Design and Verification of Search Coil Inductance for Pulse Induction Metal Detection

David Desrochers

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Design and Verification of Search Coil Inductance for Pulse Induction Metal Detection

An undergraduate honors thesis submitted in partial fulfillment of the honors requirements for the degree of Bachelor of Science in Electrical Engineering

by

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May 2020
University of Arkansas

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Thesis Adviser
Abstract

As violent attacks have increased at different venues such as schools, the need for affordable and effective metallic weapon detection has increased. Probing and scanning detection wands are the most common seen in use by guards. This project seeks to combine both probing and scanning coils into one pulse induction metal detector. The use of one drive circuit for both LC coil tank circuits further economizes the system. ANSYS Maxwell electromagnetic simulations are used to develop the geometries needed for sensitive metal detection. Analytical, simulation, and experimental methods are used to first verify the design flow for solenoid inductors. These methods are then applied to further simulations for varying inductor lengths, turn numbers, and diameter. The results of these simulations are used to formulate a final design for a sensitive detector. The inductive couplings between metallic objects and search coils is evaluated using simulation and experimental methods. Both resulted in close agreement; superimposed signals of different frequencies are found to provide useful detection value by their changes in peak to peak voltage.
Acknowledgments:

I would like to thank Magda El-Shenawee Ph.D. and Samir El-Ghazaly Ph.D. of the University of Arkansas electrical engineering department for their advice on the modelling and construction of solenoid devices. I would also like to thank my adviser, Robert Saunders for his guidance in completing this project.
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Part 1: Introduction and Analysis of Solenoid Coils

1.1 Introduction

Security at large gatherings and schools has been an increasingly important issue over the past several years with the prevalence of mass shooting and violent offenses. While security enforcement options abound such as millimeter wave scanning found at airport checkpoints, these technologies are often not affordable for small school institutions and gatherings. Hand based metal detection systems are commonplace at security checkpoints, but they are slow to use and do not often allow fast pinpointing of metallic weapons. Some handheld detectors use large area scanning coils, while others use probing coils for pinpointing. An affordable solution that combines both coil types would provide security personnel with the ability to use both coil types in one unit.

A large surface area scanning coil might be used to initially locate a metallic object on a person, while a probing coil would allow quick determination of its exact location. In addition, the probing coil would allow for probe detecting selected coil, resulting in a detector that combines probing and scanning roles with only a single drive circuit. This pulse induction type of detector uses eddy currents to detect metal [4]. Pulse induction operates in the frequency range of several hundred Hertz [1]. This design uses oscillations at 50 Hz to perform detection operations. While the coil is pulsed at this lower frequency, the system described here utilizes two LC tank circuits with resonant frequencies in the tens of kHz range. It is because of the lower frequency pulse that the higher frequency signal is generated.

The ANSYS Maxwell Magneto-static simulation suite is used to design and evaluate the inductance of the metal detector coils. Scanning and probing coils are designed using a copper material definition. Each coil is modeled inside a column of air. A 1cm$^3$ piece of steel is then
moved through the column at varying distances from the coil, while the mutual inductance at each location is evaluated.

These simulations provide a basis to verify the theoretical equation for the inductance of a solenoid. With these values in mind, a test probing coil is wound around a 3D printed spool. This coil is designed to closely match the specifications of that created in ANSYS Maxwell. A low pass filter is created with the coil and a resistor in series. A sinusoidal signal is generated using a function generator and passed through the series connection. At the node connecting the coil and resistor, an oscilloscope is placed to measure the resulting drop in amplitude of the signal. This value is used to calculate the inductance of the coil and provided a comparison metric to simulations and theoretical values.

Once the simulation and design methods are validated with a test coil, an optimized search coil is developed using further ANSYS Maxwell simulations. Two coils are produced using the results from this analysis and incorporated into a single drive circuit as series LC tank circuits. Simulations and experimental analysis will be presented here, showing close correspondence between simulated and actual couplings to metallic objects.

1.2 Detector Requirements

A security metal detector will only be useful if it is able to detect common weapons such as knives and guns. These objects are commonly made of several cubic centimeters of ferrous material.

The effectiveness of a wand type detector depends on proper training for operators of the device such as venue security guards. This is the greatest challenge for this type of detector [2].
Scanning coil size must therefore be made as large as possible to increase the ease of use and sensitivity.

Another important specification for the detector is its total size. The size depends strongly on the dimensions of the coils used. Therefore, a balance between coil size and inductance is desired. Generally, the device is set at around 30 cm long with a maximum width of 8 cm. This results in the scanning coil being oblong, while simulations in this report use a circular coil. As long as the area of an analogous oblong coil is similar to that of a circular coil, the inductance differences will be negligible. A circular coil is chosen for simulation due to its ease of creating in the ANSYS modelling suite. The detector consists of both a scanning coil and probing coil to compete with the current marketplace of single purpose detectors. For large distances, a large area coil seeks to scan an area and find a region with a metallic object. Then a probing coil takes over to pinpoint the metal’s location. The magnetic field of a small coil decays more quickly than that of a large coil, so it works well at the shorter distances assigned to it [5]. The converse is true for the scanning coil’s magnetic field strength. This detector works by pulsing current through a detector coil. The detector coil’s inductance varies when the magnetic permeability of its core changes. If a metallic object is placed near the coil, the inductance then increases. Higher inductance then results in a longer pulse decay duration. The length of each pulse decay is then measured by a microcontroller and used to determine whether a metal is present.

1.3 Theoretical Coil Analysis

Each search coil is equivalent to an air core solenoid, so the analysis of that device will be used here. A solenoid is a length of metal wire wound in multiple turns around a cylindrical core. Cores of ferrite are often used for chokes in radios and other electronic devices to mitigate electronic noise, but an air core is chosen here for its lower magnetic permeability [6]. An air
A core inductor has a lower absolute inductance than a ferrite core. However, the relative change in inductance for an air core is larger than that for a ferrite core. This yields a higher sensitivity when used a metal detector coil.

First, the magnetic field generated by a solenoid is evaluated. Each helical turn is treated as a planar circle loop [3]. Equation 1 shows the result of this analysis, assuming the solenoid is much longer than its cylindrical radius.

\[
B \approx z \mu NI \frac{l}{l}
\]

Equation 1. Magnetic field of a long coil where \( z \) is in +z direction unit vector.

With the magnetic field of the solenoid system in hand, next the inductance is obtained. The total flux linkage of a solenoid is defined as the number of turns multiplied by the flux contribution of each turn. This is shown in Equation 2, an evolution of Equation 1.

\[
\Lambda = N \Phi = \mu \frac{N^2}{l} IS
\]

Equation 2. The flux linkage of a long solenoid.

Finally, the inductance of the solenoid in Henries is defined as the ratio of the flux linkage to the current flowing through the wire. “S” defines the surface geometry the flux is flowing through. In practice, this can be equated to the surface area, A, the longitudinal axis of the coil takes up. Equation 3 shows this final progression.

\[
L = \frac{\lambda}{l} = \mu \frac{N^2}{l} S = \mu \frac{N^2}{l} A
\]

Equation 3. This expression describes the definition of inductance as the flux linkage divided by the current through the solenoid. “A” has been substituted for “S” as the area of the coil’s geometry.
Inductance values are calculated for the probing coil and will later be repeated for the scanning coil. The results of Equation 3 show that large surface area and number of turns will increase the sensitivity of the detector [7].

The diameter of the coil wire should also be assessed in any analysis of a solenoid. If the wire diameter to coil diameter ratio is sufficiently large, then Equation 4 becomes necessary for calculating the actual effective area of the coil [8].

\[
A_{eff} = \frac{1}{d_o - d_i} \int_{d_i}^{d_o} \frac{\pi y^2}{4} dy = \frac{\pi}{12} \frac{d_o^3 - d_i^3}{d_o - d_i}
\]

Equation 4. Effective solenoid detection area calculation. \(d_o\) is the outer diameter while \(d_i\) is the inner coil diameter as measured from the inside surface of the coil’s wires [8].

For typical handheld metal detectors with coils meant to detect tangible objects, Equation 4 will become zero as the difference between \(d_o\) and \(d_i\) is negligible.

Another consideration for coil design is whether the solenoid will be operated in current mode or voltage mode. In current mode the coil is shorted across a low input impedance amplifier. This method reduces the effects of parasitic coil capacitances. In contrast, the voltage mode depends on read out amplification with high input impedance. Voltage mode is chosen for use in this report, and results in a linear amplitude response below the resonant frequency of the coil [8].

A pulse induction metal detector relies on changes in the inductance of a solenoid coil sensor. The basis for any sensitive detector is to achieve the highest relative inductance change within the circuit. This will directly impact the inductor’s impedance and consequent voltage drop measured by a downstream amplifier.
1.4 Inductance Baseline Simulation

ANSYS Maxwell parametric simulations are used to analyze the inductance level of each coil setup. This software allows for accurate simulations of different geometries associated with materials and magnetic fields.

Performing an analysis begins with the creation of a 3D model for the system being analyzed. In this case, a helical coil with 100 turns is created using the included CAD modelling tools. This coil will serve as a verification of coil construction and simulation techniques. Figure 1 shows the probing coil geometry used for analysis.

![Probing coil in ANSYS Maxwell](image)

**Figure 1.** Probing coil in ANSYS Maxwell.

Due to the high level of computing power needed to simulate the fields of the resulting coils, a choice is made to change the 3D mesh slightly of each coil. Figure 2 shows how each
coil’s wire is changed to an extruded triangular model. This allows for significant reduction in simulation time with only a marginal loss in accuracy.

![Figure 2](image)

**Figure 2.** Triangular wire used in coils for higher simulation efficiency.

Once the main model is created, connecting terminals with excitations are connected for simulation. This involves uniting long rectangular prism wires to each end of the coil. Then current excitations are added to the end face of each terminal. **Figure 3** shows this terminal setup with an excitation in place. One excitation for input and one for output current are placed. An arbitrary current of 1 A is used because the final inductance value is independent of the current passing through the coil.
Figure 3. excitation marker showing input current to the coil system.

When running a magneto static simulation in ANSYS Maxwell, an enclosing medium box must be added to surround the model. In addition, the excitation terminals must touch the outer boundary edge. For this probing coil simulation, the effect of moving a 1 cm³ steel cube closer and further away from the coil is explored. As a result, the simulation environment boundaries are expanded to allow for this changing distance of the object as shown in Figure 4.

The material of the environment is defined as air, while the coil model is defined as copper. These settings are employed to properly set the magnetic permeabilities for each material in the simulation.
The simulation is then performed using a parametric analysis. A variable “dist” is set as the z axis position for the metal cube centered inside the coil. This variable is swept from 0 to 100 mm. This means the cube begins on the XY plane and then rises through the coil, with a final exit from the coil and ascent above it. One limitation of this simulation is that a metal object will never be inside the metal detector search coil in practice.
1.5 Experimental Inductance Measurement Procedure

The inductance of the coils is evaluated using experimental methods. The probing coil is prepared by first 3D printing a spool so that wire can be wrapped around it. Figure 5 shows a Fusion 360 model of the probing coil spool. This spool serves as the cylindrical form to wrap turns of wire around.

![Fusion 360 drawing of the probing coil spool.](image)

**Figure 5.** Fusion 360 drawing of the probing coil spool.

The cylindrical form is printed using polylactic acid (PLA). Cyanoacrylate glue is used to glue the end cap onto the spool, creating a complete unit. This set up allows for printing without the use of support material.
Enamel coated; 26-gauge copper wire is used to wrap 100 turns around the cylindrical form. Clear tape is used to hold the wire on the spool and prevent unspooling. 100 turns are used in the experimental setup to allow for the highest attenuation and best possible measurement resolution with an oscilloscope. With the coil formed on the spool, the new air core coil inductance is evaluated. The coil is placed in series with a 554 Ω resistor. A 10 MHz, 1V amplitude sinusoidal signal is connected to the coil and the resulting waveform at the node between the coil and resistor is measured. This setup is equivalent to a low pass RL network, therefore there is attenuation of the signal at the node between inductor and resistor.
The value of the voltage across the series resistance can be used to determine the inductance used in the circuit shown below in Figure 7. The transfer function of the circuit is shown in Equation 5.

\[
\frac{V_o}{V_{in}} = \frac{R}{jwL + R}
\]

**Equation 5.** Low pass filter transfer function.

Equation 6 shows a reevaluated set of variables to find the inductance of the solenoid. This expression is used to find the values to fill in the experimental inductance values for the test coil.

\[
L = \frac{RV_{in}}{V_o} - R
\]

**Equation 6.** Solved transfer function for inductance of the solenoid coil.
1.5 Coil Optimization Simulations

After verifying that constructed coils closely match the inductance of those analyzed in simulation, several solenoid coil geometries are tested to gain more sensitivity for metal detection. As cylindrical solenoid coils, there are three clear parameters to optimize: number of wire turns, cross sectional radius, and coil length.

For each simulation, a model similar to that used for the test coil is employed. In all coil simulations, an enclosing air-filled box is used. Also, again a triangular cross section wire is used to create each coil. A 50mm steel 1008 cube is also placed along the central axis of each coil as before with variable proximity.

![Figure 8. Model used in simulations for varying the radius of the coil.](image)

Part 2: Construction of a pulse induction search coil pair

After performing optimization simulations and building a test verification coil, a pair of search coils are developed. Two different sized search coils in one unit would allow a user to screen large areas and then focus on smaller areas once a metallic object has been detected. This section focuses on the construction of the two different search coils and the measurements of their inductances.
2.1: Design Considerations

Two coils are assembled with the diameters of 115mm and 37mm. The dimensions chosen are influenced directly by the results of Part 1’s optimization simulations. Short length, high turn density coils are constructed to maximize sensitivity. Because sensitivity decreases with larger diameter, two coils with different diameters are constructed to serve a wider object range by the detector.

In a production model metal detector, it would be desirable to place the smaller coil within the larger coil; the resulting device would be smaller and more portable. As a result, the coupling coefficient between the coils had to be measured and accounted for in detector circuit simulations.

2.2: Inductance Measurements

After construction of the inductor coils, their inductances are measured using a function generator and an oscilloscope. The same RL, low-pass filter measuring scheme used in Part 1 is employed here. A 1.5 MHz, 5.0 V sinusoidal signal is placed across each inductor in series with a 117 Ω resistor. The function generator is adjusted to read a 5.0 V terminal amplitude when under the load of the test circuit. Table 1 shows the resulting measured inductance values of the coils.

<table>
<thead>
<tr>
<th>Table 1. Experimentally measured inductance of search coils.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Probing</td>
</tr>
<tr>
<td>Scanning</td>
</tr>
</tbody>
</table>

2.3 Inductive Coupling Coefficient Measurement

Since concentric coils are desired for increased object size sensitivity, the effect of inductive coupling is measured for the two coils. The probing coil is placed inside the scanning coil. Next, a 1 MHz, 4.0 V sinusoidal signal is placed across the terminals of the larger scanning coil.
coil. Two oscilloscope probes are then used to differentially measure the induced voltage across the probing coil. This setup is shown in Figure 9 below.

![Figure 9. Coupling coefficient measurement setup.](image)

Once the induced voltage is acquired, Equation 7 is used to determine the coupling coefficient [Source 13]. Equation 7 resulted in a measured coupling coefficient of 0.24 between L1 and L2.

\[
V_2 = V_1 \times k \times \sqrt{L_2/L_1}
\]

**Equation 7.** Calculation of ‘k’, the coupling coefficient between L2 and L1.
Part 3: Design and Test of Coil Drive Circuit

A basic drive circuit is designed to drive both coils in LC tank circuits. The circuit is economized by driving both LC tank circuits in series. The resulting waveform consists of two superimposed tank circuit frequencies.

3.1 Simulation of Drive Circuit

LC tank circuits are created for each inductor coil. Common value capacitors are chosen to realize resonant frequencies in the kHz range. These frequencies are 7.6 kHz and 48.0 kHz for L1 and L2 respectively. The damping effects of series resistance in the coils is found to be non-negligible, so these values are measured and incorporated into the model along with the experimentally obtained inductance values [9]. Parasitic capacitance is not considered in these simulation models because its magnitude is overshadowed by the wide production tolerances present for the chosen capacitors [10].

The test coil drive circuit is realized by sinking current through these LC tank circuits in series. An N-channel MOSFET with low on-resistance is chosen. A 470 Ω resistor is used to limit the amount of current passed through the system and reduce consequent voltage spikes across the inductors. The drive circuit for a final detector design might benefit from clamping diodes on the signal output for added downstream voltage protection. Figure 10 shows the double coil drive circuit.
**Figure 10.** Coil drive circuit for two series LC tank circuits. Inductance values their respective series resistances are incorporated from earlier measurements.

The experimentally obtained coupling coefficient of 0.24 is also used to couple L1 and L2 in simulations. Simulations with and without the consideration of this coupling are performed. **Table 2** shows the peak to peak voltages for no coupling and coupling scenarios. Peak to peak values provide a cursory metric for characterizing the changing form of the waveform, but further processing reaches beyond the scope of this report. Full waveforms are available in the **Appendix**.

**Table 2.** Peak to Peak signal voltage

<table>
<thead>
<tr>
<th>Coupling Coefficient (L1 and L2)</th>
<th>Peak to Peak Signal Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1.55 V</td>
</tr>
<tr>
<td>0.24</td>
<td>1.68 V</td>
</tr>
</tbody>
</table>
The resulting inductive coupling did not seem to cause any distortions or overdamping to the signal. It is also assumed that this coupling would serve as a kind of baseline mark which changes caused by an added metal could be measured against. For this reason, the effects of coupling between the coils is deemed negligible, and analysis is continued with attention given only to the inductive couplings between the coils and metallic objects.

3.2 Simulation of Metallic Object Sensing

Simulation of metallic objects near the detector is accomplished with a simple model. Since eddy currents are induced in the target metal when placed under an induced magnetic field, a inductor model coupled to the search coils serves as a good representation of the system [11]. A very low resistance is placed across the inductor to simulate how within a metallic object induced currents are shorted together with the low resistance of the metal itself.

A simulation directive is used to define the induction coefficients between the metallic object, L3, with L1 and L2, the search coils. For the case where metal is near the search coil during detection, the coefficient is selected as 0.4. This value is in line with values for a few millimeter separation found in the literature [12]. Figure 11 shows the resulting model.
Next, the system is simulated with coupling coefficients of 0.4 discussed previously (near-field) and 0.001 (far field). Different coefficients are also selected for L1 and L2 coupled to L3. This describes a situation for concentric coils where an object (L3) may be inside the larger coil (L1) but not yet inside the smaller coil (L2). Peak to peak voltage values are presented again to provide an estimate of how the size of the waveform changes in response to metallic object coupling. Table 3 shows the simulated results. Note that L1 and L2 are not coupled to each other as tested previously.
Table 3. Different Peak-Peak signal values for different couplings.

<table>
<thead>
<tr>
<th>Coupling Coefficient</th>
<th>Peak-Peak Signal Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far Field</td>
<td>1.58 V</td>
</tr>
<tr>
<td>0.001 (L1 to L3) and (L2 to L3)</td>
<td></td>
</tr>
<tr>
<td>Inside scanning, outside probing</td>
<td>1.48 V</td>
</tr>
<tr>
<td>0.4 (L1 to L3)</td>
<td></td>
</tr>
<tr>
<td>0.001 (L2 to L3)</td>
<td></td>
</tr>
<tr>
<td>Inside both coils</td>
<td>1.22 V</td>
</tr>
<tr>
<td>0.4 (L1 to L3) and (L2 to L3)</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Experimental Testing of Drive Circuit

After simulating different detection scenarios, the circuit is assembled and tested experimentally. A single coil driver circuit is already designed on a printed circuit board from a previous project. The only difference from the simulation circuits is that the board is designed for one LC tank circuit. As a result, the two coils are soldered separately to each’s respective capacitor. Then the LC tank circuits themselves are soldered in series and connected to the traces built for the single LC circuit. The MOSFET on the board is driven by a 50 Hz, 3 V square wave from a function generator. Figure 12 shows the experimental setup.
Figure 12. Two LC tank circuits soldered in series to the driver board.

Power is applied to the board and the resulting waveform is measured at the base of the two LC tank circuits. Figure 13 shows the excitation square wave in yellow and the green, AC coupled output from the tank circuits.

Figure 13. Yellow square wave excitation and resulting green decaying sinusoid.

Figure 14 shows a zoomed in view of a single decaying sinusoidal waveform from the tank circuits. The green wave shows the combined signal from the both tank circuits while the blue is
measured at the larger coil’s tank circuit. The higher frequency of the smaller coil is superimposed onto the lower frequency of the larger coil, thus revealing information from two coils in one signal.

![Graph showing two frequency signals superimposed](image)

**Figure 14.** Superimposed higher frequency onto lower frequency signal is shown in green. The signal from just the lower frequency scanning coil is shown in blue.

Next, different metal objects are placed on top of the coils to evaluate their effects on the waveforms generated. First, an aluminum heat-sink small enough to not cover both coils at the same time is used for evaluation. **Figure 15** shows the two placements of the heatsink to evaluate the effects separately for each coil and consequent frequency signal component.
Figure 15. An aluminum heatsink is placed both off center and secondly centered on the probing coil.

Figure’s 16 and 17 show the resulting signal from off centered and centered orientations of a metallic object.

Figure 16. Off center metal object. Superimposed higher frequency onto lower frequency signal is shown in green. The signal from just the lower frequency scanning coil is shown in blue.
**Figure 17.** Metal object centered over probing and scanning coils. Superimposed higher frequency onto lower frequency signal is shown in green. The signal from just the lower frequency scanning coil is shown in blue.
Part 4: Final Results and Discussion

These are the final results as a culmination of simulation, construction, and testing of a two concentric coil pulse induction metal detector drive circuit.

Figure 18 shows the tested inductance values for a test coil used to validate software and analytical calculations. Calculated values are likely higher than both experimental and simulated values due to the assumption of an infinitely long solenoid. The simulated value is likely lower than the calculated and experimental values due to the use of triangular cross section wires to optimize simulation times. Finally, there is instability in the use of the oscilloscope to measure the phase angle and amplitude of the attenuated signal during experimental testing. This instability resulted in some error in the experimental value. With these factors considered, the results showed satisfactorily close matching between the three measurement methods.

![Comparison of Inductance Analysis](image)

**Figure 18.** Test coil analysis results.
Figures 19, 20, and 21 display the simulated trends of coil inductance as a function of metallic object proximity. The number of turns, length of the coil, and coil radius are varied to better understand their effects on sensitivity.

**Figure 19.** Effect of varying coil radius on coil sensitivity. Sensitivity increases as the radius is decreased.

**Figure 11** shows how there is a relative increase in inductance when the radius of the coil is decreases. The 50 mm coil shows much larger relative changes in inductance at short distances than do the other larger sizes. This is likely because a higher percentage of all magnetic flux from the coil is concentrated by the metallic object.
**Figure 20.** Effect of number of turns on coil sensitivity. Sensitivity increases as the number of turns is decreased.

**Figure 12** shows how the number of turns affects coil sensitivity. Similar to the magnetic flux in the small radius coil, as the flux density decreases, a conductive object has a greater relative effect on the inductance. This is evident with the increase in sensitivity with fewer turns.

**Figure 21.** Simulated effect of different coil lengths. Sensitivity increases as coil length is decreased.
**Figure 13** shows similar results as length is decreased, the sensitivity in inductance change increases. These results should be interpreted carefully. The smaller the inductance of the coil, the higher the resulting relative inductance change. However, with smaller inductances there will be a smaller absolute inductance change, so amplification circuitry must have ever higher resolution.

The following figures show the peak to peak voltages for simulated and experimental coupling between the search coils and a metallic object. The peak to peak voltages provide a convenient metric to gauge the effects of the coupling on the LC tank circuits. As coupling increases, the induced magnetic fields become stronger and oppose the change in direction of current flow in the search coil. This results in a higher effective impedance and voltage drop across the LC tank circuits, thus lowering the peak to peak voltage across the switching transistor and current limiting resistor. **Figures 22 and 23** show this progression from the left to right from least to most metallic object coupling.

![Simulated Effect of Object Coupling](image)

**Figure 22.** Simulated effect of metallic object coupling.
**Figure 22** starts with no coupling in simulation, analogous to no metal present for detection and progresses to one coil coupling at $k = 0.4$ and finally both coils coupling at $k = 0.4$. **Figure 23** shows progressive coupling experimental data. A small aluminum heatsink is placed first outside, then coupled to the scanning coil, and finally to both coils. The exact coupling coefficients for this data are unknown, as the inductance and internal resistances of the aluminum heat sink cannot be easily measured. However, the experimental data shows a very similar trend to that shown through simulation.

![Experimental Effect of Object Coupling](image)

**Figure 23.** Simulated effect of metallic object coupling.

The absolute voltage levels are a few hundred millivolts lower for the experimental values. This is most likely due to the omission of a Schottky voltage fly back diode from simulations that is present on the driver circuit board.

**Part 5: Conclusions and Future Work**

Low cost metal detection will continue to be a highly demanded technology as high attendance venues try to reduce the presence of metallic weapons such as guns and knives. This report details the design of detector coils for an affordable pulse induction-based metal detector.
Verification of coil design is first achieved through computational methods. This analysis assumes the coil is infinitely long to arrive at a simplified expression for inductance. Therefore, there is some inherent error in the result of this analysis, however it provides a useful baseline for comparison with experimental and simulation methods.

Verification is continued using simulation methods in ANSYS Maxwell. This software allows for the 3D design and simulation of a coil system. The coil is modeled and the resulting inductance is measured.

Simulation and analytical verification provided the insight to produce a test coil for real world inductance measurements. With this setup a low pass filter is realized, and the attenuated signal produced at the node between the resistor and inductor can be used to find the inductance value. The resulting experimental value matched fairly closely with those found through analytical and simulated solutions.

Once the process of designing and building coil solenoids is validated through experimental measurement, further simulations are carried out to optimize the sensitivity of the coils to the presence of metallic objects. The number of turns, coil radius, and the coil length are varied. Parametric analysis allowed for the analysis of how these variables affected the coils’ relative changes in inductance.

With the results of the parametric studies, short, small diameter coils are constructed with many turns. The inductances are measured and achieved 439 μH and 110 μH for larger and smaller coils respectively. The inductive coupling coefficient is evaluated and deemed inconsequential enough to omit from simulations. Circuit simulations are performed with the two inductors in two LC tank circuit configurations. This scheme produced a single waveform with two decaying sinusoids of different frequencies superimposed onto one another.
The circuit is constructed, tested, and found to agree closely with simulated results. Superimposed frequency signals would best be processed using frequency selective active bandpass filters. Fast ADC and digital filter analysis might also be a possible route for signal processing. Concentric pulse induction search coils provide the opportunity to discriminate location and size of metallic objects.

Future work might include more precise measurement of the coils’ inductances using an impedance analyzer. Factory produced solenoids might also be acquired to attain higher regularity in the pitch and consequent stray capacitance associated with each coil.

References


Appendix

Figure 24. Test coil acting as a low pass filter. Yellow is the input while green is the output.

Figure 25. 37 mm coil waveforms used for inductance measurement.
Figure 26. 115 mm coil signals used for inductance measurement.

Figure 27. Waveform for coupling coefficient calculation. Yellow is the input voltage on the primary coil. Purple is the secondary coil induced voltage.
Figure 28. Simulated waveform with $k = 0$ between L1 and L2.

Figure 29. Simulated waveform with $k = 0.24$ between L1 and L2.