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## Effective harnessing of vibrational energy via magentic induction

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# Effective harnessing of vibrational energy via magnetic induction

Jose Miralles

April 2019



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## I. Abstract

**Advancements towards renewable energy systems demand efficiency in production and storage to avoid potential waste. This investigation delves into understanding the behavior of magnets and their effectiveness in converting environmental vibration to electrical energy. A program was written to predict the induction produced in a solenoid by a moving magnet in order to shed some light on how to treat magnets experimentally and theoretically. Various sets of solenoids ranging from six to four hundred and fifty windings were tested and their voltage outputs were compared to the program. Considering that there is a gap of 28.1 mm between the magnet and the coil windings (not optimally placed), the device produced an AC signal of 130 mV amplitude with 60 windings and about 1.4 V amplitude with 450 windings. Conclusions hint at designs of solenoids that will yield maximum power output from magnets at a fixed speed.**

## II. Introduction

Recent years have seen increased attempts to eradicate global warming. One of the most prevalent efforts has been the transition from fossil fuels to renewable energy via the research and development of new technologies. There are multiple sources of energy available to us, most coming from the sun. However, even though we know how to properly harvest most of these energies, we cannot seem to separate ourselves from the tempting fossil fuels.

The idea of harnessing ambient energy [1],[4] (i.e. anything that is incident in the general environment like sound or wind) becomes an appealing option when considering that energy is being deposited into Earth in massive amounts and in different forms [2]. Being able to harness even a fraction of this ambient energy could become extremely valuable if the conversion to electricity is made effective. The effectiveness of the conversion from an input energy (whatever its manifestation is) into usable energy (usually electricity) is paramount, since a gradual waste of energy can become substantial in the long run.

This investigation delves into the effectiveness of vibrational-to-electric energy conversion and aims to fully uncover the cryptic behavior of magnets, observing how they affect the environment while hoping to come closer to a more effective model to harness vibrational energy. The overall method pursued in this investigation involves the comparison of various solenoids that differ in wire thickness, number of windings, and number of sets. A program has been written to predict the induction produced by the magnet, consequently shedding some light on worthwhile ways to treat magnets experimentally and theoretically. Furthermore, the investigation also studies and proposes a way to harness the maximum amount of energy that is deposited into the system.

### III. Theory

#### a. Electrodynamics

To understand the nature of this experiment, one must first understand some of the laws in the field of Electrodynamics. Considering that the main device in question involves magnetic induction to produce a current, it is important to understand why and how this happens in the first place. Lenz's Law states that a current induced by a changing magnetic field will make a magnetic field of its own to oppose and cancel the initial magnetic field. David J. Griffiths summarizes this by stating that "nature abhors a change in flux" [3]. Faraday's Law defines Lenz's Law and states it mathematically with the equation

$$\varepsilon = -\frac{d\phi}{dt} \quad (1)$$

where  $\varepsilon$  is the electromotive force induced,  $\phi$  is the magnetic flux, and  $t$  is the time. The negative sign of the equation represents exactly what Lenz's Law states, the opposing field trying to stop the initial magnetic field.

Flux is defined by the equation

$$\phi \equiv \int \mathbf{B} \cdot d\mathbf{a} \quad (2)$$

where  $\mathbf{B}$  is the magnetic field vector and  $d\mathbf{a}$  is the area component vector. One must note that the function inside the integral above consists of a dot product between the magnetic field vector and the area component vector. This means that the only thing that yields a value or an effect to the flux is the parallel component of the magnetic field vector to the area component vector. If we take the simple case where  $\mathbf{B}$  is constant and the area is flat, then  $d\mathbf{a}$  will become just  $A$  (the area of that piece) and so combining it with Eq. 1 we get

$$\varepsilon = -\frac{\Delta BA \cos \theta}{\Delta t} \quad (3)$$

where  $\theta$  is the angle between both vectors.

#### i. Magnet Overview

In Figure 1 a general magnet with two poles is shown along with its magnetic field lines, a generic solenoid around it, and the area component vector. From this picture there are two important things to note. First, magnets have internal magnetic field lines. These internal magnetic field lines are opposite, much stronger, and more uniform (not completely) than the external magnetic field lines. This means that in order to acquire maximum output voltage from an induction, one must wrap around the solenoid as tightly as possible around the moving magnet to exclude as many of the weaker, opposite external

field lines as possible. This is indeed how most technologies that convert vibrational energies to electricity are designed (e.g. rechargeable flashlights).

The other thing to note is the case where one has a solenoid that is longer than the length of the magnet in use. Considering Equation 1, the numerator term is the change in flux that the entire system, the solenoid, experiences. When the magnet is moving well within a long solenoid, any flux change happening ahead of the magnet will be equal and opposite than the flux change happening behind the magnet, and hence the flux change will be zero, resulting in no AC emf inductance. This situation is also portrayed in Figure 1.

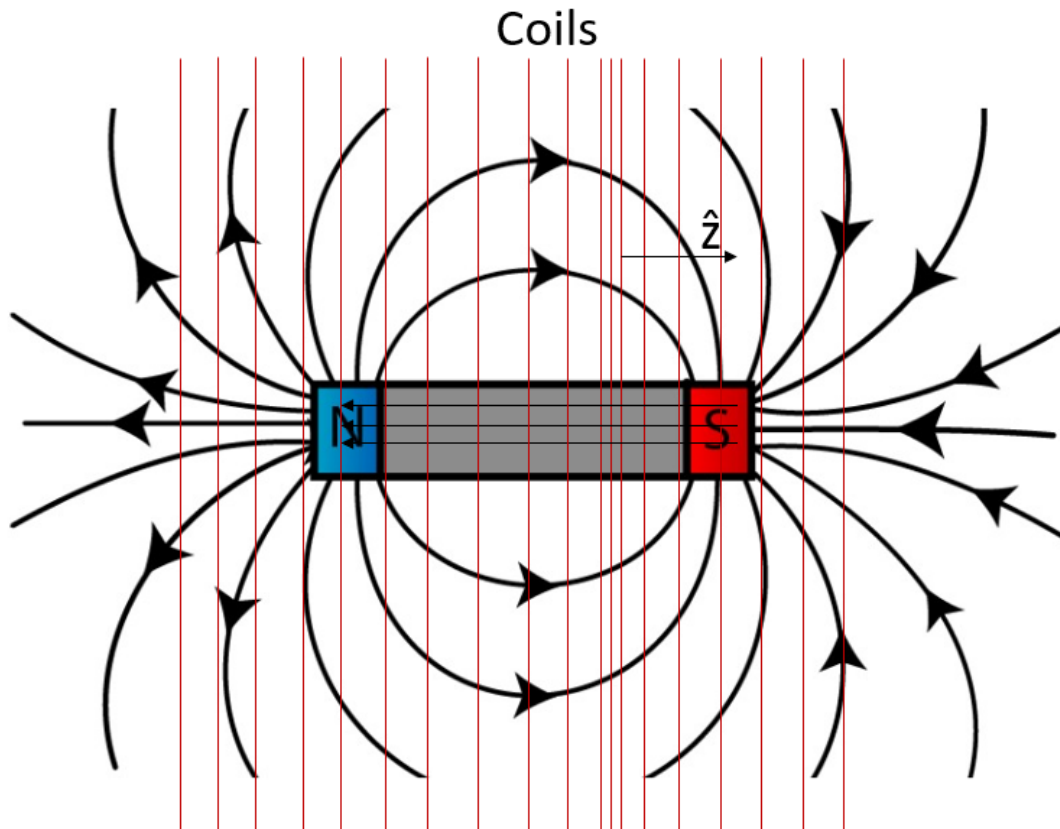


Figure 1. The area component vector is denoted by the  $\hat{z}$  pointing horizontally to the right in this case. Inside magnetic field lines are pointing to the left.

## ii. Design Proposal

Because of the latter observation on the relationship between magnets and solenoids, the design proposed for this investigation is multiple sets of solenoids into the same system. Since one solenoid cannot be longer than the length of the magnet being used since it grants no extra voltage, this study delves into how much more efficient a multiple solenoid design would be. It is already clear that the closer the solenoid is to the magnet itself the more inductance the system will output. However, due to this fact being mostly

trivial and because of the lack of a tube that could accommodate to this, the investigation focuses mainly on the effectiveness of a multiple solenoid system, neglecting this fact until the conclusion.

#### b. Electronics

While an emf is being induced into the solenoid, there must be someplace where this resulting energy can be stored. This is the second half of the experiment, and it leans heavily on the study of electronics. This section of theory does not deal much with equations as it does with the behaviors of certain components and their purpose.

In order to transform this AC voltage into DC, which is storable into batteries or a capacitor, one must rectify the signal by using diodes. Diodes, depending on the material, must receive a signal that is usually a minimum of 0.4 V in order to rectify it (this minimum requirement may vary depending on the material of the diode). In this research, Germanium diodes were used, which have a drop of about 0.24 V (measured with a DMM with uncertainty of  $\pm 0.01$  V).

Figure 2 shows the circuit diagram of a simple full wave rectifier using four diodes, meaning that the induced emf will suffer the drop of one diode per rectified amplitude.

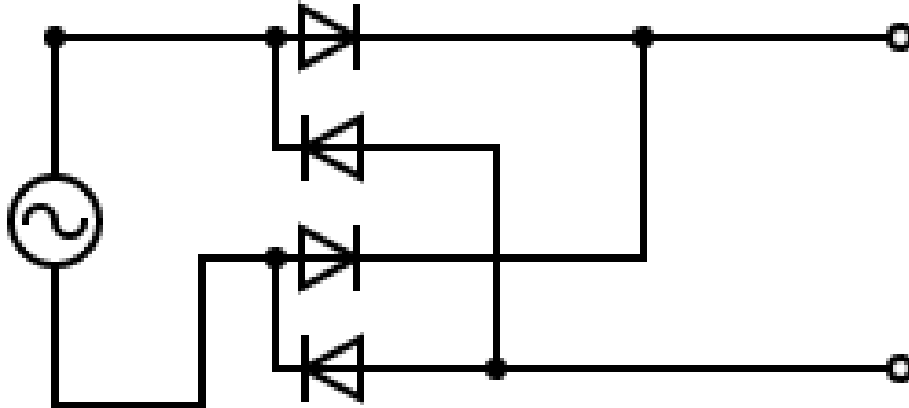


Figure 2. Full wave rectifier with four diodes. The AC source here is the solenoid with the magnet oscillating within. For this experiment, a  $1\text{k}\Omega$  resistor was used as load for data analysis.

### IV. Method

#### a. Measurements

The approach taken in this experiment involves a device that can be better understood when divided into two sections. The first section converts the input kinetic energy into

electrical energy via the mechanical vibration of a magnet within a solenoid. The second section handles the output electrical energy from the first section and stores it in batteries.

Before constructing anything, however, multiple measurements were needed. The magnet and the tube's radii were measured by using digital calipers. The magnet's magnetic field was measured by using a Gaussian meter which had a flat head. The flat head was placed perpendicularly from the magnet's lateral side, measuring only the component of the magnetic field that hits the area component parallelly in accordance to Equation 3. In order to create a program that models the experiment and hopefully brings some insight into the cryptic behavior of magnets, these measurements were paramount.

With the new data at hand, a fit between the magnetic field strength and the distance from the magnet was made, yielding surprising results shown in Figure 3.

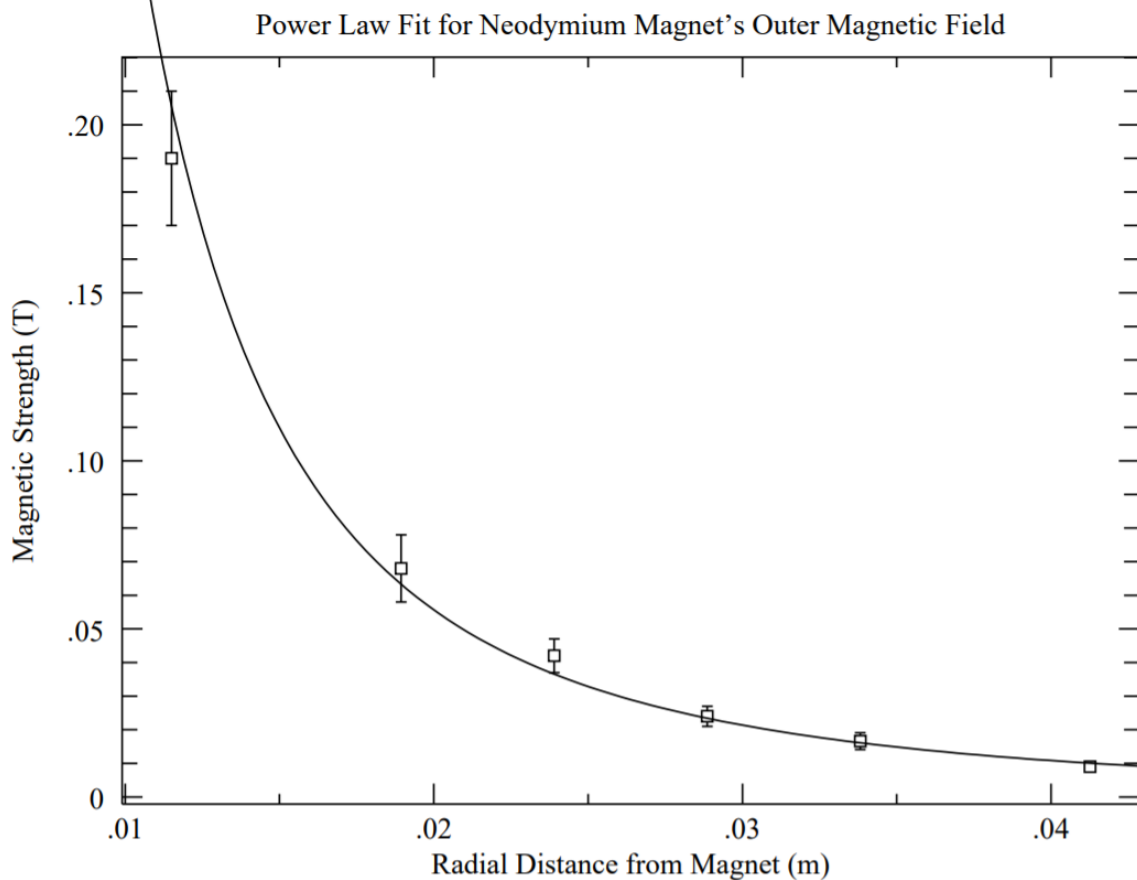


Figure 3. This graph is only descriptive of the external magnetic field of the magnet, which has a radius of 0.0115 m. Parameter values are:  $A = 0.54E-05 \pm 0.23E-05$ ;  $B = -2.36 \pm 0.11$ .

The fit results state that the reduced chi-squared for this data was 0.80 when fit to the power function

$$y = Ax^B \quad (4)$$



where  $y$  is the magnetic field strength, and  $x$  is the distance from the magnet's center. It is important to note that the data that makes up for this fit does not include data from within the magnet, and so it starts at a distance from 0.0115 m which corresponds to its radius. Also, in this experiment, it is assumed that this external magnetic field is uniform and symmetrical, even though it probably is not entirely.

#### b. Building

The section of the device that handles the magnetic induction is shown in Figure 4. A tube and copper wire are needed in order to build a simple solenoid. Having such a solenoid makes it easily modifiable, aiding the cause of testing the various types of solenoids and supporting the comparison between them and the program later in the investigation.

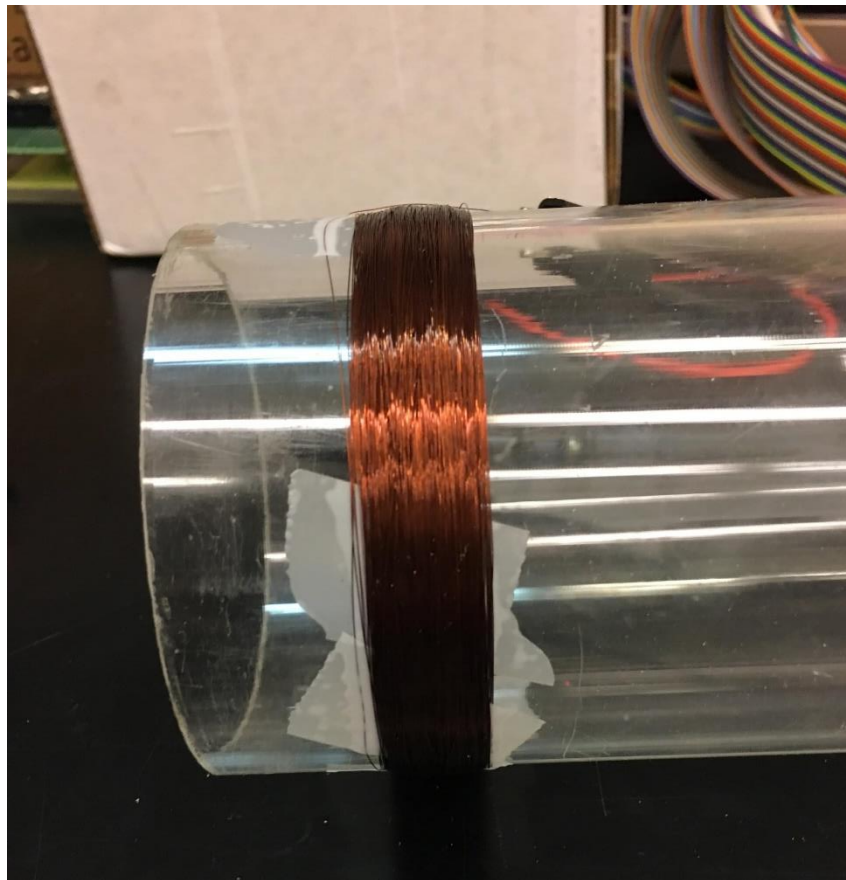


Figure 4. One of the tested solenoids (about 400 windings).

The tube that was used for the experiment suffered from two big issues. The first issue was that the tube was not a perfect cylinder, the horizontal radius differed from the vertical radius by about 0.5 mm at the end of the tube. The second issue was that these differences were inconsistent throughout the length of the tube. Due to these

imperfections, a piece that could accommodate this obstacle while holding the magnet and oscillating freely was necessary. The piece proposed for this job is shown in Figure 5. To achieve this, a few short springs, small wheels with bearings, and a 3D printing machine were used. The piece was designed in Tinker CAD and went through several changes in design due to instabilities and excessive friction in early models (the piece would stop moving right after pushing it). The settled model of the piece still suffers from some friction; however, it is by far the best version of the piece.

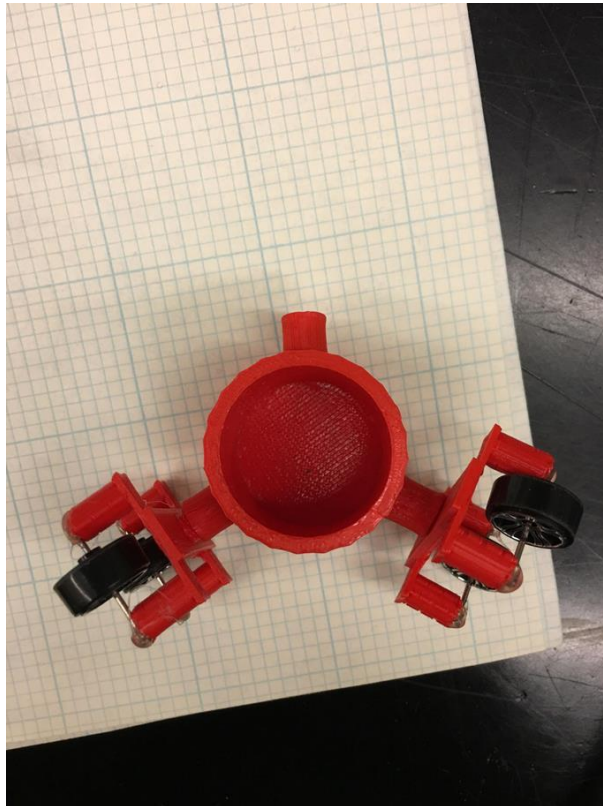


Figure 5. Piece used to allow magnet to oscillate within the tube. Here the piece is shown without the springs which would go inside each of the smaller tubes on the sides. One wheel set is missing as it was not really needed, the initial purpose for it was mainly for increased stability.

Various sets of solenoids were built and tested to see how much power would come from them. These initial tests were done by oscillating the magnet by hand, without using the piece, while watching the readings of voltage vs. time on an oscilloscope. The purpose of this was mainly to test the validity of the program modelling the experiment and the theory behind it. This is further explored in the Program subsection of the Methods section.

Finally, the proposed design was built by assembling two solenoids into one system as shown in Figure 6. The tube was set up into a fixed inclination so that all runs were standardized. For each run, the magnet was set into the oscillating piece and let go from the top of the tube.

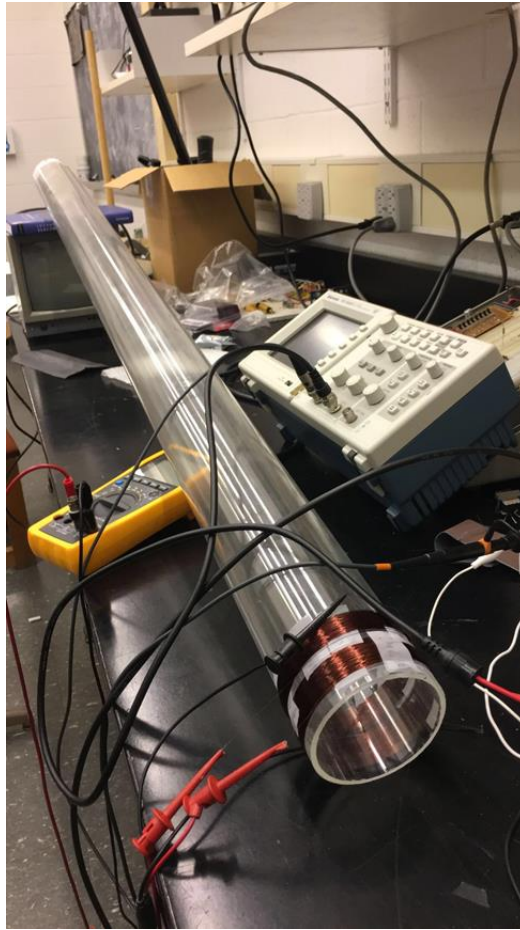


Figure 6. One tube with two solenoids of about 400 and 450 windings at a fixed inclination.

The proposed design included an electronics section that managed to handle both AC sources and connect them together (this design can be extended to an unlimited number of solenoid sets). The approach used to achieve this was to connect both sources in parallel after rectifying each. It is important to rectify these sources before connecting them together due to any possible unwanted cancellation and to prevent current from one solenoid going into another. Figure 7 shows the general circuit diagram that was used for this section, where each AC source is exactly what is shown in Figure 2. A circuit like this is expected to add the current and not the voltage from both AC sources, the former of which was particularly difficult to measure. DMMs could not act as ammeters in the system since they were not able to measure anything due the short time at which the magnet went through the solenoid.

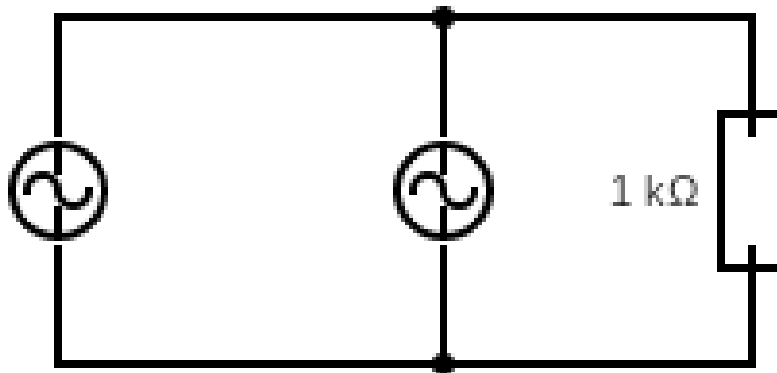


Figure 7. Circuit diagram for double AC source

To achieve effective data collection, two oscilloscopes and a  $1\text{k}\Omega$  resistor were used. Each raw source (before rectification) was measured by a channel in one oscilloscope. The final output of the system was measured by another oscilloscope across a  $1\text{k}\Omega$  resistor as shown in Figure 7. A resistor is used instead of a real load (e.g. battery or capacitor) to measure current. Considering Ohm's Law, one can measure current if resistance and voltage are known values. Ohm's Law is

$$I = \frac{V}{R} \quad (5)$$

where  $I$  is the current,  $V$  is the voltage, and  $R$  is the resistance.

### c. Program

To model the experiment, a program written in Python predicts the induced emf depending on the magnet's traits and the tube's dimensions. If we consider how the magnetic field of the magnet being used is assumed to behave (the internal field is constant, and the external field decreases radially according to the power function in Equation 4) we can see in Figure 8 how an accurate calculation of the magnetic flux works experimentally. After adding all the pieces of area (very thin rings) multiplied by the magnetic field strength affecting that area, one would get the flux at that point along the solenoid's length. Since one would need to make a new fit and attain new  $A$  and  $B$  parameters as one moves along the length of the magnet, the program adopts a reasonable approximation that ignores this due to the fast speed at which the magnet goes through the solenoid sets and to how thin these solenoids are.

The approximation begins by calculating the flux due to the external field at this one slice along the length of the magnet, the middle where the flux is at its maximum to be precise, by utilizing the sum

$$\varphi_1 = \pi \sum_{i=1}^n A \left(\frac{R}{n}\right)^B * \left[ \left(i \frac{R}{n}\right)^2 - \left((i-1) \frac{R}{n}\right)^2 \right] \quad (6)$$

where A and B are the fit parameters, R is the total radius from the side of the magnet to the coil in meters, and n is essentially the amount of times one is slicing up said radius (the larger n, the more accurate the calculation). After acquiring this flux value that corresponds to the area between the inside of the solenoid and the outside of the magnet, the program implements the approximation that the flux change goes from zero to this maximum flux in a given time change, so there is no need to fit any other data aside from the maximum outer magnetic field vs distance. The final calculation is represented as

$$\varepsilon = -N \frac{(B_0 A - \varphi_1) - 0}{t - 0} \quad (7)$$

Here,  $B_0 A$  corresponds to the flux from the internal magnetic field of the magnet, a magnetic field taken to be uniform and constant throughout (another approximation). The inner magnetic field is taken to be  $0.9 \pm 0.15$  T (a value very difficult to measure due to uncertainty being so large) and was measured by setting the Gaussian meter flat against one end of the magnet at the very center of its radius.

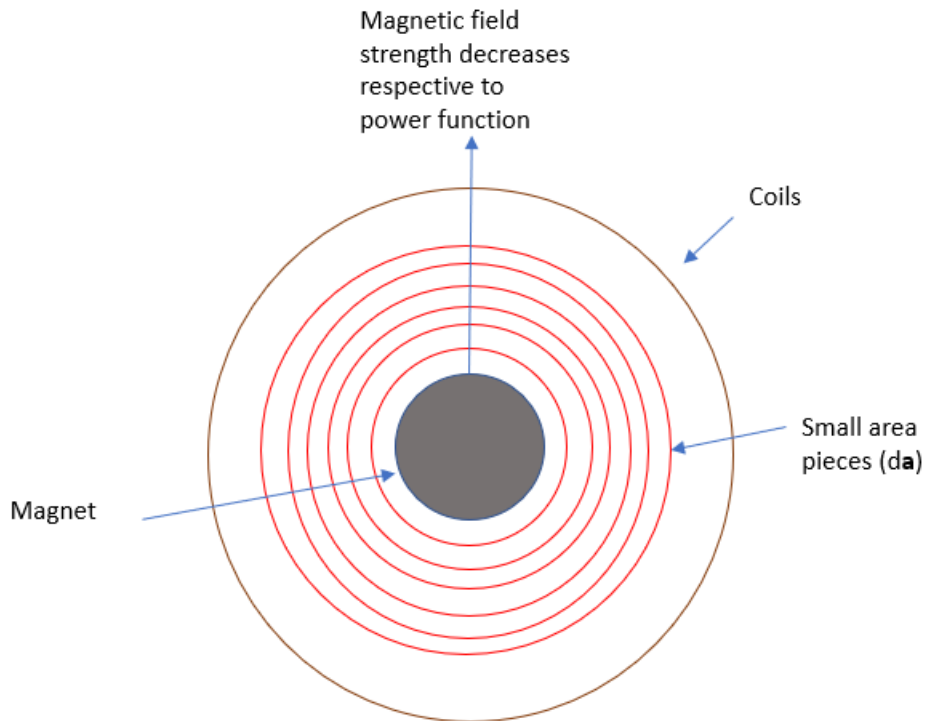


Figure 8. Frontal view of the system. This picture represents one single slice along the length of the magnet. The grey circle represents where the internal field contributes to the flux and the red circles represent where the external field contributes to the flux.

One thing to note about the program is that it ultimately utilizes the equation

$$\varepsilon = -N \frac{\Delta\varphi}{\Delta t} \quad (8)$$

to calculate the induced emf  $\varepsilon$ , where  $N$  is the number of turns,  $\varphi$  is the flux, and  $t$  is time. Technically, this equation is only correct when all said number of turns  $N$  of the coil are experiencing the same flux change over time, and this is not exactly the case in this investigation. Since the magnet is oscillating within the solenoid, all loops are not experiencing the same change in flux over time. However, due to the solenoid set being so short and the magnet going through it so quick, one can ignore this and reasonably claim that all windings indeed do experience the same flux change.

Consequently, this program is only viable when trying to predict induced emfs in short solenoid systems. If the solenoid is too long, one would find the program to overestimate the induced emf depending on how much longer a solenoid is. This is due to the fact discussed in the Magnet Overview subsection. In this case, one only gets significant

induction at the beginning and end of the solenoid set. The program, however, would multiply the instantaneous flux change and multiply it by however many loops there are, hence overestimating when dealing with long sets. When considering the following ratio

$$Ratio = \frac{N \times k}{L} \quad (9)$$

where  $N$  is the number of turns that add to the length of the solenoid,  $k$  is the thickness of the wire, and  $L$  is the length of the magnet, one should not rely on the program when the ratio is more than 1.

Even though this program generalizes the problem to an extent, it has proven itself as an invaluable tool for the task of predicting induced emf. When the program runs, the user can input the number of windings of the solenoid and the time change at which the magnets goes through it and the program will return the predicted output voltage of the device. The final version of the program is available at the Appendix section.

## V. Analysis

There were four sets of solenoids that were tested, recorded, and compared. All of these recordings had a full cycle of about 0.2 seconds. Since the program only calculates the amplitude of one peak, then it is appropriate to use 0.1 seconds as the time change in Equation 7. The table below shows this data with all the recordings running with a time change of about 0.1 seconds:

Turns	Reading from oscilloscope (mV)	Prediction from program (mV)
6	14  ± 5	13
12	28  ± 5	25
18	42  ± 5	38
60	135  ± 5	127

Table 1: Experimental and predicted values of output voltage for 0.70 mm diameter copper wire.

Considering that the readings from the oscilloscope are measured as accurately as possible and that all these runs were recorded when they presented a cycle close to 0.2 seconds, these results suffer from various systematic errors relating to the measurements made via the oscilloscope itself. Aside from this, even though the program runs the approximation given in Equation 7, this is still not the major factor that is hindering the accuracy of the program. This last factor is the resistivity of the wire itself, which increases with the number of turns, and so the program will be slightly less accurate since it does not consider the resistivity.

Resistivity is given by

$$R = \rho \frac{L}{A} \quad (10)$$

where  $R$  is the resistivity,  $L$  is the total length of the wire,  $A$  is the cross-sectional area of the wire itself, and  $\rho$  is the resistivity of copper (the material of the wire). In these first runs, a copper wire with diameter of 0.70 mm was used. Later, two solenoid sets with thinner wire with a diameter of 0.14 mm were tested and compared to the program. These two conclusive runs seem to indicate that the lack of resistivity consideration in the program is considerable when dealing with large amounts of turns and thin wires.

Turns	Readings from Oscilloscope (V)	Program Prediction (V)
400	1.3  ± 0.1	1.40
450	1.4  ± 0.1	1.56

Table 2: Experimental and predicted values of output voltage for 0.14mm diameter copper wire.

After concluding these trials, the proposed design was tested, that is two solenoids in the same system as depicted in Figure 6. This design was constructed using a copper wire with diameter of 0.14 mm, which is considerably thinner. The reason behind this was to fit as many turns in as little area as possible. Even though one can fit in many more turns with a thinner wire, it is more difficult to work with and it does bring more resistivity. The table below shows data for several runs done with this system. Even though the tube was fixed at an angle, not all the runs experienced the same exact time change.

dt (ms)	CH1 (V)	CH2 (V)	Double peak (V)
$\delta = 10$	$\delta = 0.1$		
60	1.3	1.4	1, 1.2
55	1.6	1.8	1.3, 1.4
60	1.4	1.6	1.1, 1.3
40	3.2	3.4	2.8, 3.2

Table 3: Double solenoid data showing transit time, peak voltages across individual solenoids, and the peak voltages across the resistive load.

This table shows the measured raw induced AC signal peaks, that is before rectification, and the double peaks measured that comprised the final output. Figure 8 and 9 shows these signals on an oscilloscope. There is no clear evidence that the currents are being added together, which is mainly due to both AC signals not having the same voltages. This ultimately causes irregularities that source from the fact that the solenoid with the higher voltage is providing current to the load while the solenoid with the lower voltage is “turned off”. This is why the voltage across the load (see Figure 9) is not the sum of voltages



from the individual solenoids (see Figure 8). Trying to set up both signals in series rather than in parallel is even worse since current from one solenoid would be able to go into the other solenoid.

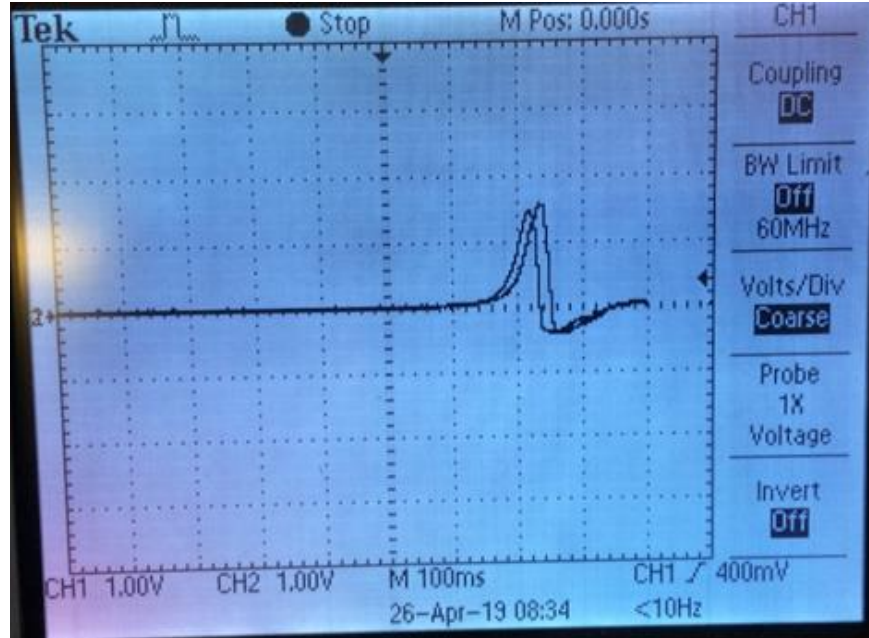


Figure 8. Induced raw AC signals from both solenoids. Solenoid with about 400 turns on the left and with about 450 turns on the right.

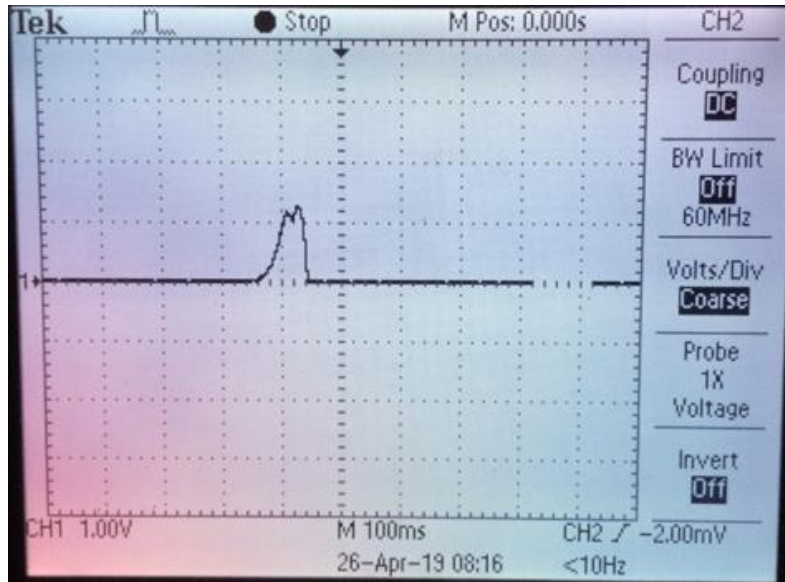


Figure 9. Both AC signals from Figure 8 added together in parallel after rectification.

## VI. Conclusions

### a. Significance

The theory and the program developed to predict the behavior of magnets has proven itself to be very reliable, shedding some light in how to treat magnets both experimentally and theoretically. Even though the program was only tested for one magnet with constraints relating to the system (the tube's measurements and the types of solenoids along with the amount of turns and the time differences), it does hint at interesting conclusions. Increasing the number of turns and magnetic strength are the factors that increase induction the most. Previously, tightly winding coils around the magnet seemed to be the factor that would influence the most on the voltage induced, but the program and results say otherwise. Although induction is increased significantly, it does not increase by much when compared to the other factors. These results are shown in the table below where time difference and number of turns are fixed at 0.1 s and 400 respectively, only varying distance between the solenoid and the magnet's radius. (NOTE: This conclusion is made solely via theory and the program, not experimentally)

Distance from radius of the magnet (11.5 mm) in mm	Induced emf (V)	Percentage increase from first calculated solenoid
26	0.84	0%
13	1.04	+24%
8.5	1.16	+38%
0.5	1.46	+74%
0.1	1.49	+77%

Table 4: Predicted output voltages for solenoids of different radii.

These results are somewhat surprising, even though the induced voltage increases, it is not as significant as increasing number of turns or magnetic strength of the magnet itself. Looking at Table 1, one can see that doubling the number of turns doubles the voltage induced, whereas reducing the radius to half (from 26 mm to 13 mm) would yield an increase of about 24%. After analyzing the results, it seems that the optimal design for a solenoid would be to have as many turns as possible with thin wire, tightly wound (even though it is not a major factor it does still increase induced voltage), and to have multiple of these solenoids along the area of oscillation with enough separation between them so that both signals do not overlap like in Figure 8. This way, there is no energy loss as hinted in Figure 9, and one would simply get current delivered over a longer time period to whatever load one chooses, may it be a battery or a capacitor. This design will maximize the energy outputted from the system regardless of the magnetic field of the magnet being used or the speed at which it is oscillating.

## b. Suggestions

There are multiple suggestions that would make this investigation significantly more effective. The first and most obvious suggestion is simply the use of better materials. The tube in which the magnet was oscillating by the small 3D printed piece produced significant friction with the wheels. Furthermore, developing a tube that is extremely tight with the magnet as well to allow it to oscillate will provide the needed testing of the proposed perfect solenoid.

One of the main drawbacks from this design is the large electronics that one needs per solenoid set. Developing a cheap, compact way of producing these would result in much more power from the device due to the larger amounts of solenoids one could put into one system. Another lesser drawback of this design is that it is more unpredictable than the usual design, since with the presence of multiple solenoid sets that are initially disconnected from one another, they might cause conflicting magnetic fields in accordance to Lenz's and Faraday's Law (the induced current in the first solenoid will cause a magnetic field on itself which causes a flux change in the proximity of the next solenoid which in turns creates another magnetic field itself). There is not much one can do for this aside from having a larger gap in between solenoid sets.

## VII. Acknowledgements

First and foremost, I would like to thank my advisor Dr. Adam T. Whitten for his constant support, advice, and help throughout the development of this thesis. This thesis would have been a complete disaster if it wasn't for his encouragement and intellect.

I would also like to thank Dr. Todd Johnson for aiding me in this investigation as well. There were multiple quick questions that he was more than happy to answer, and he never shied away from lending a helping hand.

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I thank the entire Physics department, the College of Saint Benedict and Saint John's University and my family for granting me the opportunity and encouragement to progress in a career that is a passion for me. For this and so much more, I am forever grateful.

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## X. Appendix

### Python Code

```
#Induction Project  
#Jose Miralles  
#11/2/2018
```

```
#This program does a rough prediction of what the induced emf will be given a magnet  
and a tube with a set radius and coil windings.
```

```
#Create magnet object
```

```
class Magnet:
```

```
    #Initialize the object
```

```
    def __init__(self, radius, force_high, a_par, b_par):  
        self.radius = radius  
        self.force_high = force_high  
        self.a_par = a_par  
        self.b_par = b_par
```

```
    #This method calculates magnetic force as radius increases
```

```
    def mag_force(self, position):  
        #Power approximation below  
        return self.a_par*((position)**self.b_par)
```

```
    #This method calculates the constant magnetic flux inside the magnet
```

```
    def flux_const(self):  
        return self.force_high*(self.radius**2)
```

```
#Magnet that is being used. Length measurements are in mm and magnetic force is in T.  
magnet = Magnet(0.0115, 0.9, 0.0000054, -2.36)
```

```
#Some constants
```

```
pi = 3.1415
```

```
#n is amount of splits, a higher number yields more precise results since this is a limit
```

```
n = 1000
```

```
#Steps (Here the radius of the tube could be user input, it isnt at the moment)
```

```
x = 0.0116/n
```

```
flux = []
```

```
#Flux inside calculation
```

```
for i in range(1,n+1):
```

```
#This is taken to be a constant in this approximation, so it is skipped and
substracted at the end
```

```
if i*x <= 0.0115:
```

```
    continue
```

```
#This is all of the flux outside of the magnet
```

```
else:
```

```
    #Area
```

```
    area = pi*(((i*x)**2)-(((i-1)*x)**2))
```

```
    #Magnetic strength at specific area ring
```

```
    mag = magnet.mag_force(i*x)
```

```
    #Flux at ring
```

```
    f = mag * area
```

```
    #Appends flux of ring to array
```

```
    flux.append(f)
```

```
y = int(input("How many coils?"))
```

```
dt = float(input("Time change?"))
```

```
#Sums array and applies formula for induced emf
```

```
emf = (pi*magnet.flux_const()-sum(flux))/dt
```

```
print(f'Induced emf is: {y*emf} V')
```