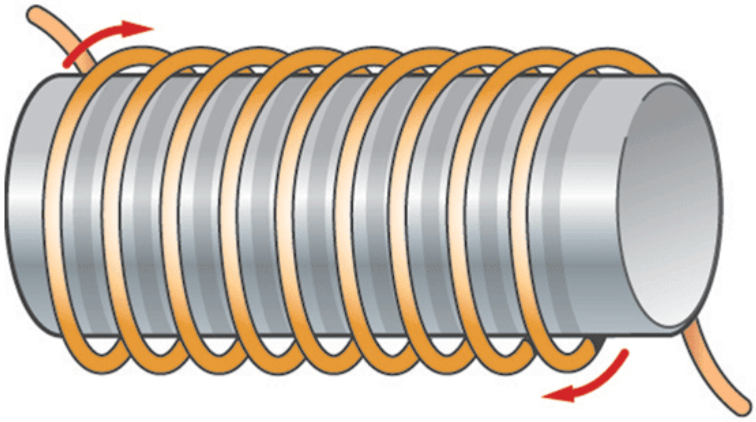
Experiment 4:

Turns in a time variable magnetic field



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Experimental Project
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1 Introduction

This experiment aims to measure the induced voltage of a coil and its dependence on the number of turns, the cross-sectional area, as well as the frequency of the alternating current. To do all of this, the alternating current will be connected to a cylindrical coil, and the smaller coil will be placed inside the internal variable magnetic field that it will generate.

The structure of the document is as follows. First, the theoretical principles behind this experiment will be explained. It will be followed by the experimental procedure and the results with their analysis. Finally, there will be the conclusions of the experiment, and we will answer some questions related to the experiment.

2 Theoretical Fundaments

This experiment explores the phenomenon of electromagnetic induction. It is explained by one of the Maxwell equations, the Faraday-Lenz law:

$$U(t) = -\frac{d}{dt}\int_S \vec{B}\cdot d\vec{S} \tag{1}$$

This principle says that an electric potential is generated when the flux of magnetic field varies with time. When this law is referred to a conductor loop the parameter N, number of turns, is added to the equation:

$$U(t) = -N\frac{d}{dt}\int_S \vec{B}\cdot d\vec{S} \tag{2}$$

In our case, we are working with a constant-area coil, so the surface integral results only in the area A of the coil:

$$U(t) = -NA\frac{dB}{dt} \tag{3}$$

Now in order to obtain the magnetic field of a coil, we can use the Ampère law, which relates how the magnetic field is produced by a current:

$$\oint_L \vec{B}\cdot d\vec{l} = \mu_o I \tag{4}$$

Where $\mu_o = 410^{-7}N/A^2$ is the magnetic permeability in vacuum. For a coil, its current generates a magnetic field following this relation:

$$B = \mu_o\frac{N_F}{L_F}I \tag{5}$$

Being N_F the number of turns and L_F the length of the cylindrical coil. Now we can obtain the potential induced by the coil by replacing the new magnetic field expression in Faraday's law:

$$U(t) = -\mu_o NA\frac{N_F}{L_F}\frac{dI(t)}{dt} \tag{6}$$

Finally, for a sinusoidal current:

$$I(t) = I_o \sin(2\pi f t) \tag{7}$$

The electric potential expression results in:

$$U(t) = -\mu_o 2\pi N A \frac{N_F}{L_F} I_o f \cos(2\pi f t) \tag{8}$$

Where we can define U_o as:

$$U_o = \mu_o 2\pi N A \frac{N_F}{L_F} I_o f \tag{9}$$

3 Experimental Procedure

The material required for this experiment is basically a function generator, which can be used to adjust the amplitude and frequency of the alternating voltage, a field coil wider enough to fit the smaller coils that are also needed to generate the changing flux, an oscilloscope, that allows viewing the waves related to the input voltage and the induced voltage, a resistance, to control the cap of the amperage, and finally the structure and cables of the experiment to connect all the different components.

After connecting and adjusting every parameter and component we need to introduce one of the smaller coils inside the bigger one to visualize the induced voltage due to the alternating current.

Finally, we write down the data to find the relation between the induced voltage and the frequency of the input current, then we increase the voltage and repeat the process.

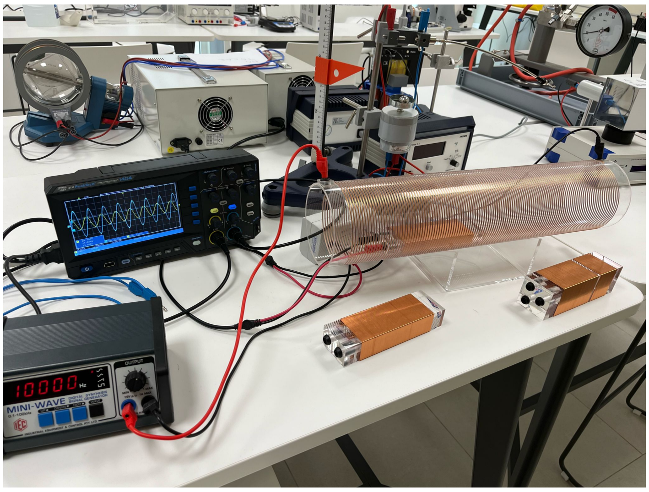

Figure 1: Experimental Set-up

4 Experiment Data and Final Results

4.1 Frequency Dependency of the Potential

In the chart and plot shown below we will discuss the relation between the obtained data and what it says about the experiment.

Frequency (Hz)	Measure 1 (V)	Measure 2 (V)	Measure 3 (V)	Average
2000	6,2	6,8	6,4	6,466666667
3000	9,8	9,6	10	9,8
4000	12,6	12,4	12	12,33333333
5000	16,6	16,8	15,8	16,4
6000	18	18,2	17,8	18
7000	22,2	22	21,8	22
8000	24,6	24,8	24,4	24,6
9000	27,4	27,8	27,6	27,6
10000	31,2	30,8	30,6	30,86666667
11000	33,4	33,2	33,3	33,3

Table 1: Chart of the measured inducted potential vs Frequency of the Alternating Current

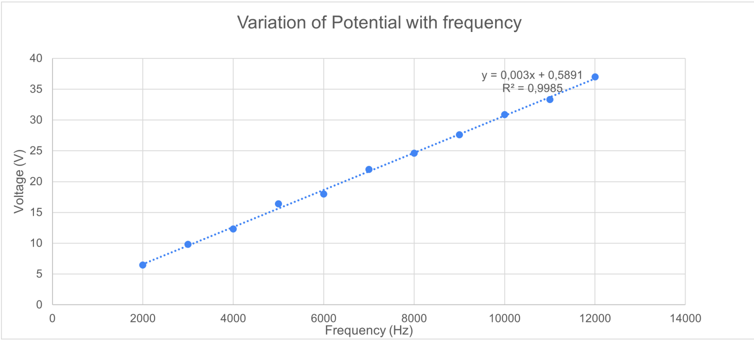

Figure 2: Dispersion plot - Frequency (Hz) vs Potential (V)

We can see that the potential increases linearly with the frequency. Following approximately the equation of U_o:

$$U_o = \mu_o 2\pi N A \frac{N_F}{L_F} I_o f = bf \tag{10}$$

Where b is the slope of the line. Looking at the Linear Regression, its slope is $b_{exp} = 0.003$, we can calculate the theoretical slope by using the following data noted in the laboratory: $N = 120$ turns , $A = 0.011309m^2$, $N_F = 100$ turns , $L_F = 0.05$ m and $I_o = 0.5A$. This results in $b_{th} = 0.0034$, meaning that the error is minimum, it can also be noticed by the determination coefficient: $R^2 = 0.9985$ which tells how accurate the regression is with the given data. If we calculate the error respect to the theoretical value:

$$error = \frac{|b_{exp} - b_{th}|}{b_{th}} = 0.12 \Rightarrow 12\% \tag{11}$$

4.2 Area Dependency

Now we will show how the inducted potential varies depending on the cross-sectional area of the field coil. This experiment is performed by fixing the frequency at a determined value, in our case $f = 1000Hz$, and changing the coil placed inside the cylindrical coil.

Coil	Area (cm^2)	Measure 1	Measure 2	Measure 3	Average
Coil 1	0.001	24	24,4	24,2	24,2
Coil 2	0.0015	37,4	37	37,2	37,2
Coil 3	0.0025	60	60,4	59,8	60,06666667

Table 2: Chart of the variation of the inducted potential U vs Cross-section Area

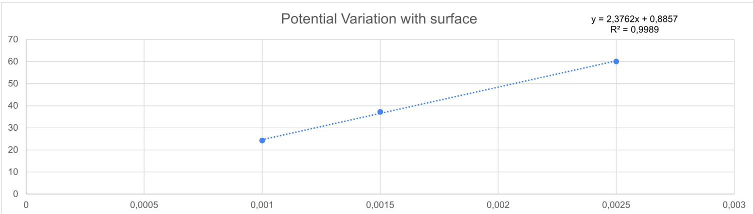

Figure 3: Dispersion plot - Cross-section Area (m^2) vs Potential (V)

Both, the dispersion plot and the chart prove that the potential changes linearly with the area, as the Faraday-Lenz law states, with $R^2 = 0.9989$ and a slope $b = 2.3762$.

4.3 Error Treatment

In this section we will show the calculation of the error in the measurements . In order to do this we will use the next equation:

$$\delta U_o = \sqrt{\sum_i \left(\frac{\partial U_o}{\partial x_i} \delta x_i \right)^2} \tag{12}$$

Where the error is related with the sum of all the partial derivatives respect to the parameters that we use in Faraday's law:

$$U_o = \mu_o 2\pi N A \frac{N_F}{L_F} I_o f \tag{13}$$

And δx_i is the uncertainty in the measurement of the parameter x_i. Each error will be shown in the chart below.

Applying the error propagation equation (12), we obtain that the total uncertainty is $\delta U_o = 0.082$. Since this value is lower than an error of 10%. We can confirm that the measurements are reliable and precise.

$\frac{\partial U_o}{\partial N}$	2,84245E-05	δN	± 1
$\frac{\partial U_o}{\partial A}$	0,301592895	δA (m^2)	± 0.25
$\frac{\partial U_o}{\partial N_F}$	3,41094E-05	δN_F	± 1
$\frac{\partial U_o}{\partial L_F}$	-0,068218706	δL_F (m)	± 0.5
$\frac{\partial U_o}{\partial I_o}$	0,006821871	δI_o (A)	± 0.3
$\frac{\partial U_o}{\partial f}$	0,003410935	δf (Hz)	± 1

Table 3: Error in each parameter of the potential U_o

5 Discussion and Evaluation

How can the phenomenon of magnetic induction in a changing magnetic field be described?

When some conducting material is immersed within a magnetic field, we can visualize the number of field lines that go through the conductor as the magnetic flux inside this material.

When and only when this flux changes, either by decreasing the intensity of the field, or the surface or by rotating the conductor, we can see that an induced voltage is generated inside the conductor, this new created circuit also creates magnetic field lines that are always opposite to the direction of change of the flux.

What are the fundamental laws governing electromagnetic induction in the presence of a changing magnetic field?

This phenomenon, as mentioned in the theoretical part, is described by the Faraday-Lenz law. As shown before, it follows this equation:

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \int_S \vec{B} \cdot d\vec{S} \tag{14}$$

Also, it can be written in its differential form:

$$\vec{\nabla} \cdot \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{15}$$

Both of them have the same meaning. When a magnetic field varies with time an electric potential is induced.

How does the rate of change of magnetic flux affect the magnitude of the induced current in a circuit ?

As the Faraday-Lenz law states, the magnitude of the induced current will be greater as the rate of change in the magnetic flux increases. This is by, for example and as presented in previous sections, increasing the frequency of the alternating voltage.

What are the practical applications of magnetic induction in changing fields in electronic devices or energy generation systems?

They are lots of applications of this phenomenon in present electronic devices. Things like the induction hob, wireless chargers, guitar pickups or electric transformers take advantage of this to transport energy without needing a conducting circuit or transform the electric energy into heat or sound.

Also in the energy generation systems is widely used to make generators that make use of the spinning of a turbine to generate energy via this phenomena.