drop, V');
title('Surgically Excised Lymphoma: 907762962')
legend(['Healthy Sample','Cancerous Sample'])
axis([1 5 0 4])
set(gca,'xtick',[2 3 4])
grid on
Excised Tissue: Signet Ring Cell Cancer

Data reduced in Excel format for entry into MATLAB .m file

<table>
<thead>
<tr>
<th>Healthy</th>
<th>Left Tumor</th>
<th>Center Tumor</th>
<th>Right Tumor</th>
<th>Healthy</th>
<th>Left Tumor</th>
<th>Center Tumor</th>
<th>Right Tumor</th>
</tr>
</thead>
<tbody>
<tr>
<td>high</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>a 0.03175</td>
<td>-6.53075</td>
<td>-4.469</td>
<td>-4.87525</td>
<td>0.06225</td>
<td>-4.81275</td>
<td>0.063</td>
<td>-2.812</td>
</tr>
<tr>
<td>b -0.09325</td>
<td>-6.59325</td>
<td>-0.594</td>
<td>-4.87525</td>
<td>0.06225</td>
<td>-4.5315</td>
<td>0.0005</td>
<td>-2.8745</td>
</tr>
<tr>
<td>c -0.187</td>
<td>-6.6575</td>
<td>-0.56275</td>
<td>-5.094</td>
<td>0.0935</td>
<td>-4.5315</td>
<td>-0.1245</td>
<td>-2.96825</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coordinates</th>
<th>High</th>
<th>Low</th>
<th>Average</th>
<th>1-2-2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>6.5625</td>
<td>4.53125</td>
<td>4.875</td>
</tr>
<tr>
<td>Healthy</td>
<td>0</td>
<td>0</td>
<td>6.511</td>
<td>4.40625</td>
</tr>
<tr>
<td>Left Tumor</td>
<td>-2.4622</td>
<td>-1.578</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center Tumor</td>
<td>-0.8045</td>
<td>-1.423</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Tumor</td>
<td>0.425</td>
<td>-1.578</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Matlab Script for plotting the Lymphoma results:

```matlab
% Plotter for Signet Ring Cell Cancer
% Same Plotting methods can be used for any point-wise cancer methods
% excised_plotter01_05.m
clear; clc; clf;

location=[1 2 3 4];

avg=[6.511 4.40625 4.697916667 2.864583333]; % Determined by observing
% the voltage drops across the
%average high=[6.5625 4.53125 4.875 2.875]; % Corresponds to largest voltage drop observed on the scope
low=[6.4705 4.28125 4.59375 2.84375]; % Corresponds to the smallest voltage drop observed on the scope

e_high=high-avg;
e_low=avg-low;

figure(1)
errorbar(location,avg,e_low,e_high,'ro', 'MarkerFaceColor','r', 'MarkerEdgeColor','r');
xlabel('Location');
ylabel('Average voltage drop, V');
title('Signet Ring Cell Cancer Case: 1-2-2009')
%grid on
set(gca,'xtick',[1 2 3 4])
x=[0 -2.4622 -0.8045 0.425];
y=[0 -1.578 -1.423 -1.578];
```

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Matlab Script for plotting the experimental results of different wire loop diameters:

```matlab
% RESPONSE OF A6 TO WIRE LOOPS OF DIFFERENT DIAMETERS
% Plots experimental and theoretical results showing the magnitude and
% phase response of A6 to 18 gage copper wire loops of different
diameters.
% Driving signals: 7 Vpp, 99 kHz sawtooth.
% SR510 Lock-in Amplifier
% fully surrounded ring with probe.

clear; clc; close all;

a_in=[0 0.146 0.192 0.232 .291]; %loop diameter, inches
a=a_in.*25.4; %loop diameter, mm
Dvv=[0 0.146 0.192 0.232 0.291 0.514 0.867 1.411];
D_mm=Dvv*25.4; %wire loop diameters in mm

%Experimental Data A6 Sawtooth
Roff=[-260.0 -261.8 -261.5 -261.8 -260.8 -260.8 -258.6];
high1=abs((Roff-[0.2 0.7 5.0 -10.3 -18.7 -45.8 -38.7 -9.3])/50); %V
low1=abs((Roff-[0 0.2 4.6 -10.2 -18.6 -45.7 -38.5 -9.2])/50);
avg1=(high1+low1)./2;
H1=high1-avg1;
L1=avg1-low1;

% Phase
phi1=[0 -0.25 2.3 5.85 9.5 43.15 32.05 8.2];
high_phi1=0.1;
low_phi1=0.1;

% EXPERIMENTAL DATA A2 Sinusoid
% Magnitude
high2=[819 813 807 794 788 719 738 794]./1000.*6.4; %Vpp receiver
low2=[800 800 794 788 782 713 719 788]./1000.*6.4;
avg2=(high2+low2)./2;
H2=high2-avg2;
L2=avg2-low2;

% Phase
phi2=[0 0.075 0.125 0.175 0.225 0.285 0.400 0.050]*50;
high_phi2=0.025;
low_phi2=0.025;

figure(1)
errorbar(D_mm,phi1,low_phi1,high_phi1,'rd','linewidth',2); hold on;
errorbar(D_mm,phi2,low_phi2,high_phi2,'ko','linewidth',2); hold off;
title('Phase Response of EM Probe to changes in Eddy Current Domain Size')
legend('Sawtooth','50x Sinusoid');
xlabel('Loop Diameter, mm'); ylabel('Phase Shift, deg')

figure(2)
errorbar(D_mm,avg1,L1,H1,'rd','linewidth',2); hold on;
```
errorbar(D_mm,avg2,L2,H2,'ko','linewidth',2); hold off
title('Magnitude Response of EM Probe to changes in Eddy Current Domain Size')
legend('Sawtooth','6.4x Sinusoid');
xlabel('Loop Diameter, mm'); ylabel({'Peak to Peak', 'Voltage Drop, V'});

a_in=[0 0.146 0.192 0.232 0.291]; %loop diameter, inches
a=a_in.*25.4; %loop diameter, mm
Dvv=[0 0.146 0.192 0.232 0.291 0.514 0.867 1.411];
D_mm=Dvv*25.4; %wire loop diameters in mm

%Sawtooth
%Magnitude
Roff=[-260.0 -261.8 -261.5 -261.1 -260.8 -260.8 -258.6];
high1=abs((Roff-[.2 -2.7 -5.0 -10.3 -18.7 -45.8 -38.7 -9.3])/50); %V
low1=abs((Roff-[0 -2.5 -4.6 -10.2 -18.6 -45.7 -38.5 -9.2])/50);
avg1=(high1+low1)./2;
H1=high1-avg1;
L1=avg1-low1;

% Phase
phi1=[0 -0.25 2.3 5.85 9.95 43.15 32.05 8.2];
high_phi1=0.1;
low_phi1=0.1;

% EXPERIMENTAL DATA A2 Sinusoid
% Magnitude
high2=[819 813 807 794 788 719 738 794]./1000; %Vpp receiver
low2=[800 800 794 788 782 713 719 788]./1000;
avg2=(high2+low2)./2;
H2=high2-avg2;
L2=avg2-low2;

% Phase
phi2=[0 0.075 0.125 0.175 0.225 0.225 0.400 0.050];
high_phi2=0.025;
low_phi2=0.025;

figure(3)
subplot(2,1,1)
errorbar(D_mm,avg1,L1,H1,'rd','linewidth',2);
title('Phase Response of EM Probe to changes in Eddy Current Domain Size', '99kHz 7Vpp Sawtooth');
xlabel('Loop Diameter, mm'); ylabel({'Peak to Peak', 'Voltage, V'});
subplot(2,1,2)
errorbar(D_mm,phi1,low_phi1,high_phi1,'rd','linewidth',2);
xlabel('Loop Diameter, mm'); ylabel('Phase Shift, deg');

figure(4)
subplot(2,1,1)
errorbar(D_mm,avg2,L2,H2,'rd','linewidth',2);
title({'Phase Response of EM Probe to changes in Eddy Current Domain Size', '99kHz 7Vpp Sinusoid'});
xlabel('Loop Diameter, mm'); ylabel({'Peak to Peak', 'Voltage, V'});

subplot(2,1,2)
errorbar(D_mm, phi2, low_phi2, high_phi2, 'rd', 'linewidth', 2);
xlabel('Loop Diameter, mm'); ylabel('Phase Shift, deg');
Matlab Script for Numerical Model Simulation of the phase and voltage output of each wire loop simultaneously, there is no time domain output (utilizes the solver function file: A6_solver_final.m):

% Uses the A6_solver_final to calculate phase and magnitude shifts for each current loop diameter Dvv, for the number of periods, n.
clear; clc; clf; close all;
global Vo w Ld Lr Ll Rd_plus_Rb Rr Rl Md1 Mdr Mld Mrd Mr1 Cd D cr RsRscope
n=6;

% 99 kHz 7VPP Sawtooth

%%%%%%%%%Input Function Characteristics%%%%%%%
Vo=7; %Vpp
freq=99000; %Hz, driving frequency
w=2*pi*freq; %rad/sec, circular driving frequency
T=1/freq; %sec, period of driving frequency
dt=1e-9; %step in time, 1 ns
Rscope = 1e7; % 10 MOhms or 100 MOhms depending on the scope or device used

%%%%%%%%%Driver%%%%%%%
Cd=.3e-9; % capacitance in parallel with driver coil, Farads
% Cd=5e-11;
Ld=69.6e-6; %H, self inductance of driver
% Ld=1e-4;
Rd_plus_Rb=832.54; %ohm, ballast resistance + resistance of driver coil
Rb=830; %ohm, ballast resistance?

%%%%%%%%%Receiver%%%%%%%
Cr=.25e-9; % capacitance in parallel with receiver coil, Farads
Rr=6.36; %ohm, resistance of receiver
Lr=475.25e-6; %henry, self inductance of receiver

%%%%%%%%%Loop%%%%%
Dvv=[0 0.146 0.192 0.232 0.291 0.514 0.867 1.411];
for vv=1:length(Dvv)
D=Dvv(vv); %in, diameter of loop
Dia=D;
Rl_vv=[0 .1628 .2755 .3734 .5179 1.0641 1.9287 3.2610]./1000;
Rl=Rl_vv(vv); %ohm, resistance of the loop
Ll_vv=[0 1.24879350761857e-009 2.75894738140862e-009...
  4.29423449575244e-009 6.82835761444735e-009 18.2584743251578e-009...
  39.8291291590544e-009 77.7630043346054e-009]; % Henry, self inductance
% of loop
Ll_vv=Ll_vv;
% Ll = adjusted inductance of the loop

%%%%% Mutual Inductances %%%%
Mdl_vv = [0 8.62368567372776e-009 24.6818107229983e-009 ... 354.640538909824e-009 ... 402.098956119e-009];
Mlr_vv = [0 59.7950262523893e-009 122.808803074210e-009 ... 334.48851113700e-009 ... 1.53349667242936e-006 ... 1.15861762092737e-006];

Mld_vv = [0 2.202177e-08 4.519879e-08 7.201838e-08 ... 4.0445e-07 ... 3.945316e-07];
Mrd = 1.5306e-004;

Mrl_vv = [0 2.340714e-08 6.702270e-08 ... 2.370063e-07 ... 1.560295e-06 ... 1.182771e-06];

if D~=0;
    tspan = [0:dt:n*T];
    y0 = [0,0,0,0,0];
    options = odeset('OutputFcn','odeplot');
    [t, I_o] = ode15s('A6_solver_final', tspan, y0, options);
    I = zeros(length(I_o), 3);
    I(:,1) = I_o(:,1);
    I(:,3) = I_o(:,3);
    I(:,2) = I_o(:,2);
    I(:,4) = I_o(:,4);
    I(:,5) = I_o(:,5);
else
    tspan = [0:dt:n*T];
    y0 = [0,0,0,0,0];
    options = odeset('OutputFcn','odeplot');
    [t, I] = ode15s('A6_solver_final', tspan, y0, options);

end
end

if D~=0;
    \% I(1)=I_R; I(2)=I_D; I(3)=V_CR; I(4)=V_CD;
    num=-I(:,4) - (Rr*I(:,1)) + ((Mlr*Mdl-Mdr*Ll)*I(:,5)/(Ll*Ld-Mdl*Mld));
    num=num + ((Mdr*Ll-Mlr*Mdl)*(Rd_plus_Rb-Rb)*I(:,3)/(Ll*Ld-Mdl*Mld));
    num=num + ((Mlr*Ld-Mdr*Mld)*(Rd_plus_Rb-Rb)*I(:,3)/(Ll*Ld-Mdl*Mld));
    denom=denom/Ld/(Ll*Ld-Mdl*Mld);
    dIr=num/denom;
    dIl=-((Rl*Ld*I(:,2)/(Ll*Ld-Mdl*Mld)) - (Mdl*I(:,5)/(Ll*Ld-Mdl*Mld)));
    dIl=dIl + (Mdl*(Rd_plus_Rb-Rb)*I(:,3)/(Ll*Ld-Mdl*Mld));
    dIl=dIl + ((Mdr*Mdl-Mrl*Ld)*dIr/(Ll*Ld-Mdl*Mld));
    dIl=dIl + (Mdl*(Rd_plus_Rb-Rb)*I(:,3)/(Ll*Ld-Mdl*Mld));
    dId=(I(:,4)/Ld) - ((Rd_plus_Rb-Rb)*I(:,3)/Ld) - (Mld*dIl/Ld) - (Mrd*dIr/Ld);
    Vd=((Rd_plus_Rb-Rb)*I(:,3))+(Ld*dId)+(Mld*dIl)+(Mrd*dIr);
    Vl=Rl*I(:,2)+Ll*dIl;
    Vr=-Rr*I(:,1)-Lr*dIr-(Mlr*dIl)-(Mdr*dId);
    Ir=I(:,1); Id=I(:,3); Il=I(:,2);
else
    \% I(1)=I_R; I(2)=I_D; I(3)=V_CR; I(4)=V_CD;
    dIr=(Ld*I(:,3)/(Mdr*Mrd-Ld*lr)) + (Rr*Ld*I(1)/(Mdr*Mrd-Ld*lr));
    dIr=dIr + (Mdr*I(:,4)/(Mdr*Mrd-Ld*lr));
    dIr=dIr - (Mdr*(Rd_plus_Rb-Rb)*I(:,2)/(Mdr*Mrd-Ld*lr));
    dId=(I(:,4)/Ld) - ((Rd_plus_Rb-Rb)*I(:,2)/Ld) - (Mrd*dIr/Ld);
    Vd=(Rd_plus_Rb-Rb)*I(:,2))+(Ld*dId)+(Mrd*dIr);
    Vl=Rl*I(:,2)+Ll*dIl;
    Vr=-Rr*I(:,1)-Lr*dIr-(Mlr*dIl);
    Ir=I(:,1); Id=I(:,3); Il=I(:,2);
end

tt=t; \%
DD=Vr; \%
DDD=Vd; \%
N=length(tt);

\% FFT of receiver
deltat=(tt(N)-tt(1))/(N-1); \% samples per second
sample_freq=1/deltat;
D=fft(DD);
MD=abs(D)*2/N;
PD=(angle(D));
f=(0:length(D)-1)*sample_freq/length(D);
\% Extract phase of 99 kHz harmonic
condition=0;

125
eps=5; % tolerance for conditional statement
c=1; % counter for while loop
while condition==0
    if abs(99000-f(c))<=eps
        condition=1;
    else
        c=c+1;
    end
    if c==N
        condition=1;
        disp('WARNING: No 99 kHz harmonic within tolerance');
    end
end
phase_receiver_99(vv)=PD(c)*180/pi;
mag_receiver_99(vv)=MD(c);
    mag_receiver_model(vv)=max(Vr)-min(Vr);

% Extract phase of 198 kHz harmonic
condition=0;
eps=5; % tolerance for conditional statement
c=1; % counter for while loop
while condition==0
    if abs(198000-f(c))<=eps
        condition=1;
    else
        c=c+1;
    end
    if c==N
        condition=1;
        disp('WARNING: No 198 kHz harmonic within tolerance');
    end
end
phase_receiver_198(vv)=PD(c)*180/pi;
mag_receiver_198(vv)=MD(c);

% FFT of driver
DVd=fft(DDD);
MDVd=abs(DVd)*2/N;
PDVd=(angle(DVd));
f=(0:length(DVd)-1)*sample_freq/length(DVd);

% Extract phase of 99 kHz harmonic
condition=0;
eps=5; % tolerance for conditional statement
c=1; % counter for while loop
while condition==0
    if abs(99000-f(c))<=eps
        condition=1;
    else
        c=c+1;
    end
end
if c==N
    condition=1;
    disp('WARNING: No 99 kHz harmonic within tolerance');
end
end
mag_driver_99(vv)=max(Vd)-min(Vd);
phase_driver_99(vv)=PDVd(c)*180/pi;
mag_driver_model(vv)=max(Vd)-min(Vd);

% Extract phase of 198
eps=5; %tolerance for conditional statement
c=1; %counter for while loop
while condition==0
    if abs(198000-f(c))<=eps
        condition=1;
    else
        c=c+1;
    end
    if c==N
        condition=1;
        disp('WARNING: No 198 kHz harmonic within tolerance');
    end
end
mag_driver_198(vv)=max(Vd)-min(Vd);
phase_driver_198(vv)=PDVd(c)*180/pi;

phase_driver_model=phase_driver_99;
phase_receiver_model=phase_receiver_99;

% Display experimental results and compare with experiment (optional)
D_mm=Dvv*25.4; %wire loop diameters in mm
phi_model=abs(phase_driver_model-phase_receiver_model);

% EXPERIMENTAL DATA
% Magnitude
Roff=[-260.0 -261.8 -261.5 -261.1 -260.8 -261.8 -260.8 -258.6];
high1=abs((Roff-[0 -2.5 -4.6 -10.2 -18.6 -45.7 -38.5 -9.2])/50); %V
low1=abs((Roff-[0 -2.5 -4.6 -10.2 -18.6 -45.7 -38.5 -9.2])/50);
avg1=(high1+low1)./2;
H1=high1-avg1;
L1=avg1-low1;

% Phase, 7-10-2009
phi1=[0 0.25 2.3 5.85 9.95 43.15 32.05 8.2];
high_phi1=0.1;
low_phi1=0.1;

figure(50)
plot(D_mm,phi_model,'o'); hold on;
% errorbar(D_mm,avg1,H1,L1,'rd');
% legend('Numerical','Experimental');
xlabel('Wire loop diameter, mm'); ylabel('|\phi_d_r - \phi_r_e_c|');
title('Phase shift between driver and receiver');

figure(51)
plot(D_mm,mag_receiver_model,'o'); hold on;
errorbar(D_mm,avg1,L1,H1,'rd');
legend('Numerical','Experimental');
xlabel('Wire loop diameter, mm'); ylabel('V_p_p receiver, V');
title('Magnitude response of receiver');

figure(59)
phi_receiver_shift=abs(phase_receiver_model(1)-phase_receiver_model);
plot(D_mm,phi_receiver_shift,'o'); hold on;
errorbar(D_mm,phi1,low_phi1,high_phi1,'rd');
legend('Numerical','Experimental');
xlabel('Wire loop diameter, mm'); ylabel('|\phi_s_h_i_f_t|, deg');
title('Phase response of receiver');

figure(3)
errorbar(D_mm,phi1,low_phi1,high_phi1,'rd','linewidth',2); hold on;
plot(D_mm,phi_receiver_shift,'ko','linewidth',2,'markerfacecolor','black');
xlabel('Loop diameter, mm','fontsize',14);
ylabel('|\Delta \phi receiver, deg','fontsize',14);
legend('Experimental A6','Numerical');
title('Response of sawtooth input to single copper loops, varying D, 99 kHz','fontsize',14);

figure(1)
errorbar(D_mm,avg1,L1,H1,'rd','linewidth',2); hold on;
plot(D_mm,mag_receiver_model,'ko','linewidth',2,'markerfacecolor','black');
xlabel('Loop diameter, mm','fontsize',14);
ylabel('V_p_p receiver, V','fontsize',14);
legend('Experimental','Numerical');
title('Response of sawtooth input to single copper loops', 'varying D, 99 kHz','fontsize',14);

figure(2)
errorbar(D_mm,phi1,low_phi1,high_phi1,'rd','linewidth',2); hold on;
plot(D_mm,phi_receiver_shift,'ko','linewidth',2,'markerfacecolor','black');
xlabel('Loop diameter, mm','fontsize',14);
ylabel('|\Delta \phi receiver, deg','fontsize',14);
legend('Experimental','Numerical');
title('Response of sawtooth input to single copper loops', 'varying D, 99 kHz','fontsize',14);

num_sine_phi=[ 0    0.0186    0.0145    0.0658  0.1262    0.8671  
0.4443    0.0591];
num_sine_mag=[1.2090    1.2067    1.2022    1.1972  1.1833    1.0651  
1.1114    1.1821];
figure(615)
plot(D_mm,mag_receiver_model,'ko','linewidth',2,'markerfacecolor','black');hold on;
plot(D_mm,num_sine_mag,'b^','linewidth',2,'markerfacecolor','blue')
xlabel('Loop diameter, mm','fontsize',14);
ylabel('V_p_p receiver, V','fontsize',14);
legend('Sawtooth','Sine');
title({'Numerical model magnitude response to varying loop diameter',
'Forcing Function Comparison'},'fontsize',14);

figure(616)
plot(D_mm,phi_receiver_shift,'ko','linewidth',2,'markerfacecolor','black');hold on;
plot(D_mm,num_sine_phi,'b^','linewidth',2,'markerfacecolor','blue');
xlabel('Loop diameter, mm','fontsize',14);
ylabel('\Delta\phi receiver, deg','fontsize',14);
legend('Sawtooth','Sine');
title({'Numerical model phase response to varying loop diameter',
'Forcing Function Comparison'},'fontsize',14);
Matlab Script for Numerical Model Simulation of the phase and voltage output of each wire loop individually, time domain signals output from this script (utilizes the solver function file: A6_solver_final.m):

```matlab
%Numerical Model solver that outputs a time domain signal for a given single wire loop. Loops are indexed vv, number of periods is n.
clear; clc; clf; close all;
global Vo w Ld Lr Ll Rd_plus_Rb Rr Rb Rl Mdl Mdr Mld Mrd Mrl Cd D Cr Rscope
vv=1; n=5;
% 99 kHz 7VPP Sawtooth---------------------------------------------
%---------------------------------------------------------------- Beverage
%%%%%Input Function Characteristics%%%%%
Vo=7; %Vpp
freq=99000; %Hz, driving frequency
w=2*pi*freq; %rad/sec, circular driving frequency
T=1/freq; %sec, period of driving frequency
dt=1e-9; %step in time, 1 ns
Rscope = 1e7; % 10 MOhm or 100 MOhm depending on the scope or device used

%%%%%Driver%%%%%
Cd=.3e-9; % capacitance in parallel with driver coil, Farads
%Cd=1e-9;
Ld=69.6e-6; %H, self inductance of driver % Ld=1e-4;
Rd_plus_Rb=832.54; %ohm, ballast resistance + resistance of driver coil
Rb=830; %ohm, ballast resistance?

%%%%%Receiver%%%%%
Cr=.25e-9; % capacitance in parallel with receiver coil, Farads
%Cr=1e-9;
Rr=6.36; %ohm, resistance of receiver
Lr=475.25e-6; %Henry, self inductance of receiver

%%%%Loop%%%%%
Dvv=[0 0.146 0.192 0.232 0.291 0.514 0.867 1.411];
D=Dvv(vv); %in, diameter of loop
Dia=D;
Rl_vv=[0 .1628 .2755 .3734 .5179 1.0641 1.9287 3.2610]/1000;
Rl=Rl_vv(vv); %ohm, resistance of the loop
Ll_vv=[0 1.2487935761857e-009 2.75894738140862e-009... 4.29423449575244e-009 6.82835761444735e-009 18.258743251578e-009 ... 39.8291291590544e-009 77.7630043346054e-009]; % Henry, self inductance of loop
```
Ll=Ll_vv(vv); %adjusted inductance of the loop

%%%Mutual Inductances%%%
Mdl_vv=[0 8.62368567372776e-009 24.6818107229983e-009 ...
-45.3390176255201e-009 87.1095548889436e-009 354.640538909824e-009 ...
402.098958456119e-009 303.099604828975e-009];
Mlr_vv=[0 59.7950262523893e-009 122.808803074210e-009 ...
195.845373947338e-009 334.488511113700e-009 1.17011149888997e-006 ...
1.53349667242936e-006 1.15861762092737e-006];
Mlr_vv=Mlr_vv;
Mdl_vv=Mdl_vv;

Mld_vv=[0 2.202177e-8 4.519879e-8 7.201838e-8 1.227712e-7 ...
3.945316e-7 2.969447e-7];
Mld_vv=Mld_vv;
Mrl_vv=[0 2.340714e-8 6.702270e-8 1.231903e-6 2.370063e-7 ...
1.560295e-6 1.18271e-6];
Mld=Mdl_vv(vv);
Mdr=1.5306e-004; 
Mdr=Mdr;
Mir=Mlr_vv(vv);
Mrd=Mdr;
Mrl=Mrl_vv(vv)*0; %************************
Mld=Mld_vv(vv)*0; %************************

if D~=0;
   tspan=[0:dt:n*T];
   y0=[0,0,0,0,0];
   options = odeset('OutputFcn', 'odeplot');
   [t, I_o]=ode15s('A6_solver_final', tspan, y0, options);
   I=zeros(length(I_o),3);
   I(:,1)=I_o(:,1);
   I(:,3)=I_o(:,3);
   I(:,2)=I_o(:,2);
   I(:,2)=0;
   I(:,4)=I_o(:,4);
   I(:,5)=I_o(:,5);
else
   tspan=[0:dt:n*T];
   y0=[0,0,0,0,0];
   options = odeset('OutputFcn', 'odeplot');
[t, I]=ode15s('A6_solver_final',tspan,y0,options);

end

if D~=0;
    % I(1)=I_R; I(2)=I_L; I(3)=I_D; I(4)=V_CR; I(5)=V_CD;
    num=-I(:,4) - (Rr*I(:,1)) + ((Mlr*Mdl-Mdr*Ll)*I(:,5)/(Ll*Ld-Mdl*Lmd));
    num=num + ((Mdr*Ll-Mlr*Mdl)*(Rd_plus_Rb-Rb)*I(:,3)/(Ll*Ld-Mdl*Lmd));
    dIr=num/denom;
    dIl=-(Rl*Ld*I(:,2)/(Ll*Ld-Mdl*Mld));
    dIl=dIl + (Mdl*I(:,5)/(Ll*Ld-Mdl*Mld));
    dIl=dIl + ((Mdr*Mdl-Mrl*Ld)*dIr/(Ll*Ld-Mdl*Mld));
    dId=(I(:,5)/Ld) - ((Rd_plus_Rb-Rb)*I(:,3)/Ld) - (Mld*dIl/Ld) - (Mrd*dIr/Ld);
    Vd=((Rd_plus_Rb-Rb)*I(:,2))+(Ld*dId)+(Mrd*dIr);
    %Vd=I(:,5);
    Vl=Rl*I(:,2)+Ll*dIl;
    Vr=-Rr*I(:,1)-Lr*dIr-(Mlr*dIl)-Mrd*dId;
    %Vr=I(:,4);
    Ir=I(:,1); Id=I(:,3); Il=I(:,2);
else
    % I(1)=I_R; I(2)=I_D; I(3)=V_CR; I(4)=V_CD;
    dIr=(Ld*I(:,3)/(Mdr*Mrd-Ld*lr)) + (Rr*Ld*I(1)/(Mdr*Mrd-Ld*lr));
    dIl=dIl + (Mdr*I(:,4)/(Mdr*Mrd-Ld*lr));
    dIl=dIl - (Mdr*(Rd_plus_Rb-Rb)*I(:,2)/(Mdr*Mrd-Ld*lr));
    dId=(I(:,4)/Ld) - ((Rd_plus_Rb-Rb)*I(:,2)/Ld) - (Mrd*dIr/Ld);
    Vd=((Rd_plus_Rb-Rb)*I(:,2))+(Ld*dId)+(Mrd*dIr);
    %Vd=I(:,4);
    Vr=-Rr*I(:,1)-Lr*dIr-(Mdr*dId);
    %Vr=I(:,3);
    Ir=I(:,1); Id=I(:,2);
end

figure(1)
subplot(2,2,1)
pplot(t,Id)
xlabel('Time, sec')
ylabel('Current, Amp')
title('Driver Current')
subplot(2,2,2)
pplot(t,Ir)
xlabel('Time, sec')
ylabel('Current, Amp')
title('Receiver Current')
subplot(2,2,3)
pplot(t,(Vd)-830.*I(:,1))
xlabel('Time, sec')
ylabel('Voltage, V')
title('Driver Voltage')
subplot(2,2,4)
plot(t,Vr)
xlabel('Time, sec')
ylabel('Voltage, V')
title('Receiver Voltage')

[t1,Vd_1,Vr_1] = textread('D_1.txt','%f%f%f','commentstyle','matlab');
t1=t1-t1(1);

figure (2)
subplot(2,1,1)
plot(t,Vd,'k');
xlabel('Time, sec'); ylabel('Driver voltage, V');
title({'C_d =0.3e-9 F, C_r = 0.25e-9 F','Driver Signal, time domain'});
hold on
plot(t1,Vd_1,'r')
legend('Numerical Model', 'Experimental')
hold off

subplot(2,1,2)
plot(t,Vr,'k');
xlabel('Time, sec'); ylabel('Receiver signal, V');
title('Receiver Signal, time domain');
hold on
plot(t1,Vr_1,'r')
hold off
legend('Numerical Model', 'Experimental')

% tt=t;
% DD=Vr;
% DDD=Vd;
% Vo/2*sawtooth(w*t);
N=length(tt);

% FFT
deltat=(tt(N)-tt(1))/(N-1); % samples per second
sample_freq=1/deltat;
D=fft(DD);
MD=abs(D)*2/N;
PD=(angle(D));
f=(0:length(D)-1)*sample_freq/length(D);
figure(4)
plot(f(1:length(D)/2)/1000,MD(1:length(D)/2));
axis([0 1000 0 1])
xlabel('f, kHz'); ylabel('Magnitude, V');
title('Frequency content of receiver signal');
figure(5)
plot(f(1:length(D)/2)/1000,PD(1:length(D)/2)*180/pi)
xlabel('f, kHz'); ylabel('Phase, deg'); title('Phase content of the receiver signal')
axis([0 1000 -360 360])

% FFT
DVd=fft(DDD);
MDVd=abs(DVd)*2/N;
PDVd=angle(DVd);
f=(0:length(DVd)-1)*sample_freq/length(DVd);
figure(6)
plot(f(1:length(DVd)/2)/1000,MDVd(1:length(DVd)/2));
axis([0 1000 0 1])
xlabel('f, kHz'); ylabel('Magnitude, V');
title('Frequency content of Driver signal');

figure(7)
plot(f(1:length(DVd)/2)/1000,PDVd(1:length(DVd)/2)*180/pi)
xlabel('f, kHz'); ylabel('Phase, deg');
title('Phase content of the Driver signal')
axis([0 1000 -360 360])
Matlab Script for function file ran by the numerical model scripts:

```matlab
function dI=A6_solver_final(t,I,options)
%Solver designed to work with numerical model files, Circuit model
%numerical model

global Vo w Ld Lr L1 Rd_plus_Rb Rr Rb Rl Md1 Mdr Mld Mrd Mrl Cd D Cr Rscope

Vo_plus=Vo*sawtooth(w*(1+1.0e-9)*t,0.99)/2;  Vo_minus=Vo*sawtooth(w*(1-1.0e-9)*t,0.99)/2;

dVodt=(Vo_plus-Vo_minus)/(2.0e-9);
if D~0;
    % I(1)=I_R; I(2)=I_L; I(3)=I_D; I(4)=V_CR; I(5)=V_CD;
    num=-I(4) - (Rr*I(1)) + ((Mlr*Mdl-Mdr*Ll)*I(5)/(Ll*Ld-Mdl*Mld));
    num=num + ((Mdr*Ll-Mlr*Mdl)*(Rd_plus_Rb-Rb)*I(3)/(Ll*Ld-Mdl*Mld));
    num=num + ((Mlr*Ld-Mdr*Mld)*Rl*I(2)/(Ll*Ld-Mdl*Mld));
    denom=denom/Ld/(Ll*Ld-Mdl*Mld);
    dI(1)=num/denom;
    dI(2)=-(Rl*Ld*I(2)/(Ll*Ld-Mdl*Mld)) - (Mdl*I(5)/(Ll*Ld-Mdl*Mld));
    dI(2)=dI(2) + (Mdl*(Rd_plus_Rb-Rb)*I(3)/(Ll*Ld-Mdl*Mld));
    dI(2)=dI(2) + ((Mrd*Mdl-Mrl*Ld)*dI(1)/(Ll*Ld-Mdl*Mld));
    dI(3)=(I(5)/Ld) - ((Rd_plus_Rb-Rb)*I(3)/Ld) - (Mdl*dI(2)/Ld) -
    (Mrd*dI(1)/Ld);
    dI(4)=(I(1)/Cr) - (I(4)/Cr/Rscope);
    dI(5)=((Vo*sawtooth(w*t,0.99)/2-I(5))/Rb/Cd) - (I(3)/Cd);
else
    % I(1)=I_R; I(2)=I_D; I(3)=V_CR; I(4)=V_CD;
    dI(1)=(Ld*I(3)/(Mdr*Mrd-Ld*Lr)) + (Rr*Ld*I(1)/(Mdr*Mrd-Ld*Lr));
    dI(1)=dI(1) + (Mdr*I(4)/(Mdr*Mrd-Ld*Lr));
    dI(1)=dI(1) - (Mdr*(Rd_plus_Rb-Rb)*I(2)/(Mdr*Mrd-Ld*Lr));
    dI(2)=(I(4)/Ld) - ((Rd_plus_Rb-Rb)*I(2)/Ld) - (Mrd*dI(1)/Ld);
    dI(3)=(I(1)/Cr) - (I(3)/Cr/Rscope);
    dI(4)=((Vo*sawtooth(w*t,0.99)/2-I(4))/Rb/Cd) - (I(2)/Cd);
end

dI=dI';
```
Matlab Script to process and plot line scans over both round phantoms, reads text files with arrays of the experimental data:

```matlab
clear; clc; close all;
ymax=1.7;%inches
ystep=0.1;%inches
feed=711; %Velmx, Steps/sec
degconv=50; %mV/deg
step=9.84E-5; %in/step
%reads data from text files
[t,M01,P01] = textread('Ring01.txt','%f%f%f','commentstyle','matlab');% data taken 6-29-09
[t,M02,P02] = textread('Ring02.txt','%f%f%f','commentstyle','matlab');% data taken 6-29-09
[t,M03,P03] = textread('Line01.txt','%f%f%f','commentstyle','matlab');% data taken 6-29-09
[t,M04,P04] = textread('Line02.txt','%f%f%f','commentstyle','matlab');% data taken 6-29-09
[t,M05,P05] = textread('Ring05.txt','%f%f%f','commentstyle','matlab');% data taken 6-30-09
M=[ M01 M02 M03 M04 M05]; %Magnitude Array, Volts
Pmv=[ P01 P02 P03 P04 P05];%Phase Array, mV
P=Pmv*degconv; %Phase, Degrees
x=t*feed*(step)*25; %25 converts inches to mm

%%%%%%%%Plotting Round Phantom with copper ring
figure(1)
plot(x, P(:,5), 'k')
axis([0 87.5 -22 2])
y=-22.001:1:5.001;
yc=y./y;
x=(.73*25).*yc;%position of probe at the start of the ring
xe=(.98*25).*yc;%position of probe at the end of the ring
xp=(.98+.4999)*25.*yc; %position of probe "sight" edge with respect to end of ring
hold on
plot(xs,y,'xk')
hold on
plot(xe,y,'.k')
hold on
plot(xp,y,'*k')
hold off
title({'Phase: Round Phantom with 6.25mm diameter ring';'99 kHz, 7Vpp Sawtooth, 500mV Sens','fontsize',14})
xlabel('Position, mm','fontsize',14);ylabel('Phase Shift, deg','fontsize',14);
legend('Lock-in Phase Output','Front edge of ring','Back edge of ring','Position where probe cannot "see" ring','4','Location','SouthEast')
```
figure(3)
plot(x, M(:,5), 'k')
axis([0 87.5 5.0 5.3])
y=1.001:.01:6.001;
yc=y./y;
xs=(.73*25).*yc;%position of probe at the start of the ring
xe=(.98*25).*yc;%position of probe at the end of the ring
xp=(.98+.4999)*25.*yc;%position of probe "sight" edge with respect to end of ring
hold on
plot(xs,y,'xk')
hold on
plot(xe,y,'.k')
hold on
plot(xp,y,'*k')
hold off
title({'Magnitude: Round Phantom with 6.25mm diameter ring';'99 kHz,'  
7Vpp Sawtooth, 500mV Sens'},'fontsize',14)
xlabel('Position, mm','fontsize',14);ylabel('Voltage, V','fontsize',14)
legend('Lock-in Phase Output','Front edge of ring','Back edge of ring','Position where probe cannot "see" ring','4','Location','SouthEast')

figure(2)
plot(x, P(:,3), 'k')
axis([0 87.5 -5 2])
y=-22.001:.3:5.001;
yc=y./y;
xs=(1.05*25).*yc;%position of probe at the start of the copper length
xp=(1.05+.4999)*25.*yc;%position of probe "sight" edge with respect to end of length
hold on
plot(xs,y,'xk')
hold on
plot(xp,y,'*k')
hold off
title({'Phase: Round Phantom with 18AWG copper wire length';'99 kHz,'  
7Vpp Sawtooth, 500mV Sens'},'fontsize',14)
xlabel('Position, mm','fontsize',14);ylabel('Phase Shift, deg','fontsize',14)
legend('Lock-in Phase Output','Front edge of wire length','Position where probe cannot "see" wire length','3','Location','SouthEast')

figure(4)
plot(x, M(:,3), 'k')
axis([0 87.5 5.0 5.3])
y=1.001:.01:6.001;
yc=y./y;
xs=(1.05*25).*yc;%position of probe at the start of the copper length
xp=(1.05+.4999)*25.*yc; %position of probe "sight" edge with respect to end of length
hold on
plot(xs,y,'xk')
hold on
plot(xp,y,'*k')
hold off
title({'Magnitude: Round Phantom with 18AWG copper wire length';'99 kHz, 7Vpp Sawtooth, 500mV Sens'},'fontsize',14)
xlabel('Position, mm','fontsize',14);ylabel('Voltage, V','fontsize',14)
legend('Lock-in Phase Output','Front edge of wire length','Position where probe cannot "see" wire length','3','Location','SouthEast')
Matlab Script to assemble process and plot line scans over the rectangular phantom with one large ring, reads text files with arrays of the experimental data:

```matlab
clear; clc; close all;
ymax=1.5;%inches
ystep=0.1;%inches
feed=5; %MAXNC feedrate, inches/min
degconv=50; %mV/deg
%reads data from text files
[t,M0_0,P0_0] = textread('0_0.txt','%f%f%f','commentstyle','matlab');
[t,M0_1,P0_1] = textread('0_1.txt','%f%f%f','commentstyle','matlab');
[t,M0_2,P0_2] = textread('0_2.txt','%f%f%f','commentstyle','matlab');
[t,M0_3,P0_3] = textread('0_3.txt','%f%f%f','commentstyle','matlab');
[t,M0_4,P0_4] = textread('0_4.txt','%f%f%f','commentstyle','matlab');
[t,M0_5,P0_5] = textread('0_5.txt','%f%f%f','commentstyle','matlab');
[t,M0_6,P0_6] = textread('0_6.txt','%f%f%f','commentstyle','matlab');
[t,M0_7,P0_7] = textread('0_7.txt','%f%f%f','commentstyle','matlab');
[t,M0_8,P0_8] = textread('0_8.txt','%f%f%f','commentstyle','matlab');
[t,M0_9,P0_9] = textread('0_9.txt','%f%f%f','commentstyle','matlab');

[t,M1_0,P1_0] = textread('1_0.txt','%f%f%f','commentstyle','matlab');
[t,M1_1,P1_1] = textread('1_1.txt','%f%f%f','commentstyle','matlab');
[t,M1_2,P1_2] = textread('1_2.txt','%f%f%f','commentstyle','matlab');
[t,M1_3,P1_3] = textread('1_3.txt','%f%f%f','commentstyle','matlab');
[t,M1_4,P1_4] = textread('1_4.txt','%f%f%f','commentstyle','matlab');
[t,M1_5,P1_5] = textread('1_5.txt','%f%f%f','commentstyle','matlab');
% [t,M1_6,P1_6] = textread('1_6.txt','%f%f%f','commentstyle','matlab');
% [t,M1_7,P1_7] = textread('1_7.txt','%f%f%f','commentstyle','matlab');
% [t,M1_8,P1_8] = textread('1_8.txt','%f%f%f','commentstyle','matlab');

M=[M0_0 M0_1 M0_2 M0_3 M0_4 M0_5 M0_6 M0_7 M0_8 M0_9...]
M1_0 M1_1 M1_2 M1_3 M1_4 M1_5]; %Magnitude Array, Volts
for i=1:16
    M_adjust(:,i)=M(:,i)-M(1,i);
end

Pmv=[P0_0 P0_1 P0_2 P0_3 P0_4 P0_5 P0_6 P0_7 P0_8 P0_9...]
P1_0 P1_1 P1_2 P1_3 P1_4 P1_5]; %Phase Array, mV
P=Pmv*degconv; %Phase, Degrees
Lxin=(t-t(1))*feed/60;
Lyin=0:ystep:ymax;
Lx=Lxin*25;
Ly=Lyin*25;

figure(1)
surf(Lx,Ly,P');
shading interp
xlabel('Long Edge, mm')
ylabel('Short Edge, mm')
zlabel('Phase, deg')
```

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% colormap hsv
title('Ring Phantom Phase: 2.5 mm steps along short edge, 2.08 mm/sec Rate')

figure(2)
surf(Lx,Ly,M_adjust);
shading interp
xlabel('Long Edge, mm','fontsize',14)
ylabel('Short Edge, mm','fontsize',14)
zlabel('Magnitude, V','fontsize',14)
%colormap hsv
title('Ring Phantom Magnitude: 2.5 mm steps along short edge, 2.08 mm/sec Rate','fontsize',14)
Matlab Script to assemble process and plot line scans over the rectangular phantom with three small rings, reads text files with arrays of the experimental data:

clear; clc; close all;
ymax=1.7;%inches
ystep=0.1;%inches
feed=5;%MAXNC feedrate, inches/min
degconv=50;%mV/deg
%reads data from text files
[t,M0_0,P0_0] = textread('0_0.txt','%f%f%f','commentstyle','matlab');
[t,M0_1,P0_1] = textread('0_1.txt','%f%f%f','commentstyle','matlab');
[t,M0_2,P0_2] = textread('0_2.txt','%f%f%f','commentstyle','matlab');
[t,M0_3,P0_3] = textread('0_3.txt','%f%f%f','commentstyle','matlab');
[t,M0_4,P0_4] = textread('0_4.txt','%f%f%f','commentstyle','matlab');
[t,M0_5,P0_5] = textread('0_5.txt','%f%f%f','commentstyle','matlab');
[t,M0_6,P0_6] = textread('0_6.txt','%f%f%f','commentstyle','matlab');
[t,M0_7,P0_7] = textread('0_7.txt','%f%f%f','commentstyle','matlab');
[t,M0_8,P0_8] = textread('0_8.txt','%f%f%f','commentstyle','matlab');
[t,M0_9,P0_9] = textread('0_9.txt','%f%f%f','commentstyle','matlab');

[t,M1_0,P1_0] = textread('1_0.txt','%f%f%f','commentstyle','matlab');
[t,M1_1,P1_1] = textread('1_1.txt','%f%f%f','commentstyle','matlab');
[t,M1_2,P1_2] = textread('1_2.txt','%f%f%f','commentstyle','matlab');
[t,M1_3,P1_3] = textread('1_3.txt','%f%f%f','commentstyle','matlab');
[t,M1_4,P1_4] = textread('1_4.txt','%f%f%f','commentstyle','matlab');
[t,M1_5,P1_5] = textread('1_5.txt','%f%f%f','commentstyle','matlab');
[t,M1_6,P1_6] = textread('1_6.txt','%f%f%f','commentstyle','matlab');
[t,M1_7,P1_7] = textread('1_7.txt','%f%f%f','commentstyle','matlab');
%[t,M1_8,P1_8] = textread('1_8.txt','%f%f%f','commentstyle','matlab');

M=[M0_0 M0_1 M0_2 M0_3 M0_4 M0_5 M0_6 M0_7 M0_8 M0_9 ... 
  M1_0 M1_1 M1_2 M1_3 M1_4 M1_5 M1_6 M1_7]; %Magnitude Array, Volts

Pmv=[P0_0 P0_1 P0_2 P0_3 P0_4 P0_5 P0_6 P0_7 P0_8 P0_9 ... 
  P1_0 P1_1 P1_2 P1_3 P1_4 P1_5 P1_6 P1_7]; %Phase Array, mV
P=Pmv*degconv; %Phase, Degrees
Lxin=(t-t(1))*feed/60;
Lyin=0:ystep:ymax;
Lx=Lxin*25;
Ly=Lyin*25;

figure(1)
surf(Lx,Ly,P');
shading interp
xlabel('Long Edge, mm')
ylabel('Short Edge, mm')
zlabel('Phase, deg')
colormap hsv
title('Ring Phantom Phase: 2.5 mm steps along short edge, 2.08 mm/sec Rate')
figure(2)
surf(Lx, Ly, M);
shading interp
xlabel('Long Edge, mm')
ylabel('Short Edge, mm')
zlabel('Magnitude, V')
colormap hsv
title('Ring Phantom Magnitude: 2.5 mm steps along short edge, 2.08 mm/sec Rate')
Matlab Script to assemble process and plot line scans over the rectangular phantom with three straight wire lengths, reads text files with arrays of the experimental data:

clear; clc; close all;
ymax=1.8;%inches
ystep=0.1;%inches
feed=5;%MAXNC feedrate, inches/min
degconv=50;%mV/deg

%reads data from text files
[t,M0_0,P0_0] = textread('0_0.txt','%f%f%f','commentstyle','matlab');
[t,M0_1,P0_1] = textread('0_1.txt','%f%f%f','commentstyle','matlab');
[t,M0_2,P0_2] = textread('0_2.txt','%f%f%f','commentstyle','matlab');
[t,M0_3,P0_3] = textread('0_3.txt','%f%f%f','commentstyle','matlab');
[t,M0_4,P0_4] = textread('0_4.txt','%f%f%f','commentstyle','matlab');
[t,M0_5,P0_5] = textread('0_5.txt','%f%f%f','commentstyle','matlab');
[t,M0_6,P0_6] = textread('0_6.txt','%f%f%f','commentstyle','matlab');
[t,M0_7,P0_7] = textread('0_7.txt','%f%f%f','commentstyle','matlab');
[t,M0_8,P0_8] = textread('0_8.txt','%f%f%f','commentstyle','matlab');
[t,M0_9,P0_9] = textread('0_9.txt','%f%f%f','commentstyle','matlab');

[t,M1_0,P1_0] = textread('1_0.txt','%f%f%f','commentstyle','matlab');
[t,M1_1,P1_1] = textread('1_1.txt','%f%f%f','commentstyle','matlab');
[t,M1_2,P1_2] = textread('1_2.txt','%f%f%f','commentstyle','matlab');
[t,M1_3,P1_3] = textread('1_3.txt','%f%f%f','commentstyle','matlab');
[t,M1_4,P1_4] = textread('1_4.txt','%f%f%f','commentstyle','matlab');
[t,M1_5,P1_5] = textread('1_5.txt','%f%f%f','commentstyle','matlab');
[t,M1_6,P1_6] = textread('1_6.txt','%f%f%f','commentstyle','matlab');
[t,M1_7,P1_7] = textread('1_7.txt','%f%f%f','commentstyle','matlab');
[t,M1_8,P1_8] = textread('1_8.txt','%f%f%f','commentstyle','matlab');

M=[M0_0 M0_1 M0_2 M0_3 M0_4 M0_5 M0_6 M0_7 M0_8 M0_9... 
M1_0 M1_1 M1_2 M1_3 M1_4 M1_5 M1_6 M1_7 M1_8];

%Magnitude Array, Volts
Pmv=[P0_0 P0_1 P0_2 P0_3 P0_4 P0_5 P0_6 P0_7 P0_8 P0_9... 
P1_0 P1_1 P1_2 P1_3 P1_4 P1_5 P1_6 P1_7 P1_8];

P=Pmv*degconv;%Phase, Degrees
Lxin=(t-t(1))*feed/60;
Lyin=ystep:ystep:ymax;

Lx=Lxin*25;
Ly=Lyin*25;

figure(1)
surf(Lx,Ly,P');
shading interp
xlabel('Long Edge, mm','fontsize',14)
ylabel('Short Edge, mm','fontsize',14)
zlabel('Phase, deg','fontsize',14)
colormap hsv

colorbar

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title('Line Phantom Phase: 2.5 mm steps along short edge, 2.08 mm/sec Rate','fontsize',14)

figure(2)
surf(Lx,Ly,M');
shading interp
xlabel('Long Edge, mm','fontsize',14)
ylabel('Short Edge, mm','fontsize',14)
zlabel('Magnitude, V','fontsize',14)
% colormap hsv
title('Line Phantom Magnitude: 2.5 mm steps along short edge, 2.08 mm/sec Rate','fontsize',14)