Study of Magnetic Field Based Propulsion

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Submitted to:
Project Advisor:
Professor Marko Popovic, WPI
Charles Recchia, WPI
Submitted by:
Brian Scholwin
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Abstract

The possibility of manipulating a magnetic field that has the same the magnitude of Earth's geomagnetic field is the focus of this topic. This manipulation will be making a stronger magnetic field, that is one hundred times or greater then the supplied magnetic field. The approach to investigate this concept was with magnetic shielding material. This material is designed to protect an area from external magnetic fields. During this experiment the material will be used to focus magnetic field into a much smaller area, effectively increasing the magnetic flux. The geometry of the material will be that of a linear truncated conical shell, where the resultant magnetic field strength at the smaller radius will be proportional to the ratio of the radii of the larger and smaller radii.

If this type of result is obtainable, whether it be obtainable through the use of magnetic shielding material or superconductors which provide a similar effect due to the Meissner effect, we can then use this stronger magnetic field to generate a microscopic force by running a wire with a current close to the smaller opening, which could be used to generate an upward lift, relative to Earth's surface. If this were to work as intended, this effect could make use of Earth's magnetic field to keep satellites in orbit.

Ideally for satellites the use superconductors would be the most beneficial, as space would be the ideal environment for these superconductors, which has a much stronger effect then magnetic shielding material. However for a higher temperature environment, where the temperature is higher the superconductor's critical temperature, then superconductors are no longer viable. In this case we would like to see if we can achieve the comparable results with magnetic shielding material.

In this experiment, a linear truncated conical shell made of magnetic shielding material with a varying permeability which is increasing from 30,000 to 444,000 as the magnetic field increases until the magnetic field becomes 7600G, at which point the material becomes saturated and the permeability falls to 1. The larger opening of this conical shell is a radius of 2.5cm and the smaller opening being a radius of 2.5mm. We have decided to use an initial magnetic field of 0.4G, thus our maximum magnetic flux we could obtain at the smaller opening would be 40G if the magnetic shielding material shielded the area perfectly.

1 Introduction

When keeping satellites in orbit, we currently use modern rocket theory. This involves generating kinetic energy in one direction by throwing mass in the opposing direction. This process large requires quantities of mass to keep these satellites in orbit. This requires an organization to invest a large amount of capital to keep the satellite in orbit for extended periods of time, thus a cost efficient alternative is required. With this problem in mind, the idea this project proposes is to augment Earths geomagnetic field to make it larger, then use this to generate propulsion for these satellites.

1.1 Obtaining a Greater Magnetic Field

Obtaining a greater magnetic field can be accomplished because magnetic flux is conserved. This means using an object with a large area opening in which the initial magnetic field would enter and then having a smaller area for the magnetic field to exit, the magnetic field strength would then increase. This property can be seen by:

$$\Phi_1 = \Phi_2 \tag{1}$$

Where;

$$\Phi_1 = B_0 \times A_1 \tag{2}$$

and;

$$\Phi_2 = B_a \times A_2 \tag{3}$$

Here Φ_1 and Φ_2 are the magnetic flux at the entrance and exit of the object being used. B_0 and B_a are the initial and augmented magnetic fields. A_1 and A_2 are the areas of the entrance and exit.

Using this in the case with two circles where the larger circle has a radius R_1, and the smaller circle has a radius R_2, we find that the augmented magnetic field strength is given by;

$$B_a = B_0 \times \frac{A_1}{A_2} = B_0 \times \frac{R_1^2}{R_2^2} \tag{4}$$

Eq.4 shows in this theory that the augmented magnetic field B_a is a ratio of the two areas. For two circles the ratio of the two radii squared. With this theory, we could use this to produce a stronger magnetic field simply by increasing the ratio between the two areas. With the right set up we could obtain magnetic fields up to several hundreds to thousands times larger than our initial magnetic field that was supplied to the object.

However this is for an idealized case where there will be no leaks, or a point where the material can no longer effectively keep the large magnetic field from flowing outside the boundaries of the material. To solve this problem, superconductors, or magnetic shielding material could be used. Both materials have properties that resist the flow of a magnetic field through, or outside the material.

1.2 Using Magnetic Field to generate a propulsion

The purpose of augmenting a magnetic field is to generate a force such that we can produce a propulsion. This can be achieved by placing a current carrying wire near the augmented magnetic field, where the field is the strongest. Then by Lorenz's Force Eq.5, this magnetic field will generate a force perpendicular to the magnetic field and current.

$$F = I\overrightarrow{l} \times \overrightarrow{B} \tag{5}$$

Eq.5 shows us is when we supply a magnetic field we can generate a force that we can use. For example a magnetic field that has a magnitude similar to Earth's geomagnetic field, $0.5G$, we can increase the strength of this field in such a way that it follows Eq.4. Taking a radius ratio of 100 or greater we can then achieve an augmented magnetic field of $50G$ or greater, by using the proposed magnetic field. With this augmented magnetic field we can run any number of current carrying wires such that Eq.5 produces a force that meets the requirements of the system would be used for

2 Materials

Materials that could achieve the desired results are superconductors, which are ideal for a low temperature environment. T his would be ideal for the satellite scenario. In a higher temperature environment the use of magnetic shielding material is another material of interest.

2.1 Superconductors

In the satellite scenario that was proposed, superconductors would be the ideal material to use for this. According to Gester (2000) superconductors are a type of phase for metals, and below certain temperatures, known as the critical temperature for superconductivity. Metals such as aluminum and tin enter this phase and they become a superconductor. What signifies this change is a change in their electrical characteristics from when they were above this critical temperature, which is the material has no electrical resistance and they show perfect diamagnetism. Perfect diamagnetism is when a current starts to flow inside of the material that opposes the external magnetic field (Gester, 2000).

According to Abrahams (2014) we can describe diamagnetism, by materials with a negative susceptibility, which means that when the object or material is magnetized, it will magnetize in the opposite of direction the external field. We can describe susceptibility given by Eq.6, where χ_d is diamagnetic term;

$$\chi = \chi_d + \chi_p \tag{6}$$

and χ_p is the paramagnetic term, and pure diamagnetism is when $\chi_p = 0$, however this diamagnetic response is small in most substances, for the case of a superconductor, they achieve perfect diamagnetism through the Meissner Effect.

2.2 Magnetic Shielding Material

When we start getting into higher temperature environments superconductors no longer become a viable option as they will require constant cooling to maintain temperatures below the superconductor's critical temperature. To solve this problem magnetic shielding material, for example Mu Metal, could be used. These materials generally have high concentration of Nickel-Iron, ranging from 36% to 80% NiFe (Mumetal is one of a family of three Nickel-Iron alloys, 2009). This material can achieve a high permeability until the magnetic flux hits a saturation point at which point the permeability falls quickly to $1\frac{H}{m}$ (Magnetic Shielding, 2012). If this happens additional layers of this material could be used to provide additional shielding (Mumetal is one of a family of three Nickel-Iron alloys, 2009). With this property in mind this material could potentially be used to obtain results similar to what we would expect with superconductors.

However magnetic shielding material is different from superconductors. Magnetic shielding works by redirecting the propagation of magnetic field lines so that magnetic flux flows through the walls of the shield itself, resulting in the by-passing of the enclosed area or object needing protection.(Magnetic Shielding, 2012). This means is that Eq.4 does not fully model what is happening when we use magnetic shielding material, because the magnetic flux flows through the material itself. Lets take a cylinder with radius R_1 and a magnetic shielding material with thickness d, thus the radius entire radius R_2 is given by:

$$R_2 = R_1 + d \tag{7}$$

Then by Eq.1 we find:

$$B_{w_1}(R_2^2 - R_1^2) = B_0 \times R_1^2 \tag{8}$$

or,

$$B_{w_1} = \frac{B_0}{\frac{R_2^2}{R_1^2} - 1} = \frac{B_0}{\frac{(R_1+d)^2}{R_1^2} - 1} \tag{9}$$

For a cylinder this would be the end result, however for a cone we can take this one step further and represent R_1 and a function of the half angle of the cone, and the length, thus:

$$R_1 = l \tan\theta \tag{10}$$

Thus making Eq.9

$$B_{w_1} = \frac{B_0}{\frac{(l\tan\theta + d)^2}{(l\tan\theta)^2} - 1} \tag{11}$$

In Eq.11 we see that the magnetic field B_{w_1}, the magnetic field inside of the wall, is dependent of the initial magnetic field B_0 and inversely dependent on the thickness of the material. This equation also assumes that the magnetic flux is actually taken into the walls of the material.

3 Designing the Experiment

When designing the experiment a student at WPI, Jeffery Blanco, joined the project as an independent study. When Blanco joined it was recommended to start modeling the experiment in a multiphysics software named COMSOL. This software allows the use of multiple types of physics while modeling a single project. This allowed the use of one program to fully model this experiment. Blanco and I got a working geometry in this software that we could use for this model. In February 2014 a working COMSOL model for both a single and double layer case. The next step was getting data out of this model that represented the theoretical model in an easy to understand way. Another student from WPI, Daniel Turnbull, joined this project as an independent study. His focus was to understand the model and extract the data from the model that could be of use.

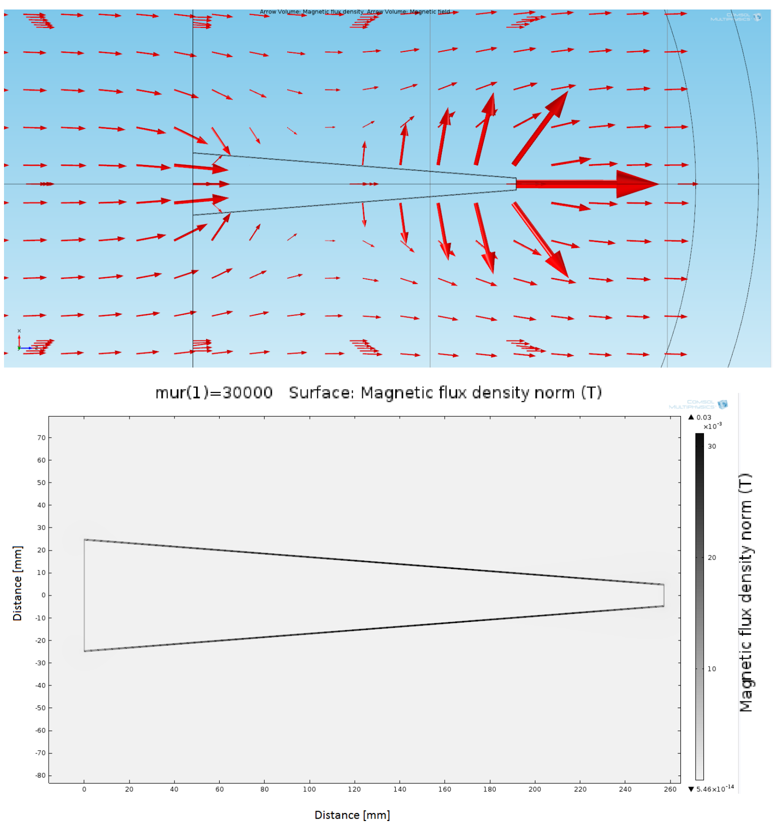


Figure 1: COMSOL computation: Top: An Arrow Plot of the magnetic field lines Bottom:Plot showing magnetic field strength density, ranging from $0.5G$, the background magnetic field to about $300G$.

The COMSOL Model did show the results that were expected. As seen in Fig.1 & 2, when the cone is placed in a uniform magnetic field we see the magnetic field strength increase as it moves down the cone, along the wall of the material. This model also shows us that the magnetic field that is being produced when the cone becomes magnetized is strongest near the wall of the cone, but then quickly decreases as we move further away from the cone, this can be seen in the arrow plot in Fig.1.

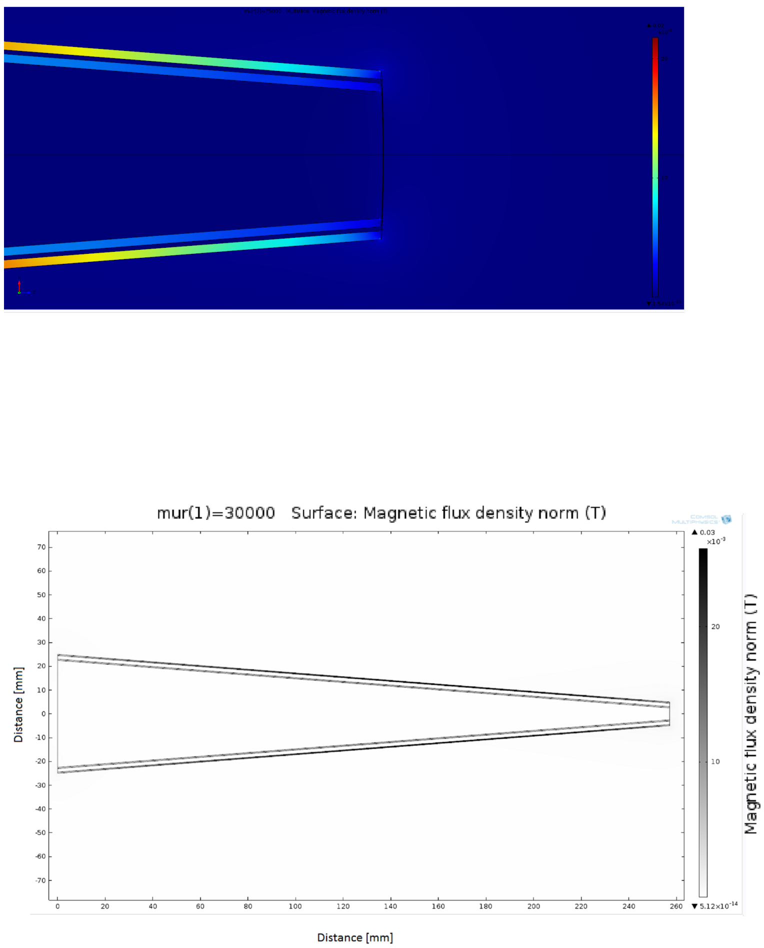


Figure 2: COMSOL computation for 2 layers: Top: Close look at the exit Bottom:Plot showing magnetic field strength density, ranging from $0.5G$, the background magnetic field to about $300G$.

4 Experiment

After looking into the materials that could be used to achieve these results, we attempted to achieve the predicted results in a lab setting. This was accomplished by generating a magnetic field by using a coil. Then by placing the larger radius of the cone inside this coil, measurements were taken to see if results similar to what would be expected to find from the theory presented in Sec.1.1 and Sec.2.2.

4.1 Material Used

4.1.1 Magnetic Shielding Material

The material we used during the experiment was a magnetic shielding material that has a relative permeability which ranged from $30,000\frac{H}{m}$ to $444,000\frac{H}{m}$ in a magnetic field strength of $0G$ to $7,600G$. At $7,600G$ the material becomes saturated and the permeability rapidly falls to 1, which means the magnetic field will act as if the material isn't there. This material was assembled in a conical shell geometry.

Three conical shells were made out of this material. They were used to test the effect of using multiple layers and to see if they were able to produce a higher change in the magnetic flux. Achieving this was done by each cone having the same smaller radius, which was 5mm. However each of the shell's larger radius and height varied. These variations were designed for the smallest shell to have a large radius of $5cm$ and a height of $0.2572m$, the middle shell had a large radius of $5.2cm$ and a height of $0.28m$, and the largest shell had a large radius of $5.4cm$ and a height of $0.32m$. To make the additional layers to stack, without making contact with each other, we use Aluminum foil to make up the $0.2cm$ radial difference between the two layers of material. This material was chosen because it has a permeability close to that of the permeability of air.

To build these conical shells the sheet of material that was measured for this had to fit the above designs. The material was then wrapped around a plastic cone with similar dimensions to the conical shells. The seams of these shells were then sealed with a chemical resin for metals called J-B Weld. This method was chosen because this material could not be heated, or the soft-ferromagnetic properties of the material would change, thus we could not weld the seams shut. However there were still some problems with the small radius being too small to comfortably wrap the material around the cone, thus resulting in an oval opening as opposed to the ideal circular shape.

4.1.2 Gaussmeter

When taking measurements of the magnetic field a transverse Hall Probe was used. This probe was placed such that it was tangential to the surface of the cone. The readings from this probe was provided by a Bell Model 640 analog Gaussmeter, as seen in Fig.3.

The Hall Probe uses the well-known property of magnetic fields and electric currents known as the Hall Effect. This effect is the potential difference in opposing sides of conducting materials. When an electric current is present, it will then generate a magnetic field perpendicular to the direction the current is traveling (Culp, 2014, p. 2088). Now when a current carrying material is placed in a magnetic field, such is the case with the Hall Probe, according to Culp (2014) the material will experience a force causing the charge carriers to drift until the force is equalized by an electric

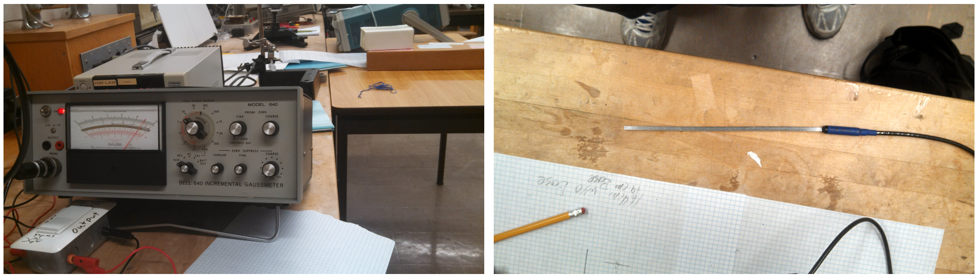


Figure 3: Tools used for measurements Left: Bell Model 640 analog Gaussmeter. Right: Transverse Hell Effect Probe.

field generated by the charges “accumulating at points on the bodys surface in the directions of the drift” (p. 2088). At the points on the body’s surface opposing the direction of the drift, “there will be an equal depletion of charge, which is equivalent to an accumulation of charge of opposite sign” (p. 2088). This electric field created by this behavior is called the Hall field and will generate a potential difference between the corresponding points on the two oppositely charged surfaces (p. 2088).

The Hall Effect allows the Hall Probe to read magnetic fields. These probes are made with what is known as Hall plates, which is “typically a small, thin square of semiconductor with connections on the input... for the current and on the output... for measuring the resultant voltage” $(Poole, 1981, p.2129)$. According to Poole (1981) this resultant voltage is given by Eq.12;

$$V_H = \frac{R_h}{d} I B_n \tag{12}$$

Where R_h is the hall coefficient of the material, d is the thickness, I is the current, and B_n is the normal component of the magnetic field. It is from this equation and the data provided by the probe that the magnetic field can be measured by the gaussmeter.

4.2 Coil

Producing a magnetic field was accomplished by using a coil with 320 turns and a radius of $7cm$. The coil was used to produce a magnetic field that could be easily controlled by adjusting the current that we supplied to the coil. This coil could also achieve a low enough magnetic field such that the magnetic forces between the material and the wire of the coil did not attract each other, which was the case for a current over 1A.

Taking measurements of this coil’s magnetic field, was done by placing the hall probe through the center of coil. After the probe was positioned, we started to move the probe in $5mm$ intervals towards the coil, taking note of the magnetic field strength as it was moved.

4.3 Procedure

4.3.1 Suspended from a Dowel

The first method to take measurements was suspending the conical shell with dowel and string, which is seen in Fig. 4. This set up allowed for easy adjustments to the cone's height and its horizontal position. This ease of movement allowed the larger radius to be placed within the coil so that we had an approximate uniform magnetic field entering the cone.

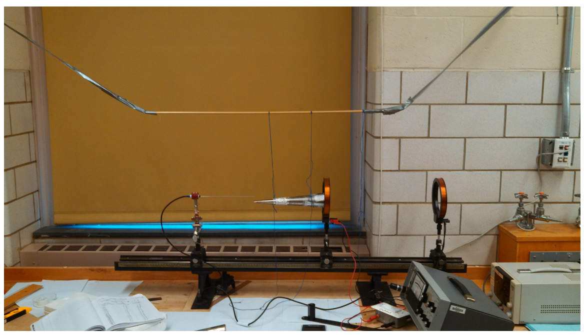


Figure 4: Photo of the cone being suspended from a dowel.

4.3.2 Clamped in Place

The second method was to clamp the cone in place. This was done by using a clamp that would be attached to a vertical rod and the main clamp on the center of the cone away from the area of the cone where measurements were being taken, as can be seen in Fig. 5.

Using this method made measurements was a simpler task, because there were less fluctuations in the cone's movement when making contact with the cone. This ultimately lead to a higher accuracy in the measured values of the magnetic field strength.

Figure 5: Cone clamped in place Left: front side veiw of the cone. Right: Back side view of the cone.

4.3.3 Methods for Taking Measurements on the Cone

Measurements were taken such that the hall probe laid flat and was tangential to the cone's surface. Starting from the smaller radius, incrementally increasing to the larger radius, with an interval of $5mm$ to a maximum of $100mm$ away for a single layer. This process was repeated for two and three layers.

5 Results

5.1 Coil

This coil was supplied a current of $0.46A$. From Table 1 we can see the measured value of the coil's magnetic field reached a peak at $0.26G$. From there the magnetic field decreased as we would expect from this type of coil.

Distance (mm)	Measured Magnetic field (G)	Distance 9mm0	Measured magnetic Field (G)
0	0.11	100	0.13
5	0.145	105	0.12
10	0.17	110	0.1
15	0.2	115	0.0855
20	0.22	120	0.077
25	0.24	125	0.0685
30	0.25	130	0.0615
35	0.25	135	0.055
40	0.25	140	0.05
45	0.255	145	0.05
50	0.25	150	0.041
55	0.26	155	0.037
60	0.23	160	0.0335
65	0.21	165	0.031
70	0.21	170	0.0305
75	0.18	175	0.029
80	0.18	180	0.028
85	0.165	185	0.025
90	0.15	190	0.023
95	0.135	195	0.022

Table 1: Numerical data for the measured magnetic field of the Coil.

5.2 Single Layer Cone

Results of the single layer a cone are seen, by referring to Fig.6 and Table 2. These results show that as the probe moved away from the smaller radius of the cone, the magnetic field strength starts to decrease from $6.5G$ to $2.2G$ $100mm$ away.

5.2.1 Inside the Cone

While taking measurements inside of the cone, in the presence an external magnetic field, it was discovered that inside the cone the measured value for the magnetic field was $0G$. This value was true from the just inside the smaller radius to $100mm$ inside the cone.

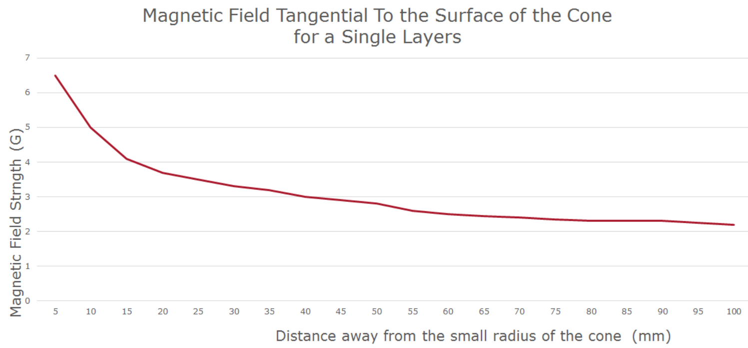


Figure 6: Plot of the data points taken for a single layer of the material

Distance away from small radius (mm)	Single Layer Magnetic Field Measurement(G)
5	6.5
10	5
15	4.1
20	3.7
25	3.5
39	3.3
35	3.2
40	3
45	2.9
50	2.8
55	2.6
60	2.5
65	2.45
70	2.4
75	2.35
80	2.3
85	2.3
90	2.3
95	2.25
100	2.2

Table 2: Numerical data for single layer cone.

5.3 Two Layer Cone

Values for the two layer cone are seen, by looking at Fig.7 and Table 3. Similar results are seen to what was found with the single layer, the difference between the two being the measured values are larger. It is seen that at $5mm$ away from the exit the strength of the field is $7.9G$. This indicates that two layers can produce a stronger magnetic field than a single layer.

5.4 Three Layer Cone

The three layer cone has the resulting values seen in Fig.8 and Table 4. Again similar results to what was presented in Sec. 5.2 & 5.3. From these results a similar measurement of $7.9G$ at $5mm$ away from the small radius.

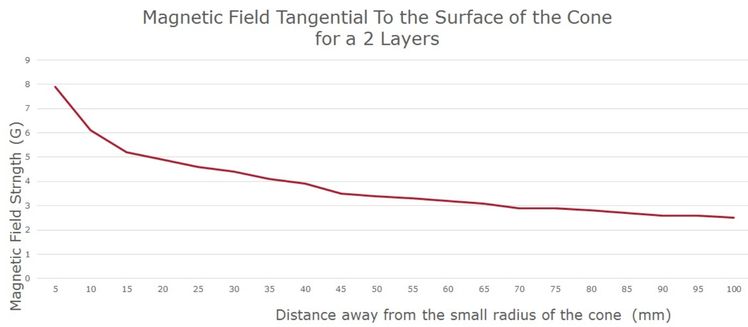


Figure 7: Plot of the data points taken for a two layer of the material

Distance away from small radius (mm)	Two Layers Magnetic Field Measurements (G)
5	7.9
10	6.1
15	5.2
20	4.9
25	4.6
39	4.4
35	4.1
40	3.9
45	3.5
50	3.4
55	3.3
60	3.2
65	3.1
70	2.9
75	2.9
80	2.8
85	2.7
90	2.6
95	2.6
100	2.5

Table 3: Numerical data for the two layer cone.

5.5 Two and Three Layer comparison

From Fig.9 we see a comparison between the measurements for both the two and three layer cone. From this and the data presented in Sec. 5.3 & 5.4, we see that the three layer cone yields slightly better results than the two layers. Overall both of these, for this weak magnetic field yield the same results near the exit of the cone.

5.6 Magnetic Field at the Exit of the Cone

This data represents the measured magnetic field taken moving away from the exit of a single layered cone. Looking at Table 5 we can see as we move $1mm$ away from the exit of the cone, the magnetic field strength decreases significantly, from $6.5G$ to $1.45G$.

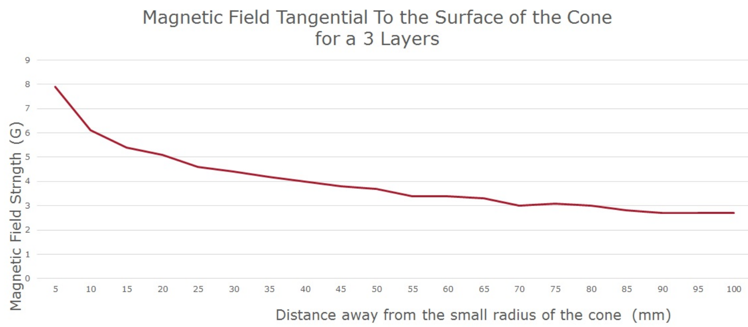


Figure 8: Plot of the data points taken for a three layers of the material

Distance away from small radius (mm)	Two Layers Magnetic Field Measurements (G)
5	7.9
10	6.1
15	5.4
20	5.1
25	4.6
39	4.4
35	4.2
40	4
45	3.8
50	3.7
55	3.4
60	3.4
65	3.3
70	3
75	3.1
80	3
85	2.8
90	2.7
95	2.7
100	2.7

Table 4: Numerical data for the three layer cone.

Distance away from the smaller radius (mm)	Magnetic Field Strength (G)
1	1.45
2	1
3	0.7

Table 5: Numerical data for the magnetic field just outside the exit of the cone.

6 Discussion

From the data that was collected it can be seen that most of the sought after results were achieved. This is seen with the input magnetic field being measured to be $0.25G$ and the maximum magnetic field was $7.9G$. This shows a 31.6 times magnification in the magnetic field on the surface of the cone. Inside the cone the measured field was $0G$, even at the inside surface of the material.

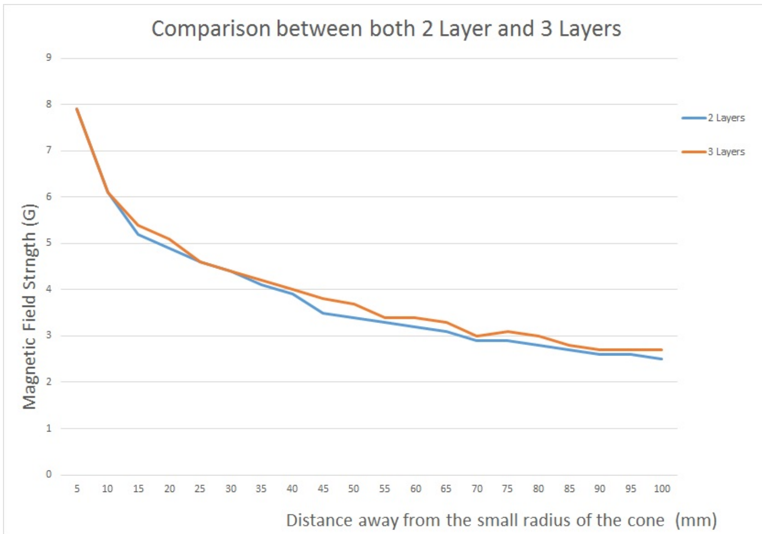


Figure 9: Plot of the comparison between two and three layers.

However the measured values were unusually low, especially for the coil and current used in the experiment. Eq.13, which is derived from Amperes Law, using a solenoid with turn per meter n, permeability μ and supplied current I:

$$B = \mu n I \tag{13}$$

By following Eq.13 using the permeability of copper, $\mu = 1.254 \times 10^{-}6 \frac{H}{m}$, $n = 1094.7$, and the supplied current, $0.50A$ the resulting magnetic field strength is $6.3X10^{-4}$T, or $6.3G$. This calculated value is larger than the measured by a factor of about 28. This shows implies that the gaussmeter was not outputting accurate values for magnetic field measurements.

Overall the data obtained through this experiment did not provide concrete values. However this data did provide evidence that the theory could work. This was found when the magnetic field did in fact rise as we moved the probe toward the smaller radius of the cone, and away from the coil. The strength of the magnetic field is in fact increased by a factor ranging from approximately 26 to 32 times greater than the initial measured magnetic field.

This experiment also confirmed a property of magnetic shielding material, which is that the magnetic field gets redirected into the walls of the material. This was seen when the magnetic field strength inside the cone was measured to be zero, while we were able to obtain a value on the outside edge of the material. We also found from Sec.5.5 that there was little difference between a two and three layered cone, the greatest difference between the two was at most $0.3G$. This lead to the conclusion that for these weak fields the third layer will not yield better results.

The final observations that was made, was about magnetic field around the outer wall of the cone. We found that the magnetic field decreased rapidly as the probe moved off of the surface of the cone. This in fact proves what the COMSOL model showed us. As seen in Fig. 1 & 2 the magnetic flux density value was increasing as it moves down the cone to the smaller radius. However this model is not completely correct as the arrow plot in Fig. 1 shows large magnetic flux being emitted by the cone, and maintains most of the strength a few millimeters off the cone. This was not seen during the experiment, as the magnetic field dropped back down to the magnitude of the background magnetic field a few millimeters away from the cone. Again as we can observe from the arrow plot in Fig. 1 the smaller radius of the cone shows a larger magnetic field line being expelled from this area, however when we took measurements at this end of the cone we found this not to be true. From the experiment we found that $1mm$ away from the end of the cone was $1.45G$, which dropped significantly when compared to the $6.5G$ when it was $1mm$ away from the end of the cone. This was not what was expected when looking at the COMSOL model.

7 Conclusion

7.1 Problems during the experiment

Throughout this experiment certain problems occurred. They ranged from assembling the cone, the setup of the experiment, and problems with the equipment being used. When assembling the cone a small radius of $2.5mm$ was difficult to obtain. During the experiment with the cone suspended from a dowel the cone was too free to move, which caused variance in the final measurements with this method. Lastly the gaussmeter that was used during the experiment did not provide accurate measurements of the magnetic field strength.

7.2 Solutions to problems that occurred

Most of these problems that occurred could be easily solved, whereas others could not be completely solved. Addressing the assembly of the cone, a $3-D$ print of the cone with the parameters of the cone was used. From there the shells were made by wrapping the magnetic shielding material around the $3-D$ printed cone. This did not completely solve the problem due to the smaller radius of the cone not being circular.

Solving the major problem that was discovered with the initial experimental design, was by making the apparatus for the cone more stable. Making this apparatus more stable, the cone was more difficult to move. However there was less variance in the value of the measured magnetic field value.

Lastly the gaussmeter problem was unable to be addressed. However the probe could still be used to get an idea of what was happening. This is seen by the magnetic field increasing as the probe was moved away from the source of the magnetic field and toward the smaller radius of the cone.

7.3 What Could be Done Better

Each of the solved problems could be approached differently. The assembly of the cone problem, could have been solved easily by increasing the dimensions. This was not consider due the price of the material, making large quantities not affordable. Lastly, finding a manufacturer that would be willing to make a cone made out of magnetic shielding material, would have simplified making the cone.

The experimental set up, was initially designed with suspending the cone by a dowel. This was done so that the cone could easily be set in place. It was found that the cone itself was too free to move which caused problems with the readings.To solve this problem it was proposed to use clamps to keep the cone in place. Due to the lack of fluctuations in the cone's position, it became more efficient to preform the necessary measurments.

The gaussmeter should have been checked for accuracy prior to committing to use of it. However the time that was allotted for the experiment was insufficient, thus it was not possible to check the accuracy in a timely manner. To fix this problem in the future, measurements of the coil itself should be taken and then compared to the expected value of the coils magnetic field found by Eq.13

7.4 Overall Results

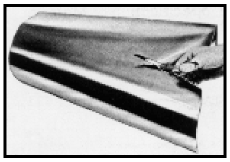
This experiment, even with it's problems, did provide evidence of the concept that was trying to be proven. This is seen by the irrefutable fact that the magnetic field strength did become larger as it moved down the cone, while the factor was not as high as the ideal setting. This could have been due to the actual building of the cones. This construction of a small radius of $2.5mm$ was difficult and the end result was an oval like shape rather than a circle, which is easily fixed by making a larger cone.

Lastly with these results one could expect that superconductors could achieve similar, or greater results than that which was achieved with Magnetic shielding material. This is largely due to the Meissner Effect, which allows superconductors act as an object with perfect diamagnetism. Instead of superconductors redirecting the magnetic field into the walls of the material it is funneled instead.

A Magnetic Shielding Material Information

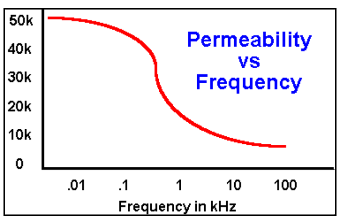
Fig.10 is additonal information on the material used during the experiment. All electrical parameters needed for the COMSOL model were supplied by this information.

MAGNETIC SHIELDING FOIL



"Best Material Available for Shielding DC, ELF & VLF Magnetic Fields"

Used for years in industry to shield delicate electronic components from EMFs, this 80% nickel alloy magnetic shielding foil is now available at affordable prices for home and office use. The thinner (0.004" thick) material is easy to trim with scissors and shape by hand. Thicker material offers better shielding performance but requires snips to cut. Can be formed into magnetic barriers on cellular phones, microwave ovens, doorbell transformers, VDTs, buried wiring, and more. With snug fitting shapes, get as much as 75% attenuation of the magnetic field with one thickness. Use multiple layers for even greater reduction. Foil is .004" (±.0004) or .010" (±.0008) in thickness and 15" wide and can be ordered in any length.



(We recommend the use of a gaussmeter to determine the proper shape and positioning of the shielding, and to confirm that the fields have been adequately reduced.) ASTM A753 Type 4.

CAUTION: Foil has sharp edges!

Attenuation is the ratio of the magnetic field strength on one side of the foil compared to the field strength on the other side.

You can estimate the amount of magnetic field reduction (Attenuation) produced by a cylinder of .004" Shielding Foil of a given Diameter (D, in inches) if you know the Permeability (P), with this formula:

Attenuation = 0.004 x P/D

For example:
You would expect an 8:1 reduction (88%) from a 10" cylinder in a 1 kHz field where permeability is about 20000 (see graph above):
Attenuation Ratio = .004 x 20000/10 = 8

Distributed by **Less EMF Inc.**, Latham NY 12110 USA +1 (518) 608-6479

IMPORTANT NOTICE:

While the special alloy in Magnetic Shielding Foil exhibits high magnetic permeability, there are many factors which affect the amount of magnetic shielding you will achieve by using this material. The list of such factors includes: size of the source of the magnetic field, size and shape of the shielded area, seams in the shielding material, frequency of the magnetic field, distance from shield to source, orientation of shield to the source, thickness and heat treatment of shielding material, etc.

Because we have no control over many of these factors, *we cannot and do not guarantee any specific shielding performance* for a specific application of this material. If you are not sure how to use this material, you may call us for suggestions or we may even be able to locate the name of an experienced shielding designer/installer in your area who can assist in designing your shield.

Mechanical Specifications:	
Specific Gravity:	8.74
Weight (lb/ft²):	.004: 0.18; .010: 0.45
Coefficient of Expansion:	12.6 x 10^{6} per °C
Tensile Strength:	64 x 10^{3} PSI
Yield Strength:	18.5 x 10^{3} PSI
Mod. of Elasticity:	25 x 10^{6} PSI
Hardness (Rockwell B):	50 Ref.
Melting Point:	1454°C
Thermal Conductivity (at 20°C):	0.138 cal/sec/cm²/cm/°C
Minimum Operating Temp:	4°K
Curie Temp:	400°C

Electromagnetic Specifications:	
Electrical Resistivity:	330 ohms/cir mil-foot
Saturation Induction:	7600 Gauss
Initial Permeabilty:	30,000
Permeability at 40 B:	75,000
Permeability at 200 B:	135,000
Maximum Permeability:	444,000
Induction at m max.:	3000
Coercive Force:	.005 Hc, Oersteds

Meets ASTM A753 Type 4
Annealed temper

Figure 10: Additional information on the Magnetic Shielding material

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