Improved Magnetic Sensor for Natural Gas and Oil Well Logging

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SENIOR DESIGN II | DEC15-17

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1. Project Overview

1.1 Introduction

Nuclear Magnetic Resonance (NMR) spectroscopy is used in multiple different industries such as medical and chemical. A key application of this technology is in the oil and gas industry where, it is used to acquire information about underground rock formations. This is done by embedding a Low Field NMR sensor into a drill tool used for down-hole drilling. The sensor is a RF Inductive antenna. In the presence of a permanent uniform magnetic field, the materials in an underground formation become magnetized. When a perturbing timed RF field is introduced in an orthogonal direction, it cause a spin flip in the magnetized materials state. When this RF signal is turned off, this causes the materials to return to their previous state releasing an Electro-magnetic (EM) radiation. The soft magnetic core is the antenna of the sensor. When EM radiation coming from the materials after spin flip hits the soft magnetic core, it causes its electrons to vibrate creating an electric current at the resonant frequency of the spin flip. This current is then sent to a receiver to process the frequency spectrum.

1.2 Purpose

The purpose of this project is to find a soft magnetic core material that can be used in an RF antenna with minimal unwanted resonances. The material will be selected from a survey of the current materials the client has prepared. The measurement system will also be redesigned to produce a uniform magnetic field of 400 Gauss and suitable EM shielding. Finally, the data processing for the measurement system will be automated with a Graphical User Interface (GUI), which allows the user to input a file path and it produces a graph of the amplitude and width of the test frequency. The soft magnetic material will be part of an RF Inductive sensor which will be part of a NMR setup used to characterize underground formations. The frequency range for this sensor will be between 0.1-1 MHz.

1.3 Deliverables

The client will be provided with a GUI that processes all of the measurements for multiple materials, a stable magnetic field produced via an arrangement of permanent magnets and shielding, and a measurements of the materials provided by our client with a recommendation on the best material with minimal resonances.

2. Requirements

2.1 Functional

➤ Ferrite epoxy soft magnetic core samples.
➤ Rod-like geometry.
➤ Reduce unwanted acoustics.
➤ Low Hysteresis losses.
➤ Uniform magnetic field of 400 Gauss encompassing the entire length of the ferrite core using neodymium boron (NIB) permanent magnets
➤ Each material we be looked at multiple frequencies. For each of the frequencies a csv file will be output containing the voltage and corresponding times.
➤ For each file, the entries will be Fourier transformed and the frequency of its max amplitude and its half width maximum (hwm) will be found.
➤ The results found in each file will be saved to a single file containing the max frequency and hwm for all files in the folder.
➤ This new file will be used to generate a chart comparing the hwm with the frequency of the test pulse.
➤ This process will be repeated for all material folders inside of a larger test folder

2.2 Non-Functional

➤ Must be one of the materials currently being explored by the client.
➤ The magnetic core samples have to be prepared using the equipment available at Ames Lab or the Microelectronic Research Center (MRC).

2.3 Operating Environment

This finished test set-up will be used in a laboratory setting. The interface and design were created with the knowledge that the users will have extensive knowledge the EM field. Once the uniform magnetic setup and shielding have been implemented, the system will be tested by the client in their lab. It will also be used exclusively at that lab to test rod like soft magnetic core materials.

3. System Description

3.1 System Analysis

The system was redesigned to include a uniform magnetic field and proper shielding. The client's current measurement setup shown doesn't have a uniform magnetic field and proper EM shielding.
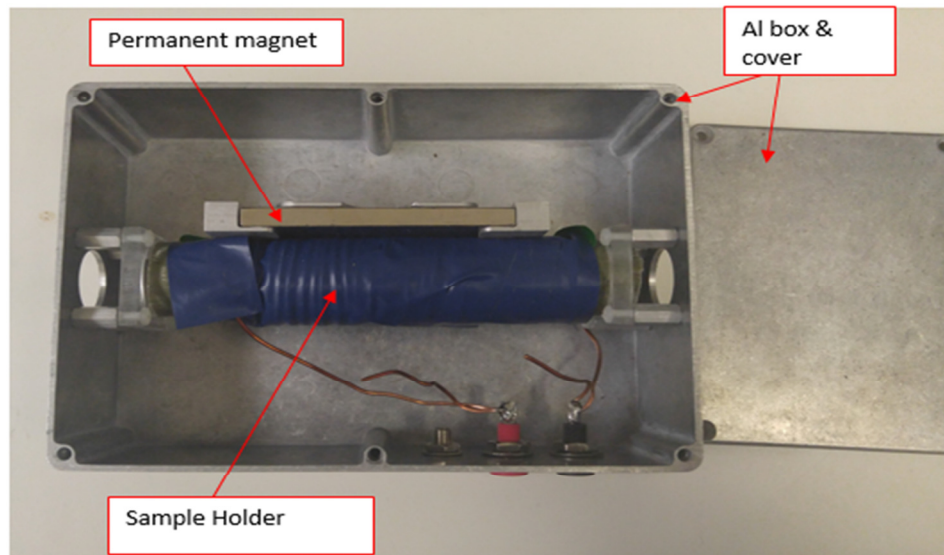

Figure 1: Sample holder

The client's current sample holder block is shown above has only one permanent magnet and the sample is enclosed in an Aluminum box. Also the measurement system does not have a batch post measurement data processing.
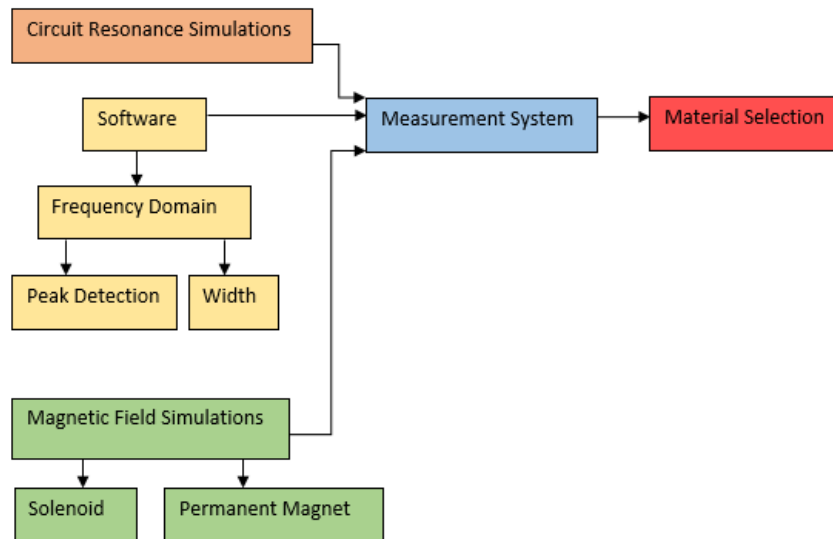
3.2 Block Diagram

3.3 Component Specifications

To that end, the following materials were chosen based on the geometric requirements, economic limitations, work of others, and magnetic physical requirements of the project.

Neodymium boron iron (N 42)
- Magnetic resonance: 13,000 Gauss
- Relative permeability: 1.05
- Dimensions: 2 inches outer diameter, 1 inch inner diameter, 1 inch height

Giron Shielding
- Relative permeability: 7,000
- Saturation: 20,000 Gauss
- 1 millimeter thick
- Flexible and easy to cut

ISU Ferrite core material
- 5 and 3/8th inch long, 3/8th inch radius cylinder
- Relative permeability: 225

4. Revised Design Process

4.1 Materials Preparation

Currently the client's sample preparation method entails mixing Ferrite powders with epoxy. Some of the powders are Commercial Ferrites (Ferrite mixed with Zinc or Magnesium) bought and mixed with epoxy. The Client also had a process in place to produce these Ferrite powders. This process entailed mixing constituent powders to create Mn-Zn ferrites, $Mn_xZn_{1\_x}Fe_2O_4$ (with x varying from 0.2 to 0.8) where M is either Mn or Ni.

Initially, the sample powders are batch mixed in a glass jar to improve homogenization. Ball milling is the next stage to create intimate contact between the particles. The ball mill used different sizes of lead balls to vary the particle size. Compaction of the sample with a hydraulic press is then done after the ball milling stage before every calcination step. Once the sample is compacted, it is calcined at 1050-1100 ^{o}C to create a solid state reaction. The sample then undergoes two more ball milling stages and one more calcination stage before it is ready to be mixed with epoxy. Sieving is done after the last ball milling stage to remove particles that were not properly milled.

After an extensive research and literature survey, we found out that adding annealing as the last stage of the sample preparation process could produce a two phase structure with improved soft magnetic properties. The two phase structure will consist of amorphous and nanocrystals. The annealing will take place in an inert atmosphere such as vacuum or inert gas at a low temperatures. We therefore recommended to our client that they should add this stage to their current sample preparation method. Once the Ferrite powders have been annealed they can then be mixed with epoxy to form the core.

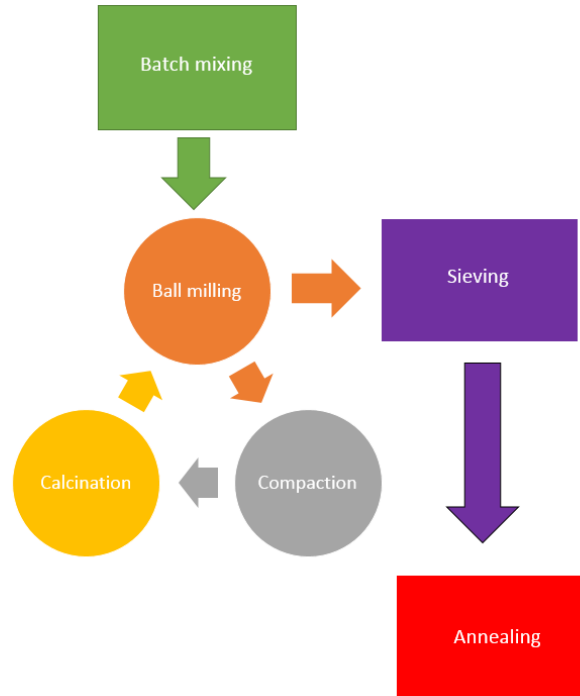The schematic of revised the sample preparation process is shown below.

Figure 3: Client current sample preparation method with proposed annealing modification

4.2 Uniform magnetic simulation

The measurement system for testing the core materials requires a constant magnetic field throughout the material. This induces a static magnetic field, magnetizing materials in underground formations and producing a small amount of spin polarization in the particles. When a pulse signal is sent through a coil around the core material, it creates an orthogonal magnetic field that can disturb the magnetic equilibrium of the materials in the underground formation. This change in equilibrium can be measured and is unique to different materials. The required magnetic field of 400 Gauss allows the sensor to have a wide detection range including both oil and water. Many COMSOL simulations were conducted in order to obtain the optimum solution which was then to be constructed.

4.3 Software Design

Goals for the software in this project was to quickly obtain the amplitude and width of the peak closest to the impulse frequency. All the results of for a single material needed to be stored in a single file and put on the same graph. Additionally the ability to process a batch of several materials was desired.

During in order to simplify troubleshooting and coding in general the design process began with three simple functions one to convert the data to the frequency domain, one to find the

desired peak, and one to find the width of that peak at half of its amplitude. The Frequency domain function was the most trouble because of complications with the output of the measurement equipment. The NMR Spectrometer data is automatically shifted so that the impulse frequency is at zero. Once we discovered this we were able to account for it by reading the impulse frequency. Once the functions were done a GUI to call them was created them on a single material was created. After this GUI was tested we created a second GUI to call multiple instances of the first one.

5. Implementation Details

5.1 Uniform Magnetic Field

The uniform static magnetic fields were simulated in COMSOL.. The cylindrical shape of the materials necessitated the cylindrical surrounding disk shape of the magnets. The magnetic flux from the neodymium boron iron (N 42) permanent magnets to the core material is a predictable constant. So the internal magnetic field of each core material is therefore variable based on that materials relative permeability. By surrounding the magnets and material with a shielding material, the magnetic flux through the core can be limited and internal material flux variation can be reduced or removed. The equation used for simulation is $B = \mu * \mu_0 * B_{rmax}$.

- Magnetic field: B
- specific permeability: μ
- permeability in free space: μ_0
- Magnetic resonance of the neodymium boron iron magnets: B_{rmax}
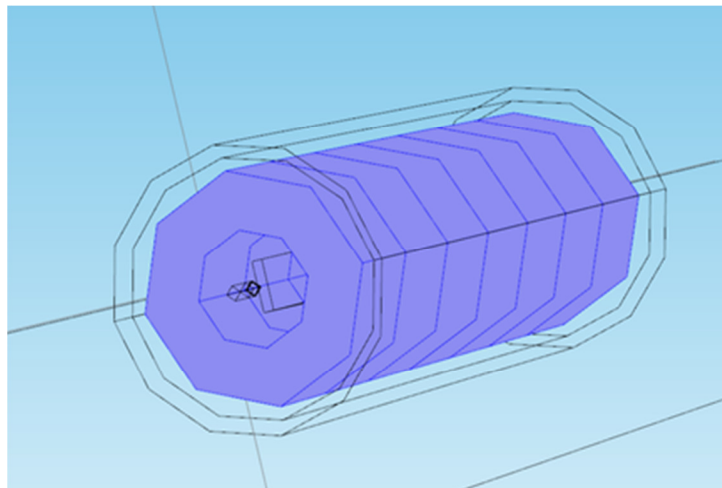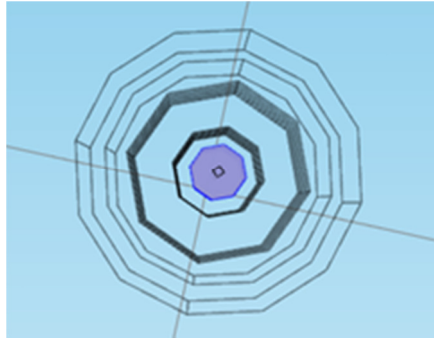

Figure 4: Seven Neodymium Boron magnets stacked

Figure 5:Cylindrical material core radially (Hexagon shape due to user interface lag. Mesh simulation is cylindrical)
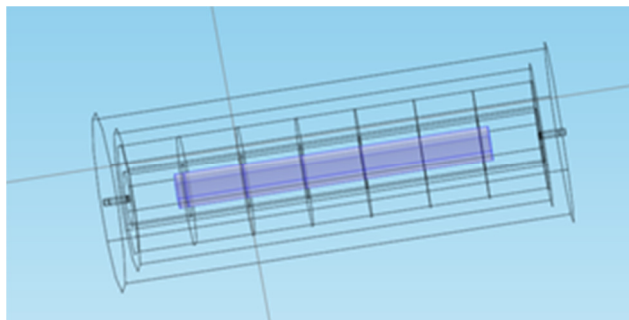

Figure 6: Cylindrical material core laterally in geometric center of stacked magnets
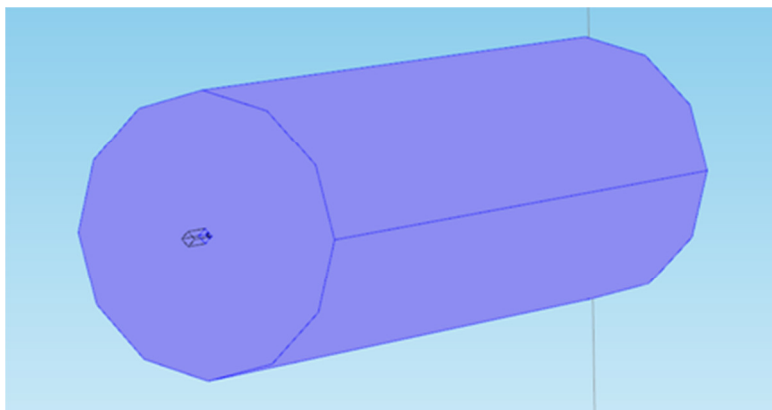

Figure 7: Cylindrical Giron shielding surrounding magnets and shielding

Therefore, for each material presented, given that material's unique geometry and unique relative permeability, a uniform magnetic field though any material can be created. Each material will require a unique solution. The variables to accomplish this are;

- the number of magnets stacked on each other, thereby increasing the magnetic field and increasing the distance from the material laterally to the edge of the permanent magnet laterally

- the distance from the permanent magnet design to the shielding lengthwise, allowing more flux to enter the core material but increasing the variation inside
- the distance from the magnet design to the shielding material radially, allowing for less saturation of the material and more flux to enter the core material
- the thickness of the shield, thicker shielding allowing for more flux saturation

5.2 GUI

The data processing software was implemented using two graphical user interfaces (GUI's), created in MATLAB. This Software consists of a main GUI named "Metagui", a secondary GUI called "Subgui", and three data processing functions tagged as: "peakdetect", "linewidth", "fouriertransform." This architecture is shown in figure 8.
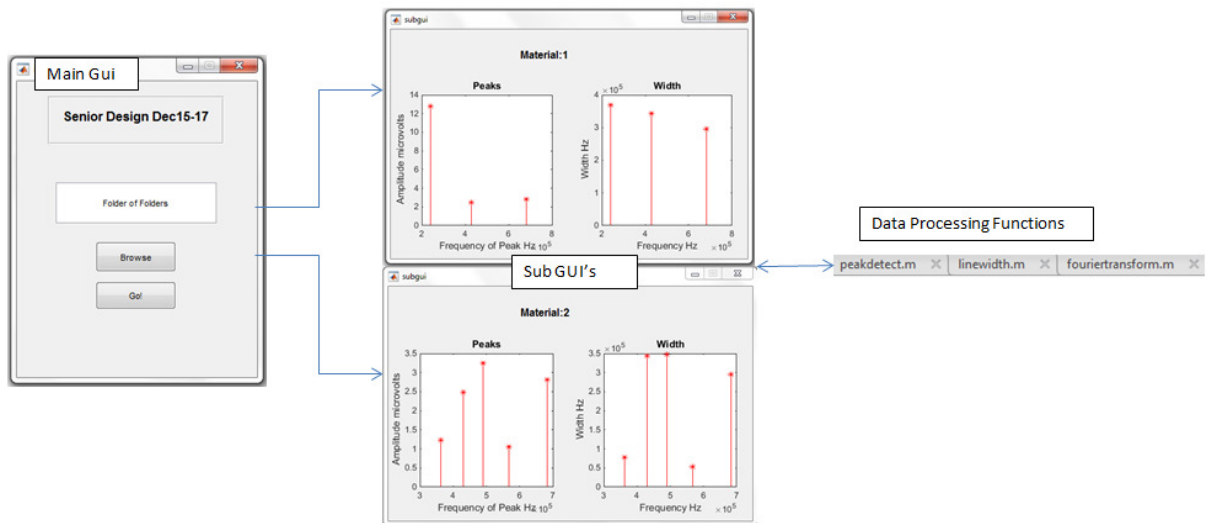

Figure 8: Code Structure Diagram

The Main GUI reads in a folder path from the user for each folder contained inside the original folder it calls an instance of 'Subgui.' Each instance of the 'Subgui' reads all of the data files in its respective file, converts that data to the frequency domain, finds the peak closest to the input frequency, finds the width of that of that peak at half its amplitude and adds both the width and the peak to its plots. These points are also added to a text file in that folder. A diagram of the functionality is included in figure 9.
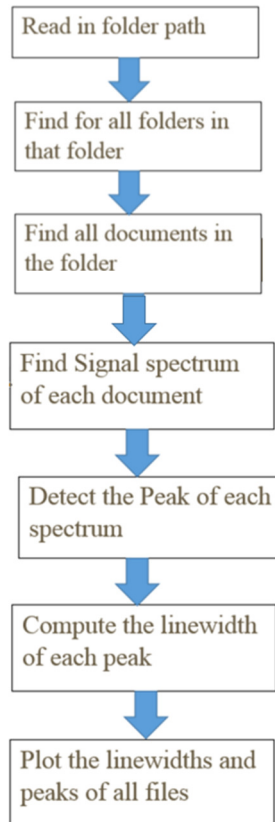
Figure 9: Data Processing Process

6. Testing Process and Testing Results

6.1 Natural Circuit Resonances

As part of the investigation to find the unknown resonances in the magnetic core, we had to make sure that they were not natural circuit resonances. Therefore, simulations of the circuit were done in MultiSim to find if the unknown resonances were coming from the circuit and not the core material. We simulated our best sample the ISU-Ferrite epoxy at one of it's resonant

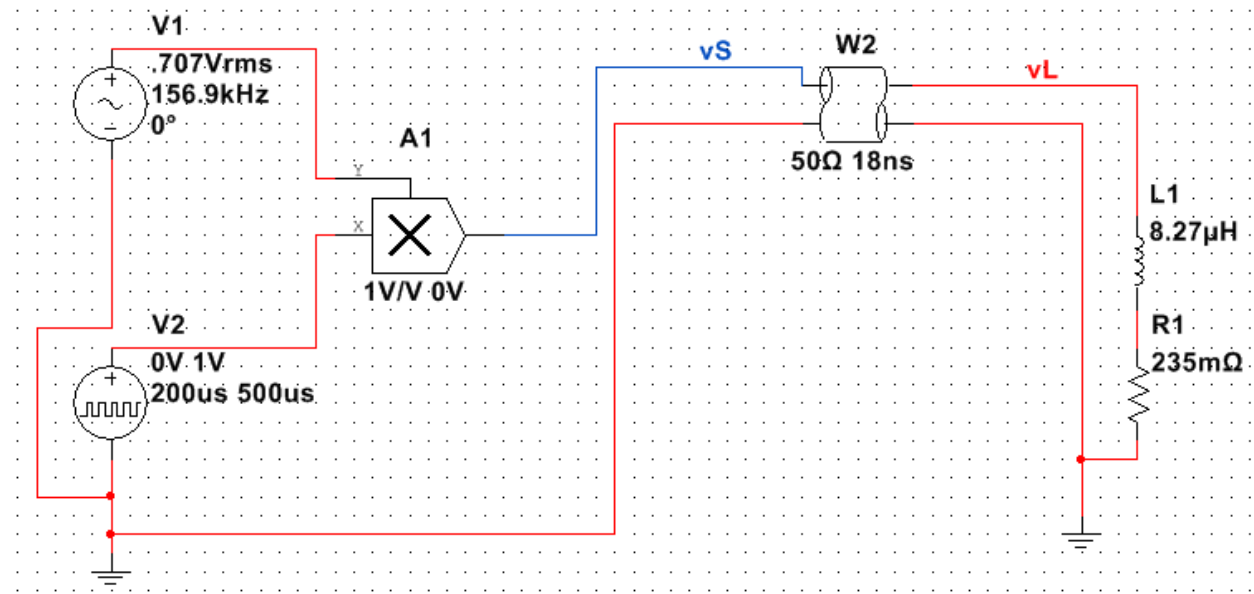frequencies, the circuit schematic is shown below.

Figure 10: Circuit simulation in MultiSim

A transient analysis of the circuit was done on the circuit and the results are shown below. The green represents the source wave and the red the reflected wave at the load.
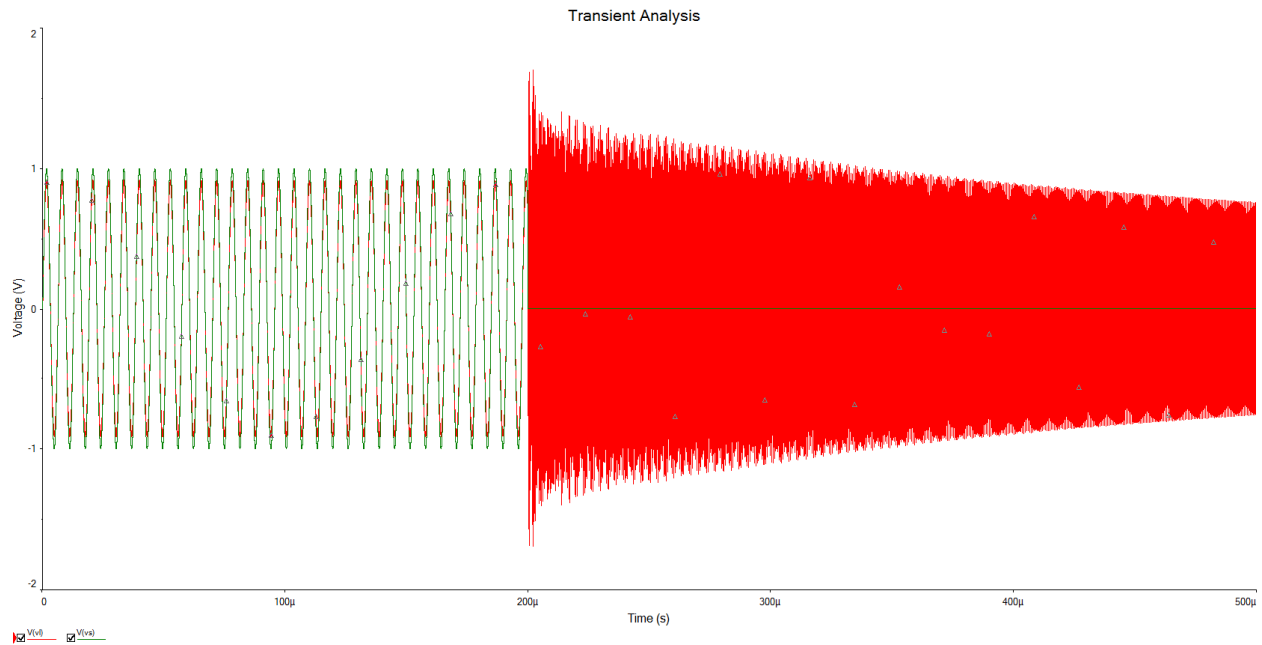

Figure 11: Transient analysis results of circuit simulation

After the pulse is turned off, there is a decaying reflected wave that persists at the load. This would be when the inductive antenna is sending back information to the receiver in the measurement system. A frequency spectrum of the decayed wave is shown below.
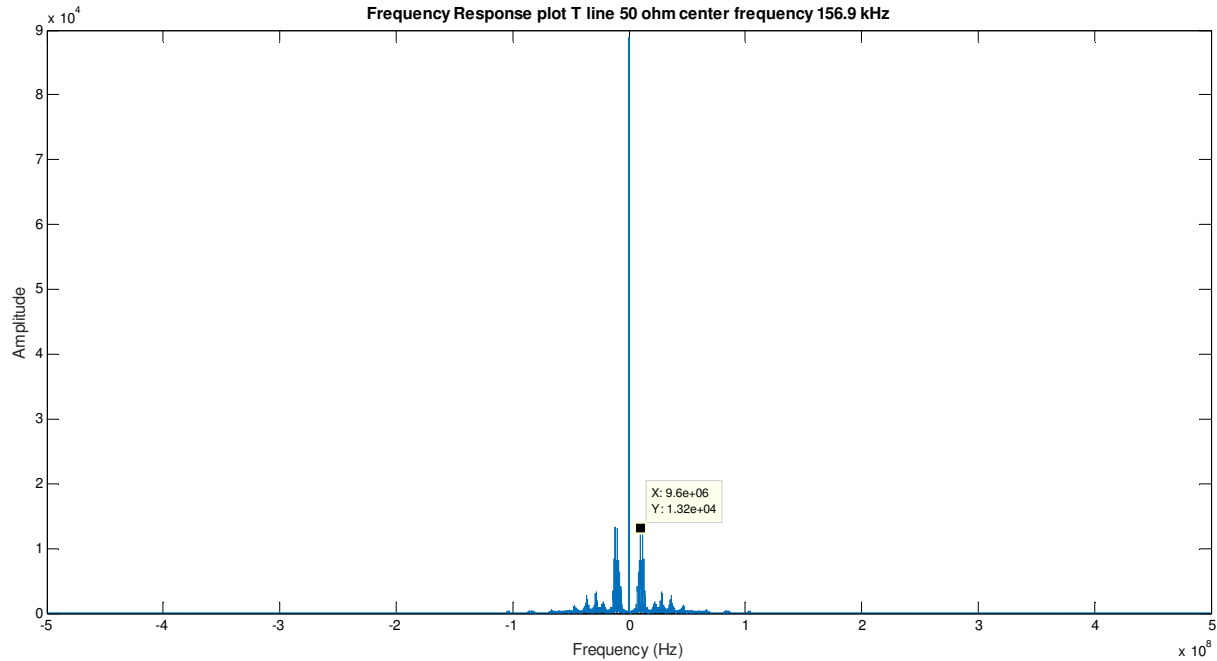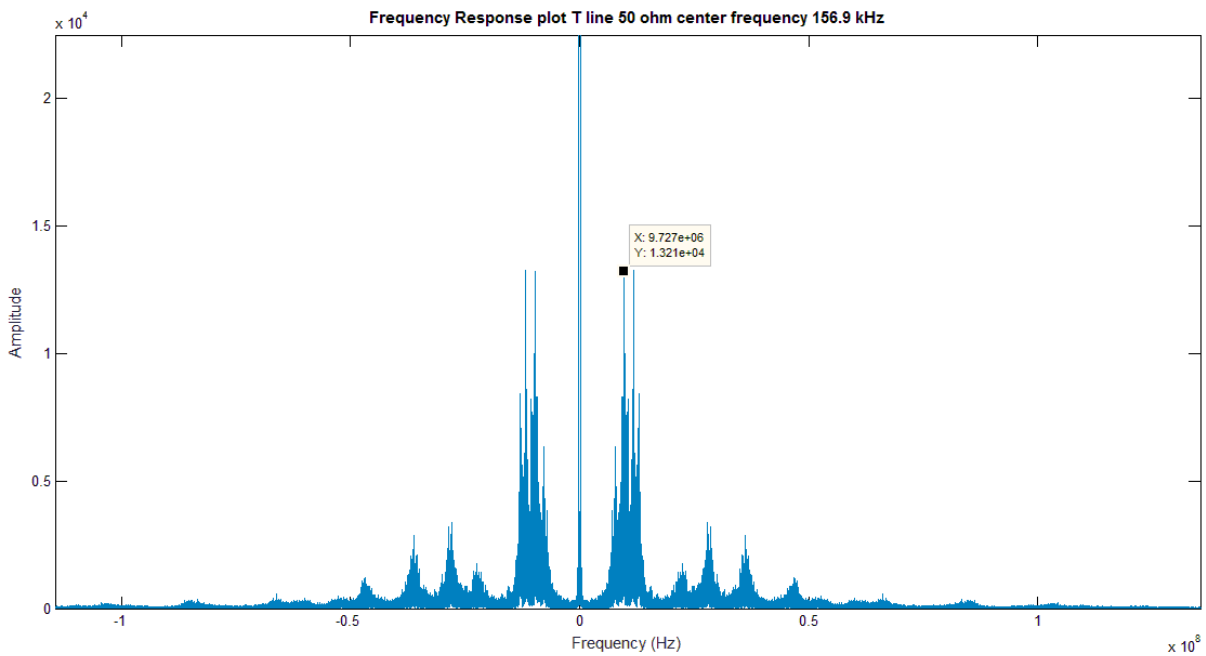
Figure 12: Frequency Spectrum

Figure 13: Frequency Spectrum

What the circuit simulations show is that the natural circuit resonances occur well beyond our measurement. They occur above 9 MHz while our maximum sensor range is 1 MHz. Hence they are not interfering with our measurements. However, the circuit does amplify noise and this could be a factor in the contribution of the unwanted resonances. A broadband impedance

matching network could be implemented after the antenna before the receiver to suppress the noise.

6.2 Measurement Results

We tested 3 of the samples the client produced. MU70, MU55 and the ISU-Fe epoxy. The MU55 is used in some of the client's tools. SA70 was the best of the premade client's materials that were not produced at Iowa State. ISU-Fe epoxy was produced using the sample preparation method explained earlier. The results of the testing are shown below.
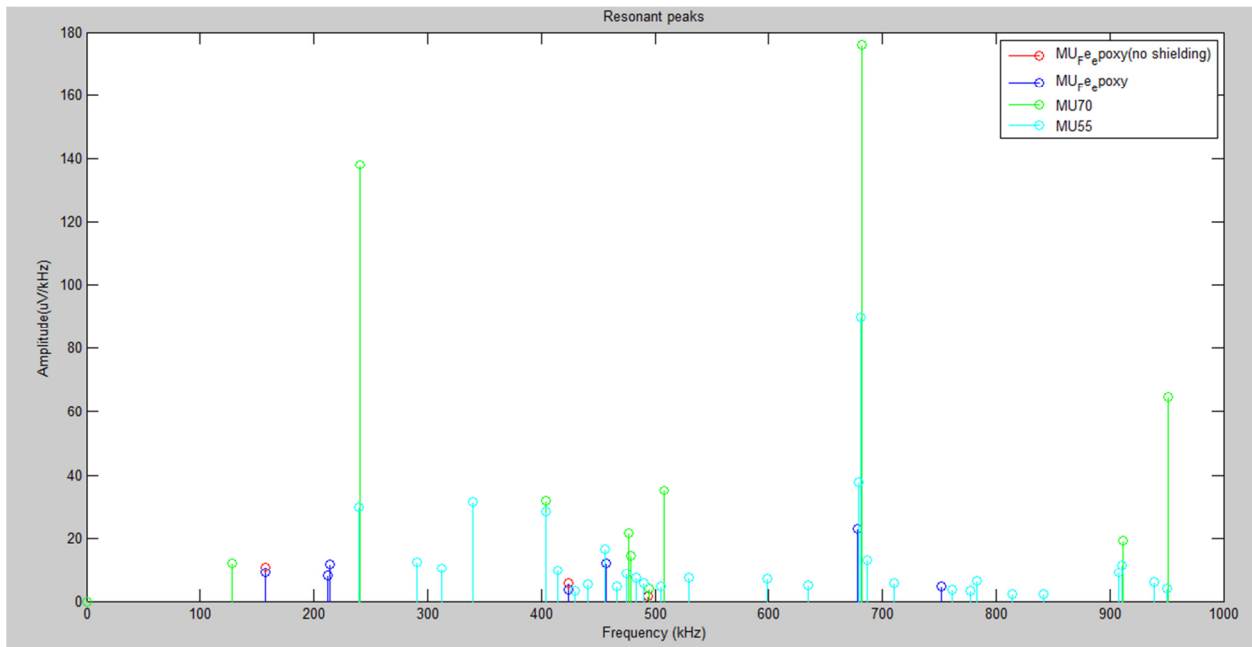

Figure 14: Resonance measurements of samples

Out of all the measurements results, the MU55 fared the worst and the ISU-Ferrite had the least amount of unwanted acoustics.

6.3 Software test matrix

The software did multiple things each of which had to be tested separately. These functions and their corresponding tests are shown in table 1.

Function	Test	Results
Create Graphical User Interface	Visual Confirmation	Good

Read in Folder Path	Typed in path and printed the resulting string to the screen	Good
Allow User to browse for a Folder	Browsed for a folder	Good
Determine all folders within Original Folder	Printed these to screen	Good
Create a Graphical User Interface for each sub folder	Visual Confirmation	Good
Determine the files in the subfolder	Printed these to the screen	Good
Read in data from file an	Included a line that printed the values to the screen and looked	Good
Fourier transform data	Plotted the results of known data sets and compared them to the existing plots	Good
Find all of the peaks	compared array of peaks to the plot	Good
Find peak closest to the impulse frequency	compared with previous processing of data sets	Good
Find the Half Width Maximum of the peak	compared with previous processing of data sets	Good
Iterate through all files in folder	Visual confirmation	Good
Plot the peaks of all files	Visual confirmation	Good
Plot the widths of all plotted peaks	Visual confirmation	Good
Create a file with all of the peaks	Visual confirmation	Good
Create a file of all the widths	Visual confirmation	Good
Iterate through all subfolders	counted graphs compared to number of subfolders	Good

Table 1: Software Test Chart

6.4 Permanent Magnetic Field Generator Simulation Test

Good simulation results have been obtained for each of the four materials currently under experimentation. Below is the linear characteristic for ISU Ferrite in several different places as well as through the entire magnetic generation design. The simulation compares the core to air in the same geometry. The geometry for this core material is the chosen design for construction. Economic limitations necessitate this as the only construction.
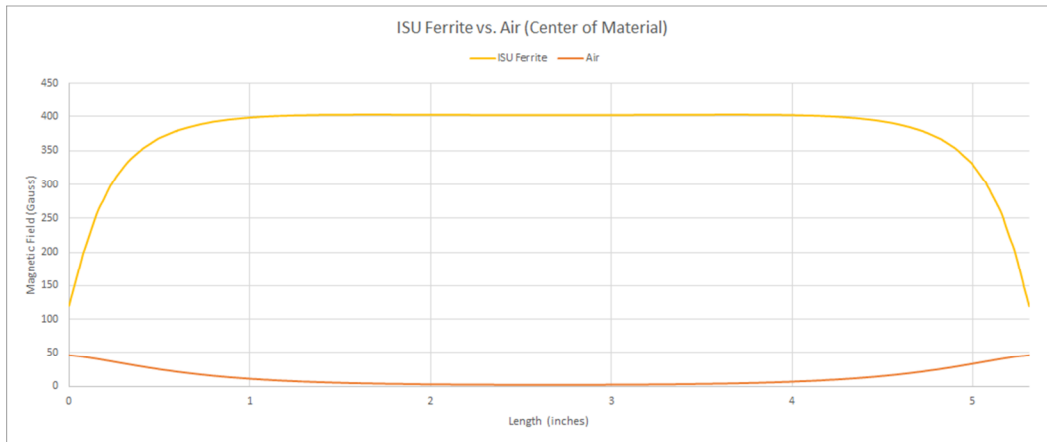

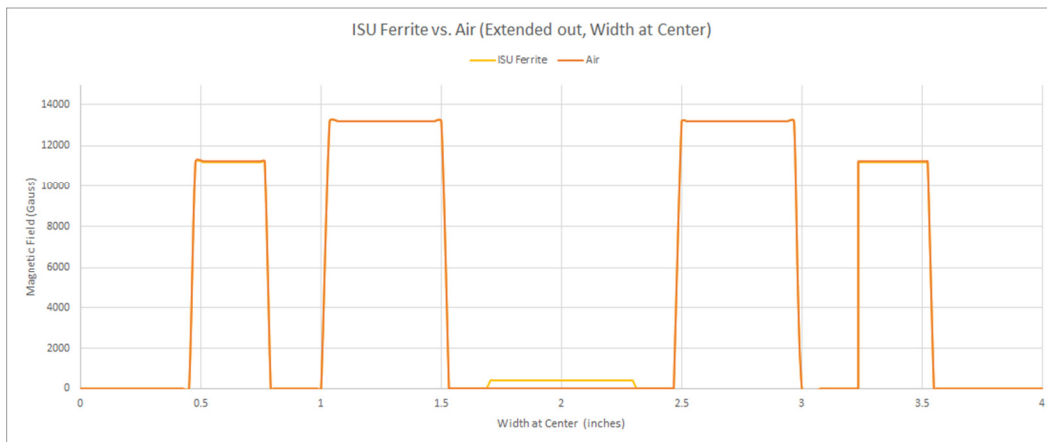**Figure 15: Magnetic field through length of core material laterally**

Figure 16: Magnetic field through entire design radially.

The center is the material at 400 Gauss. The largest peaks are the permanent magnets at 13,000 Gauss. The other two peaks are the Giron shielding, well below their saturation.
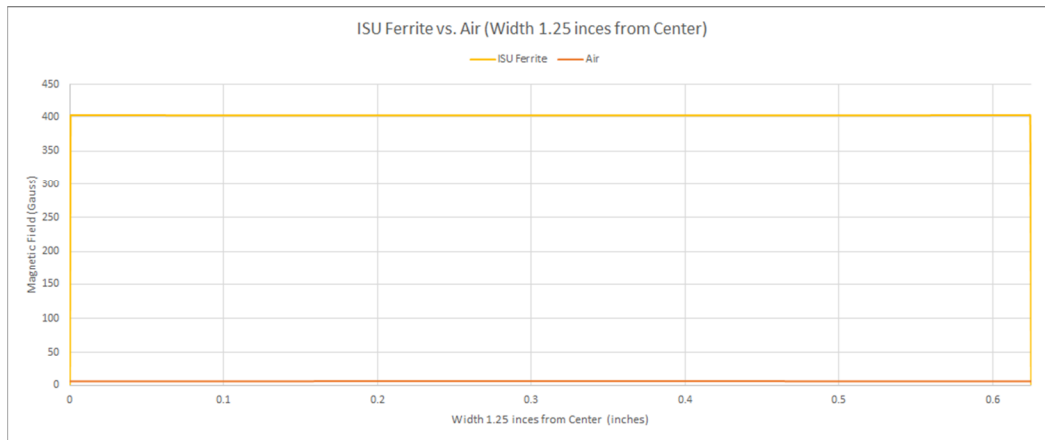
ISU Ferrite vs. Air (Width 1.25 inces from Center)

Figure 17

Appendix I: User Manual

AI.1 Measurement manual

1. Input the resonant frequency of the RF pulse
2. If a short pulse is desired, input 50 μs for the pulse width
3. If a wide pulse is desired, input 200 μs for the pulse width
4. Set 80 us for the pulse acquisition delay
5. Set 7000 ms for the repetition time
6. Set 128 for the number of repetitions
7. Set 2.048 for the number of complex points
8. Run the measurement setup

AI2. Software manual

1. Save the data as a "comma separated variable" (.csv) file.
2. The machine by default names all data files data.csv rename the file with the pulse frequency. For example if the input pulse was at 3KHz the file would be called "3000.csv"
3. Save file to a folder into for that material.
4. Repeat steps 1, 2, and 3 for all test on a given material.
5. Move all material folders that to be tested to a single folder.
6. Open the file called "metagui" in MATLAB.
7. Run "metagui" (pressing "F5" runs the current file) This window will appear

Figure 18: Main GUI

8. Click the "Browse" button.
9. Select the folder from step 5.
10. Hit the "Go"button.
11. The software is now processing your data. The graphs and text files will be updated as it goes.

Appendix II: Previous versions

AII.1 Permanent Magnetic

It was decided though calculations and simulations using COMSOL Multiphysics that the obvious answer of creating a magnetic field using a solenoid would not produce the required result for this project. The magnetic field requirement of 400 Gauss is too small; the turn ratio density of the solenoid would be too low. This would allow magnetic flux leakage that would hamper the uniform magnetic field and create inconsistent asymmetry. Therefore, it was decided to create the magnetic field using neodymium boron iron (N 42) permanent magnets.

Also, several different geometries were considered and abandoned. For the permanent magnet, these included partially surrounding the core with magnets, placing permanent magnets on the ends, spacing the magnets, and fulling encircling the core with magnets. Also, different geometries for shielding were considered. Among these ideas were placing the shielding at the ends of the magnets only without surrounding the total design. These were all inevitably used for analysis purposes when completing the final design.

AII.2 Software

There have been multiple challenges in the software development. This paper will look at the biggest changes that resulted. Our initial plans included having the GUI operate the

measurement equipment in addition to processing the data. It was later decided that in the time allotted this would not be possible, and so the GUI was reduced to purely data processing. However, since the signal processing is no longer linked to the measurement process, it became possible to process more than one material in a session. This lead to the development of the file known as "Metagui." The original GUI that was designed to process a single material is shown figure 19.
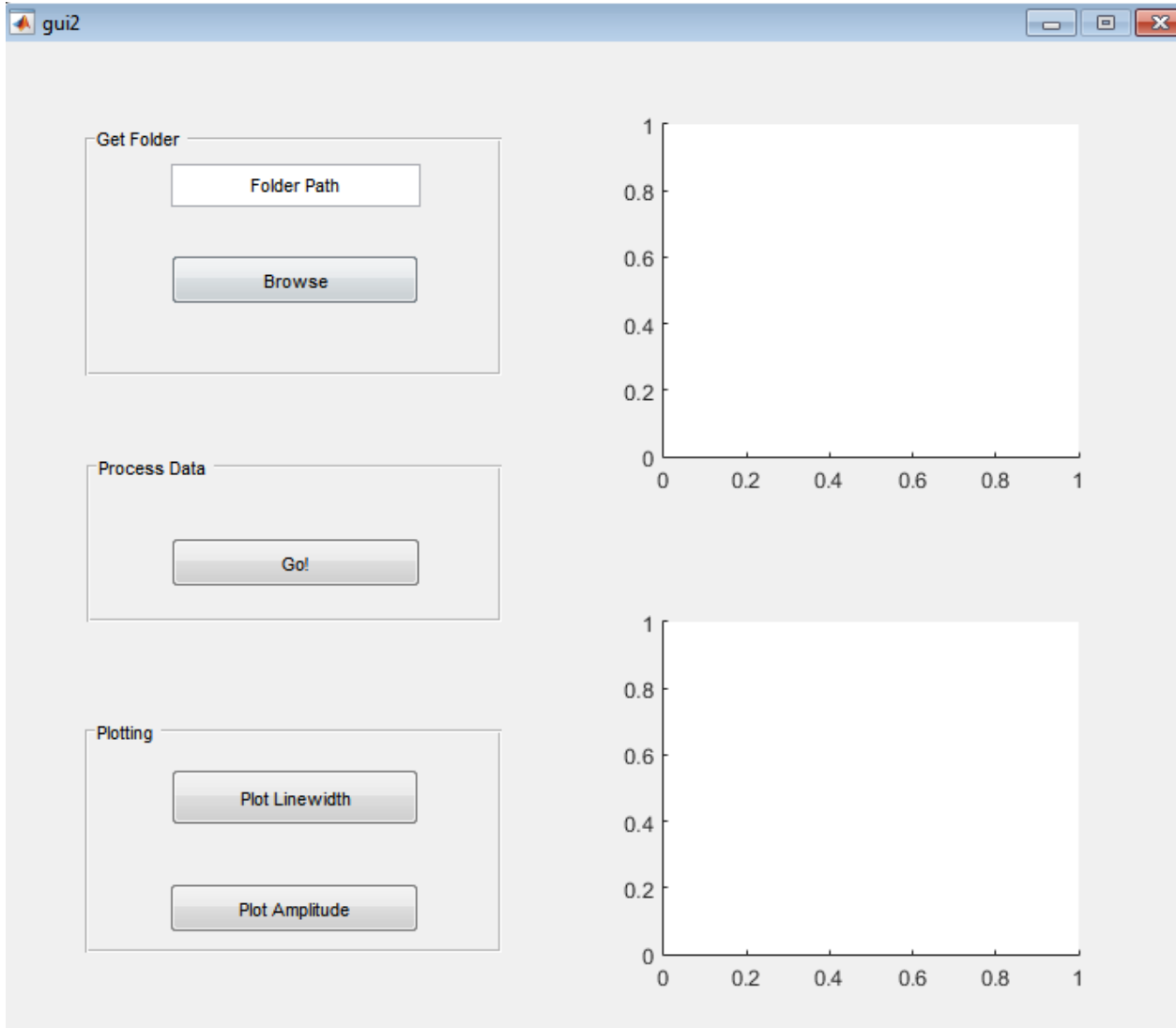

Figure 19: Old Software GUI

Appendix III: Other Considerations

We explored the possibility that some of the resonances were coming from the impedance mismatches in the circuit. We attempted to remove the resonance by attaching a broadband

impedance matching network between the receiver and the sample. The results of this exploration are shown in the following figure.
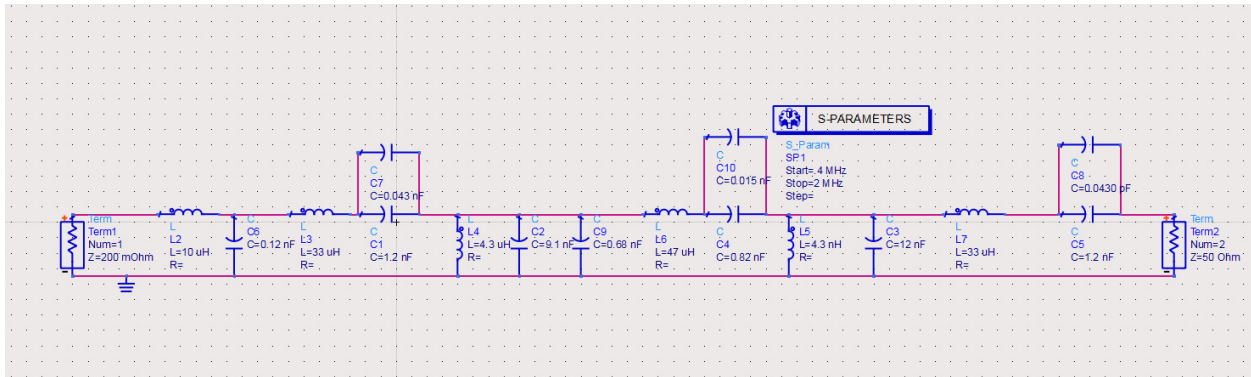

Figure 20: Impedance Matching Circuit Schematic

Our impedence matching network was a fifth order Chebyshev filter adjusted to use actual part values. Unfortunately, as is seen in the figure below, simulations in Advanced Design Systems (ADS) showed very high attenuation. This attenuation combined with the results of the circuit resonance simulations convinced us that this was not a useful line of inquirey.
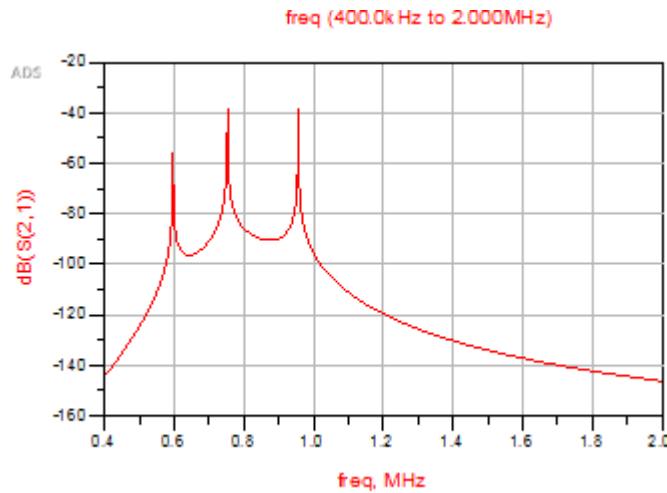

Figure 21: Results of ADS Simulation