Investigation of electromagnetic field produced by a copper wire coil under varying conditions

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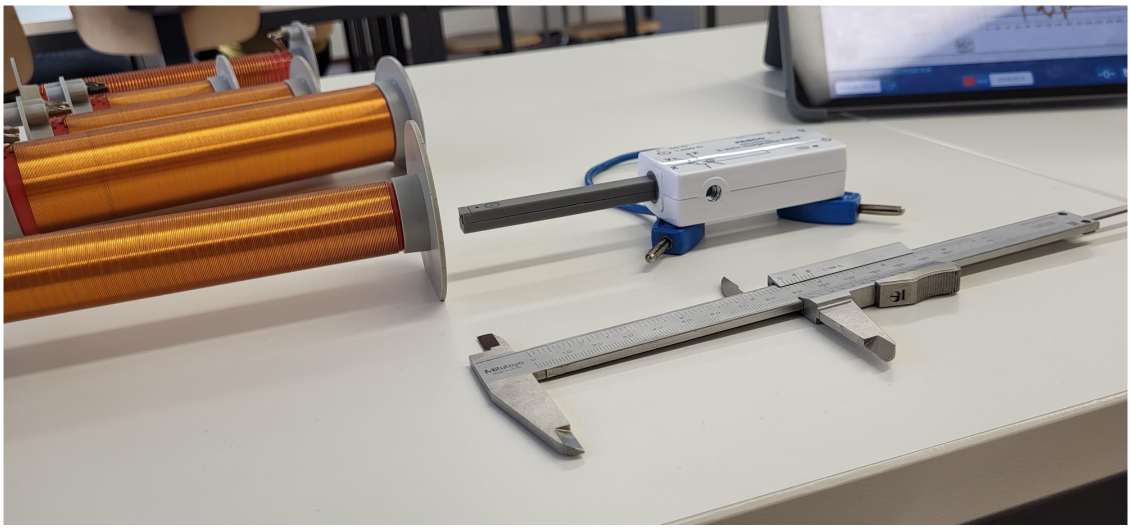


This study aims to investigate the relationship between various factors and the strength of the resulting magnetic field generated by a copper wire coil. The factors explicitly examined include the distance from the center of the coil in the axial direction, the number of wire turns, and the diameter and length of the coil. By systematically varying these factors, we measured the resulting magnetic field strengths. The experimental results provide insights into how these factors affect the magnetic field strength.

1 Introduction

Electromagnetism is a fundamental force that governs the interactions between electric charges and magnetic fields. It describes the relationship between electric currents and the magnetic fields they produce. Understanding this relationship is crucial in various fields of science and technology, as well as for the engeneering of numerous devices, including motors, generators, and transformers.

The purpose of this experiment is to investigate the electromagnetic field produced by a copper wire coil. By passing an electric current through the coil, we can observe the formation of a magnetic field. By utilizing a wireless magnetic field sensor, the strength of the magnetic field inside the coil was measured. Our objective is to examine the relationship between various factors and the strength of the resulting magnetic field. Factors that were explicitly investigated were the distance from the center of the coil in axial direction, the number of wire turns and the diameter as well as the length of the coil.

1.1 Background Knowledge

To understand the relationship between electric currents and magnetic fields, we turn to Maxwell's equations, which describe the behavior of electromagnetic fields. One of Maxwell's equations, known as Ampere's law, reveals the connection between the current flowing through a wire and the magnetic field it generates.

According to Ampere's law, when an electric current passes through a conductor, a magnetic field is created around it. The strength and direction of the magnetic field depend on the magnitude and direction of the current. The magnetic field forms a closed loop around the conductor, with the field lines curving around it.

The relationship between current and magnetic field can be further understood through the right-hand rule. If the thumb of the right hand points in the direction of the current, the curled fingers represent the direction of the magnetic field lines around the conductor. The magnetic field strength decreases as the distance from the conductor increases, proportional to the inverse of the square of the distance ($H = \frac{I}{2\pi r}$, where H is the strength of the magnetic field, I the current applied and r the distance from the wire).

In this experiment, we will investigate the electromagnetic field produced by a copper wire coil. Copper is an excellent conductor due to its high electrical conductivity. When an electric current is passed through the coil, a magnetic field is generated in its surroundings. Understanding the characteristics of the electromagnetic field generated by copper wire coils is essential for designing efficient electromagnetic devices and advancing technologies such as energy transmission, wireless communication, and magnetic sensing.

2 Hypothesis

In the first experiment we expect the stength of the magnetic field to linearly increase with an increase in the number of wire turns and length of the coil.

In the second one the magnetic is also expected to be correlated with the number of wire turns.

In the third one negative correlation between the square of the distance and the magnetic field strength is expected, as already explained.

3 Methods

3.1 Tools and material

Tools and material that were used include:

- Different premanufactured copper coils
    - The coils were specifically designed to have most traits in common with one varying
- Wireless magnetic field sensor by [Pasco](https://www.pasco.com](https://www.pasco.com)
- We used the IPad application SPARKvue to retrieve the results sent by the sensor
- Caliper

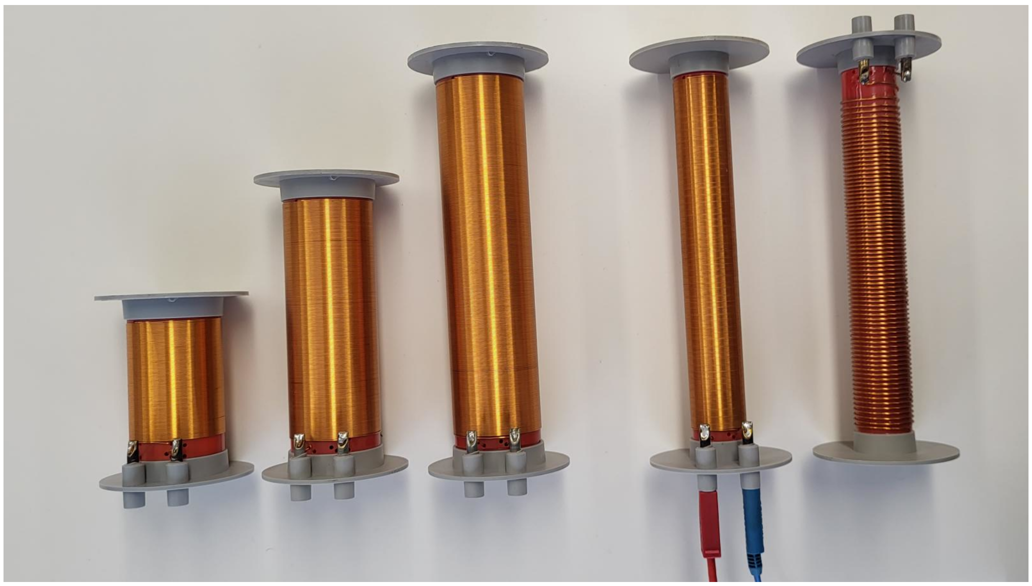


Fig. 1: Copper wire coils that were used

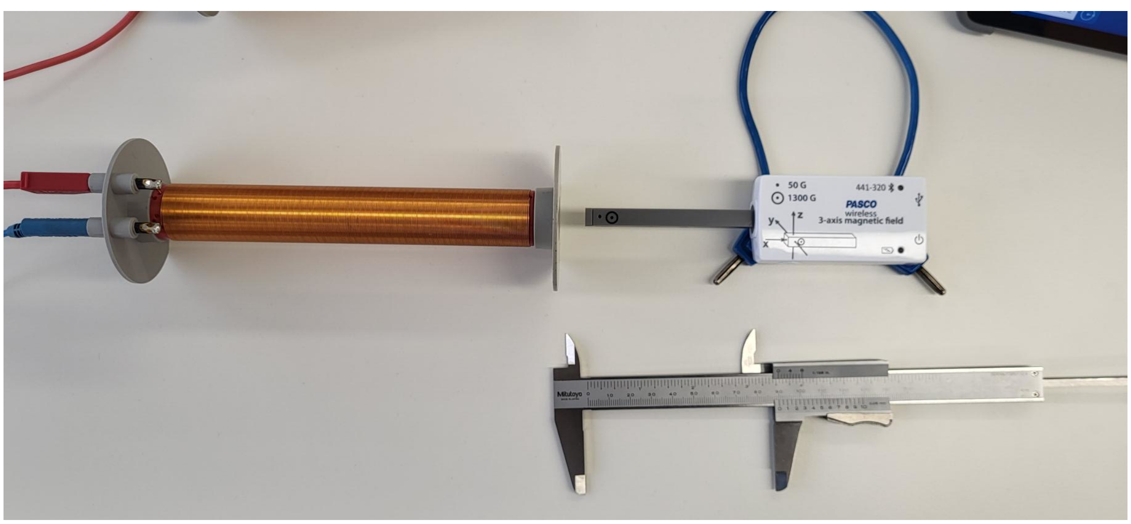


Fig. 2: How the measurements were taken

3.2 Procedure

First an open circuit was created with two ends, that could be plugged into a copper wire coil to close the circuit and apply voltage to the coil. With the power supply, the voltage as well as the maximum current could be regulated. An arbitrary current limit of around 0.5 Ampere was chosen, which allowed to easily detect the magnetic field. The effective voltage and current were then measured for each measurement directly in the circuit.

The copper coils were plugged into the circuit one at a time and the displayed voltage and current were directly read and noted into a spreadsheet (electromagneticFieldMeasurements_raw.ods). The magnetic field sensor was laid on a flat object so that it was on the same height as the axis of the coil, and then it was inserted into the hole of the coil as deep as possible for the longest one (7.6cm), and less in the following coils, proportional to the length of the coils. The data that was sent wirelessly to a IPad where it was observed and recorded.

For the last experiment the sensor was first inserted into the coil to the 7.6cm to get as close to the center as possible and then it was pulled out one centimeter at a time. A caliper was used to precisely determine the length of the visible shaft. The current and voltage weren't measured every single time in this experiment.

It was tried to keep the distance from the center as close to a certain percentage as possible. The number chosen was as close to the center as one could get on the longest coil. The deviation from this value was recorded to be analyzed later.

4 Results

The results were collected in a spreadsheet and exported into a CSV and PDF format, both of which are found in the same directory as this file or under those links:

- Spreadsheet (ODS format)
- CSV
- PDF

The most important data that was recorded is presented in the following sections.

4.1 Experiment I

In this experiment three coils were measured with the same density of copper wire but different lengths and consequently a lower number of wire turns and Resistance. The shaft has been inserted according to the length of the coil.

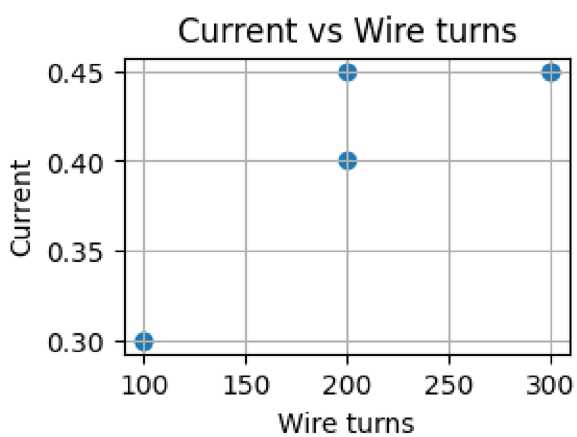
Here is the recorded data:

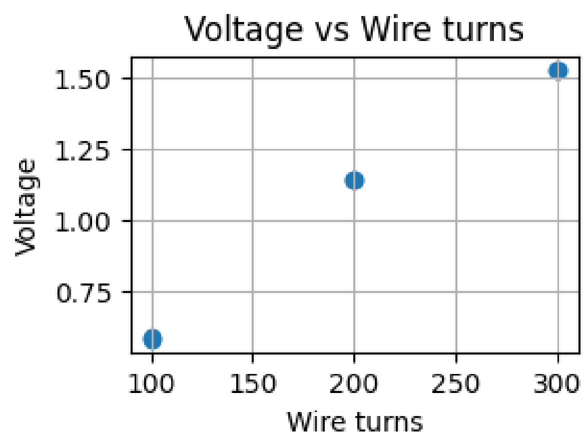
Wire turns	Length (cm)	Invisible shaft (cm)	Current (A)	Voltage (V)	Field strength (mT)	Resistance (Ω)	Diameter (mm)
300	16	7.6	0.45	1.525	1.03	3.5	41
300	16	7.6	0.45	1.526	1.02	3.5	41
200	10.6	5.035	0.4	1.14	1.11	2.2	41
200	10.6	5.035	0.45	1.141	1.12	2.2	41

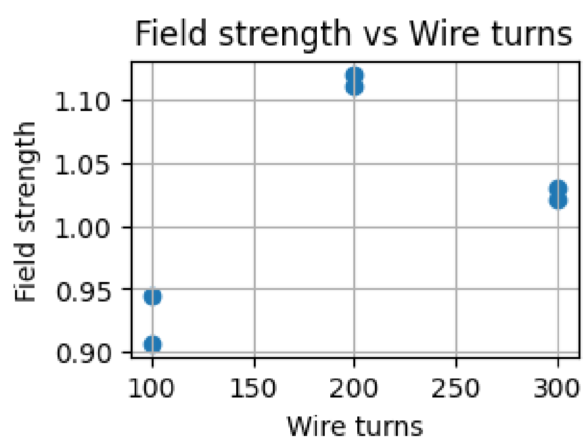
Wire turns	Length (cm)	Invisible shaft (cm)	Current (A)	Voltage (V)	Field strength (mT)	Resistance (Ω)	Diameter (mm)
100	5.3	2.5	0.3	0.585	0.944	1.1	41
100	5.3	2.5	0.3	0.589	0.907	1.1	41

[53]:

```
### Code for experiment I ###

# Extract first 6 rows of the interesting columns (the next rows are for the␣
↪other experiments)
field_strength = g_data['Electromagnetic field strength (mT)'][:6]
voltage        = g_data['Voltage (V)'][:6]
current        = g_data['Current (A)'][:6]
wire_turns     = g_data['Number wire turns'][:6]

# Plot and display the data
show_plot('Wire turns', wire_turns,
          'Current', current)

show_plot('Wire turns', wire_turns,
          'Voltage', voltage)

show_plot('Wire turns', wire_turns,
          'Field strength', field_strength)
```

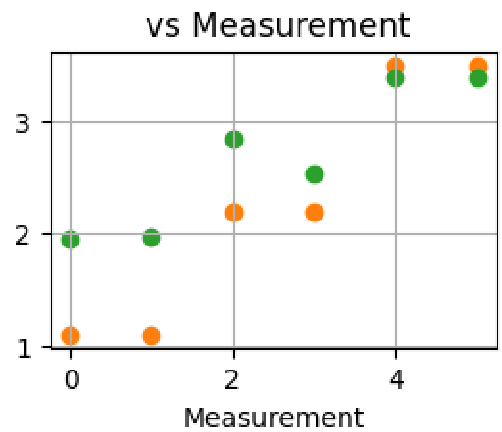






The data from the resistance annotated on the coil can also be compared with the collected voltage and current data.

[46]:
```
expected_resistance   = g_data[u'Resistance (Ω)'][:6]
calculated_resistance = [
    U / I
    for U, I in zip(voltage, current)
]

show_multiplot(xlabel='Measurement', xvalues=range(6),
               ydata = [
                   ('Expected resistance', expected_resistance),
                   ('Calculated resistance', calculated_resistance),
               ])
```



4.2 Experiment II

Two coils were measured with the a different density of copper wire and different number of wire turns:

Wire turns	Length (cm)	Invisible shaft (cm)	Current (A)	Voltage (V)	Field strength (mT)	Resistance (Ω)	Diameter (mm)
300	16	7.6	0.38	1.091	1.18	2.2	26
300	16	7.6	0.39	1.091	1.19	2.2	26
75	16	7.6	0.04	0.0755	0.334	0.15	26
75	16	7.6	0.08	0.0735	0.345	0.15	26

The data can as well be ploted:

[48]:
```
### Code for experiment II ###
```

4.3 Experiment III

On the same copper wire coil, 10 measurements at different distances from the center were taken. Those are the results:

Offset (cm)	Magnetic Field Strength (mT)
11.41	1.19
12.41	1.19
13.41	1.2
14.41	1.2
15.41	1.17
16.41	0.958
17.41	0.546

Offset (cm)	Magnetic Field Strength (mT)
18.41	0.195
19.41	0.097
20.41	0.05

Where the first column annotates the distance from the center of the coil. 11.41 is as close as one can get with the used sensor and coil.

[52]:
```
### Code for experiment III ###

# Extract first 6 rows from the data
distance_from_center    = g_data['III: Offset from center (cm)'][:8]
magnetic_field_strength = g_data['III: Magnetic field strength (mT)'][:8]

# Plot and display the data    ! Not working right now !
#show_plot('Distance from center of coil (cm)', distance_from_center,
#           'Magnetic field strength (mT)', magnetic_field_strength)
```

5 Discussion

5.1 Experiment I

As described in the methods section, in this sub experiment three coils with the same density of copper wire were measured, but with different lengths, resulting in a lower number of wire turns and resistance. The coils were accompanied by an invisible shaft, which was inserted based on the length of each coil.

From the recorded data, two main observations can be made:

- Wire Turns and Length: As the number of wire turns decreases with shorter coil lengths, it is expected that the resistance of the coil will decrease as well. This relationship is evident in the data, where coils with lower wire turn counts have lower resistance values, and the values calculated from the current and voltage data correspond to the annotations on the coil with a percision of +/- 1 Ohm.
- Field Strength: The field strength measurements represent the strength of the magnetic field produced by each coil. It can be observed that the field strength varies with different combinations of wire turn count, length, and electrical properties. It didn't vary as expected in the hypothesis. Instead, it has a peek in the measurement of the coil with 200 wire turns, not as exepted at 300 wire turns. To analyse this further, more data is needed. Since the backup measurements support the data, it could be possible that the relationship is not linear, but instead there is an optimum in the number of wire turns relative to the voltage applied.

5.2 Experiment II

Here mainly one observation has been made. As expected, the strength of the magnetic field has fallen. The similar ratios between voltage and the field strength imply that there might be a relationship.

5.3 Experiment III

Again our hypothesis was backed by the data. The strength decreases with decreasing distance.

The relation is also not linear, but the exact function could not be determined.

It is important to note that since only a few datapoints could be taken, further analysis, statistical calculations, and comparison with theoretical models would have to be done to provide deeper insights into the observed trends and relationships within the data.

6 Sources

6.1 Tools and material

1. magnetic field sensor
    2. Produced by pasco (`https://www.pasco.com`(https://www.pasco.com](https://www.pasco.com))

6.2 Information, Knowledge

1. `https://www.maxwells-equations.com/`

7 Appendix

7.1 Data

The results of the measurements can be found under this link: `https://github.com/lrshsl/data/tree/main/PHLab_ElectromagneticFields`

The bare data are in the `resources` directory.

7.2 Code

The following code specifies the modules, imports and functions that were used in the code snippets used in this document. If you run this as an interactive jupyter notebook, you probably need to run this block before the others, otherwise you may encounter errors.

[47]:
```
# Python module installation
!pip install pandas

# Import needed packages
from typing import Optional, Sequence, Dict, Tuple
import numbers

import pandas as pd
import matplotlib.pyplot as plt


# Set defaults
PLOT_SIZE: (int, int) = 3, 2
```

```
# Prepare the CSV file
g_data = pd.read_csv('resources/measurements.csv')


def prepare_plot(xlabel: str, xvalues: Sequence[numbers.Number],
                 ylabel: str, yvalues: Sequence[numbers.Number],
                 size: Optional[Tuple[int, int]] = PLOT_SIZE,
                 grid: Optional[bool] = True,
                 title: Optional[str] = None,
                 lines: Optional[bool] = False,
                ) -> None:
    # Set the figure size
    plt.figure(figsize=size)

    # Plot the data
    plt.scatter(xvalues, yvalues)
    if lines:
        plt.plot(xvalues, yvalues)
    plt.xlabel(xlabel)
    plt.ylabel(ylabel)
    plt.title(title if title else
              '{ylabel} vs {xlabel}'.format(
                  ylabel=ylabel, xlabel=xlabel))
    plt.grid(grid)


def show_plot(*args, **kwargs) -> None:
    # Prepare
    prepare_plot(*args, **kwargs)
    # Display
    plt.show()

def show_multiplot(xlabel: str, xvalues: Sequence[int],
                   ydata: Sequence[Tuple[str, Sequence[int]]],
                   *args, **kwargs) -> None:
    # Prepare
    prepare_plot(xlabel=xlabel, xvalues=[],
                 ylabel='', yvalues=[], *args, **kwargs)

    # Add data
    for label, yvalues in ydata:
        plt.scatter(xvalues, yvalues, label=label)

    # Display
    plt.show()
```

```
Defaulting to user installation because normal site-packages is not writeable
Requirement already satisfied: pandas in /home/lars/.local/lib/python3.11/site-
```

```
packages (2.0.2)
Requirement already satisfied: python-dateutil>=2.8.2 in
/home/lars/.local/lib/python3.11/site-packages (from pandas) (2.8.2)
Requirement already satisfied: pytz>=2020.1 in
/home/lars/.local/lib/python3.11/site-packages (from pandas) (2023.3)
Requirement already satisfied: tzdata>=2022.1 in
/home/lars/.local/lib/python3.11/site-packages (from pandas) (2023.3)
Requirement already satisfied: numpy>=1.21.0 in
/home/lars/.local/lib/python3.11/site-packages (from pandas) (1.24.3)
Requirement already satisfied: six>=1.5 in
/home/lars/.local/lib/python3.11/site-packages (from python-
dateutil>=2.8.2->pandas) (1.16.0)
```

[ ]:

```

```