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**Research Article**

# Using Modeling Software as an Alternative to Experiment: The Magnetic Field of a Helmholtz Coil

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**Abstract:**

In physics education and research, the integration of modeling software has emerged as a promising alternative to traditional experimental approaches. This paper focuses on the specific case of examining the magnetic field of a Helmholtz coil through computational simulation. Through a comparative analysis between simulated results and experimental data, we aim to evaluate the accuracy and reliability of using modeling software in replicating physical phenomena. Furthermore, we explore the potential of utilizing computational modeling as a viable tool for both didactic instruction and advanced research inquiries in the realm of magnetic field analysis. By addressing the overarching questions surrounding the efficacy and applicability of simulation-based methodologies, this study contributes to a deeper understanding of the role of computational physics in modern scientific exploration and educational practices.

## 1. Introduction

The purpose of this experiment is to study the magnetic field produced by two coaxial coils (Helmholtz coils) and compare the results with simulations from CST Studio software. CST Studio Suite (CST – Computer Simulation Technology) models the behavior of physical devices, allowing us to simulate the magnetic field of our physical coil.
We will study the magnetic flux density between and outside the coils, examining its dependence on the $z$-coordinate and radius $r$. This will show that the flux is homogeneous between the coils and decreases outside. We will also study one coil's flux to demonstrate that the combined field is the vector sum of both coils' fields.
Python will be used to generate theoretical graphs, as it easily produces high-quality visualizations.
We expect the software results to align with theoretical predictions.

## 2. Theory

The magnetic flux law can be written in the form of Biot-Savart Law:

$$d\vec{H} = \frac{I}{4\pi}\frac{d\vec{l}\times\vec{\rho}}{\rho^3} \qquad (1)$$

Where $\vec{l}$ is perpendicular to $\vec{\rho}$. (PHYWE)
Resolving this into radial and axial components, the radial ones cancel out, leaving:

$$H_r(z) = 0 \; and \; H(z) = H_z(z) = \frac{I}{2}\frac{R^2}{(R^2+z^2)^{3/2}} \qquad (2)$$

(PHYWE)

The magnetic flux density is:

$$B(z) = \frac{\mu_0 I}{2R}\frac{1}{\left(1+\left(\frac{z}{R}\right)^2\right)^{\frac{3}{2}}} \qquad (3)$$

(PHYWE)
For a coil of $N$ turns, the magnetic flux density for a Helmholtz configuration becomes:

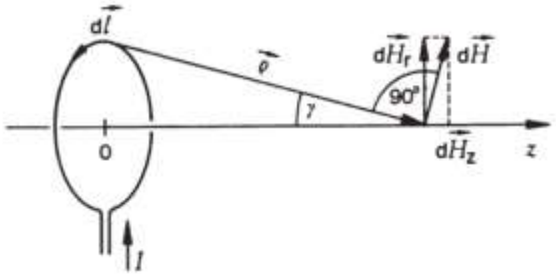


***Figure 1.*** *Drawing for the calculation of the magnetic field along the axis of a wire loop. (PHYWE)*

$$B(z) = \frac{\mu_0 N I}{2R}\left(\frac{1}{(1+A_1^2)^{\frac{3}{2}}} + \frac{1}{(1+A_2^2)^{\frac{3}{2}}}\right) \qquad (4)$$

where $A_1 = (z + \alpha/2)/R$ and $A_2 = (z - \alpha/2)/R$. This is to represent both coils in the Helmholtz configuration. (PHYWE)

When $z = 0$, flux density has a maximum value when $\alpha < R$ and a minimum value when $\alpha > R$. For $\alpha = R$, the magnetic field will be homogenous in the range:

$$\frac{-R}{2} < z < \frac{R}{2} \qquad (5)$$

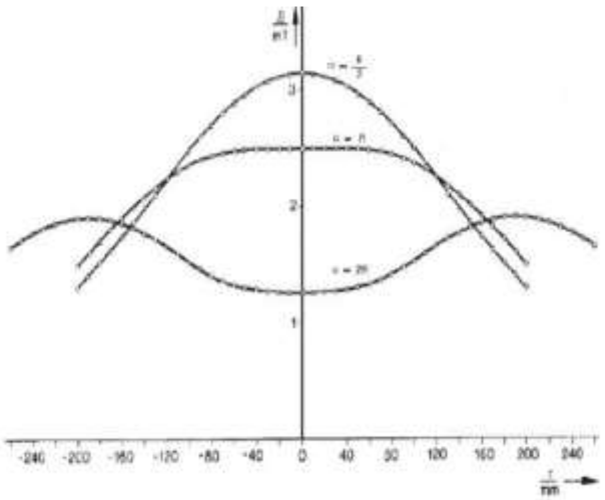


***Figure 2.*** *B (r = 0) as a function of z with the parameter α.*

(PHYWE)

Figure 2 was provided by the manufacturer of the Helmholtz coil (PHYWE). The bottom curve is the flux density $B$ vs distance $z$ when $\alpha = 2R$. This shows a minimum flux density in the region between the two coils. That is because they are not close enough for their magnetic fields to merge and create a stronger field. The middle curve is the combined magnetic flux density $B$ when $\alpha = R$. This shows a uniform field in between the two coils. Finally, the upper curve is the combined magnetic field when $\alpha = \frac{R}{2}$. This shows a maximum in the position $z = 0$.

For our coil we expect the graph to look like this:

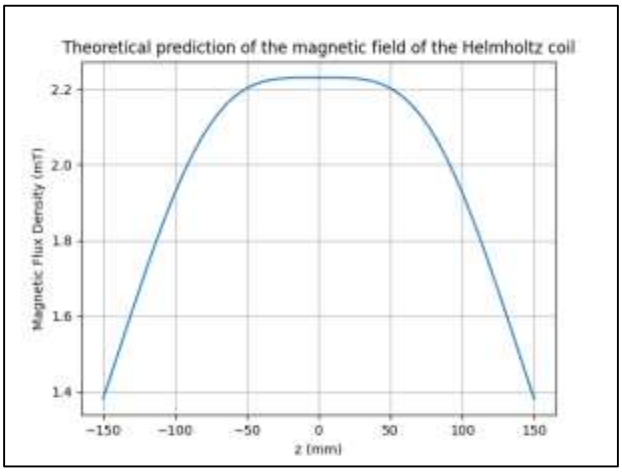


***Figure 3.*** *Theoretical prediction of the magnetic field of the Helmholtz coil with 124 turns and current 3A.*

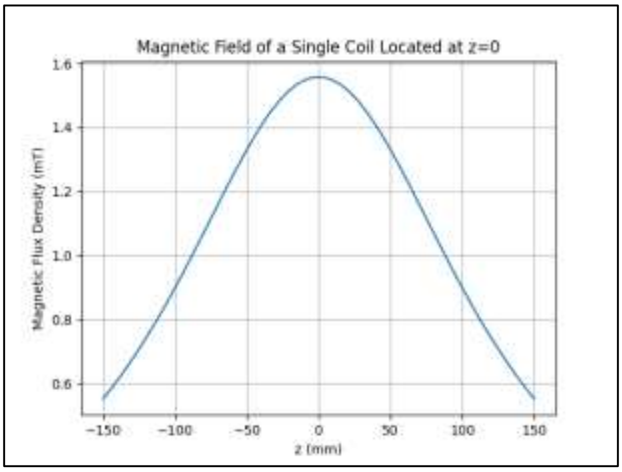


***Figure 4.*** *Theoretical prediction of the magnetic field of one coil with 124 turns and current 3A.*

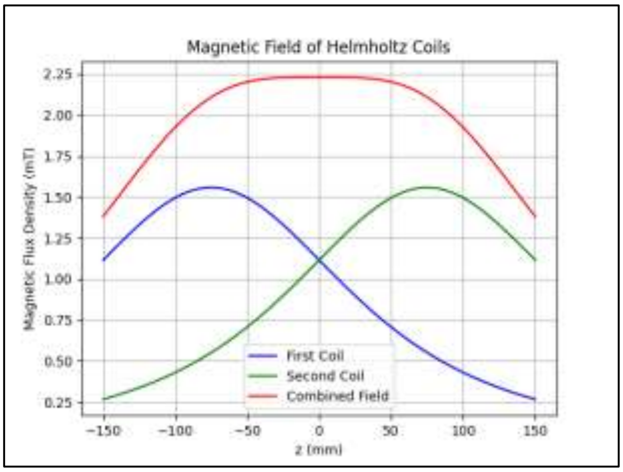


***Figure 5.*** *Magnetic Field of the Helmholtz Coils as a combination of the fields of each coil*

## 3. Material and Methods

The two coils are connected in series with a current source, and an ammeter is used to measure the current. A Hall Probe connected to a teslameter measures the magnetic flux density. To examine how the flux density depends on the *z*-coordinate, the

probe was placed along the coil axis ($r = 0, z = 0$) and moved in 10 mm steps, recording values in every step.
For the radial dependence, the probe was moved horizontally along the radius with a fixed *z*-distance. Finally, we disconnected one coil to measure the flux density of the remaining coil along the *z*-axis.

## 4. Results and Discussions

### 4.1.Experimental Results

Below are the experimental results for Magnetic Flux Density vs *z* coordinate (Table 1), Magnetic Flux Density (*B*) vs. Radial Distance (*r*) (Table 2), and Experimental Measurement of Magnetic Flux Density (*B*) vs. Radial Distance (*r*) for a Single Coil (Table 3).

***Table 1.*** *Experimental Measurement of Magnetic Flux Density vs. Distance (z-Axis) for Helmholtz Coil*

| ***z*** **(mm)** | ***B*** **(mT)** |
|---|---|
| 0 | 2.23 |
| 10 | 2.23 |
| 20 | 2.23 |
| 30 | 2.24 |
| 40 | 2.24 |
| 50 | 2.23 |
| 60 | 2.21 |
| 70 | 2.16 |
| 80 | 2.11 |
| 90 | 2.04 |
| 100 | 1.97 |
| 105 | 1.93 |
| 115 | 1.81 |
| 125 | 1.7 |
| 135 | 1.58 |
| 145 | 1.45 |
| 155 | 1.34 |

***Table 2.*** *Experimental Measurement of Magnetic Flux Density (B) vs. Radial Distance (r) for Helmholtz Coil*

| ***r*** **(mm)** | ***B*** **(mT)** |
|---|---|
| 0 | 2.25 |
| 5 | 2.24 |
| 10 | 2.24 |
| 15 | 2.25 |
| 20 | 2.24 |
| 25 | 2.24 |
| 35 | 2.22 |
| 55 | 2.2 |
| 75 | 2.12 |
| 95 | 1.95 |
| 105 | 1.79 |
| 110 | 1.7 |
| 115 | 1.59 |
| 125 | 1.48 |
| 130 | 1.21 |
| 135 | 1.12 |

***Table 3.*** *Experimental Measurement of Magnetic Flux Density (B) vs. Radial Distance (r) for a Single Coil.*

| ***r*** **(mm)** | ***B*** **(mT)** |
|---|---|
| 0 | 1.2 |
| 10 | 1.2 |
| 30 | 1.17 |
| 50 | 1.16 |
| 70 | 1.13 |

### 4.2.Results analysis

As can be seen from the tables, we made the measurements starting from $z = 0, r = 0$, which represents the position between the two coils. Both coils are displaced from this position by the distance $R/2$. If we graph these tables, we get only half of the graph (from $z = 0$ to $z = 155mm$ & from $r = 0$ to $r = 135mm$). We expect the same trend for negative values of $z$ so we can reflect the graph and get the graphs below.

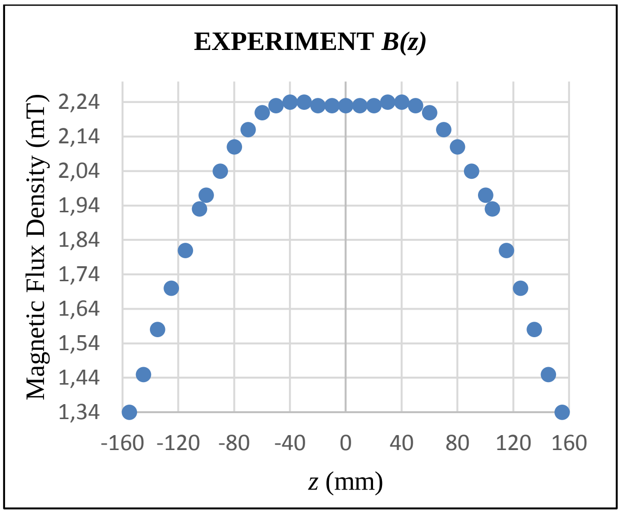


***Figure 6.*** *Experimental Measurement of Magnetic Flux Density vs. Distance (z-Axis) for Helmholtz Coil.*

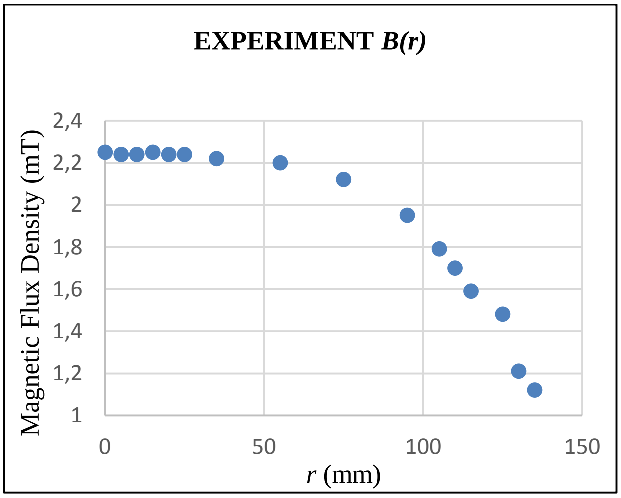


***Figure 7.*** *Experimental Measurement of Magnetic Flux Density (B) vs. Radial Distance (r) for Helmholtz Coil.*

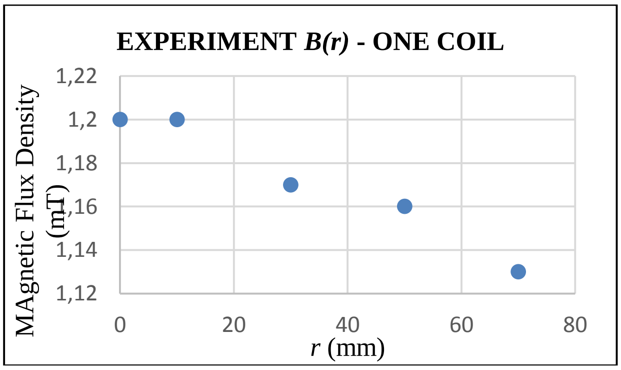


***Figure 8.*** *Experimental Measurement of Magnetic Flux Density (B) vs. Radial Distance (r) for a Single Coil.*

We see that the graphs obtained from the measurements during the experiment agree quite well with the graphs predicted theoretically using the Biot-Savart law for the magnetic field of the coil. However, there are some differences.

First, we see that the plot of magnetic field versus distance $z$ does not give us a straight horizontal line in the area between the two coils as we expected, but we have a small decline. This is justified by the fact that it is quite difficult to place the two coils at a distance exactly equal to the radius of the coil. We can see this if we increase the distance by a little more than the radius of the theoretical prediction. Setting the distance between the two coils to $1.1R$, we get the following graph.

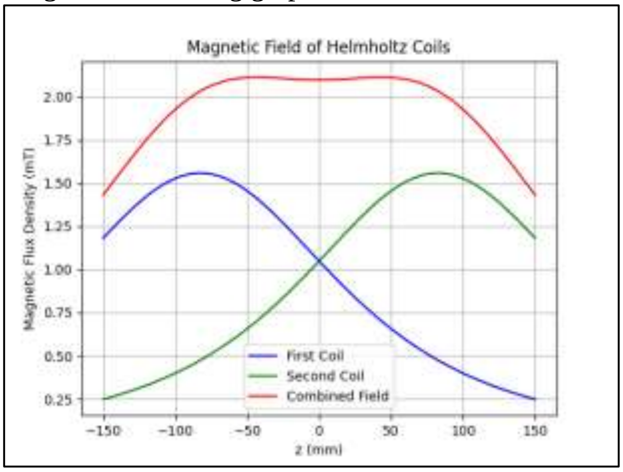


***Figure 9****. Theoretical prediction when distance is 1.1R*

So, a decrease of the magnetic field is observed in the region $-R < z < R$, similar to what the experiment gave us.

Another difference is that in the graph of the magnetic field against the radius, the curve is not as smooth as the theory gives us, but this is always expected, because the theory is the ideal case, while the experiment is the reality.

The last difference appears in the plot of the magnetic field as a function of $z$ for just one coil.

The graph of measurements looks quite "messy" and not smooth. This may be due to the not quite stable current during the measurements for a coil, in which case we noticed that the value of the current intensity was not quite stable.

## 4.3.Modelling in CST Studio

In the CST Studio Suite 2023 application, we have modelled two identical coils. We placed one coil in the position $x = 0, y = 0, z = -R/2$, and the other coil in the $position\ x = 0, y = 0, z = +R/2$. These are the coordinates of the centers of the circular coils. First, we note the parameters of the coils in the parameter table. Initially, the coils are defined only as two circles, to which we then give the properties

of the coil using the given parameters. Thus, each circle is made into a coil with 124 turns and a radius of $150mm$. In each coil we define the current of $3A$. The line seen along the $z$ axis only serves as a guide for the program to estimate the magnetic field along this line. Then we start the simulation and ask it to generate for us the plot of the magnetic field against the $z$ coordinate.
Then we start the simulation and generate the plot of the magnetic field against the $z$ coordinate.

Parameter List

| Name | Expression | Value | Description |
|---|---|---|---|
| n | 124 | 124 | number of turns |
| [illegible] | 3 | 3 | current in A |
| d | a/2 | 75 | distance from center |
| a | 150 | 150 | radius |

***Figure 10.*** *Parameter list*

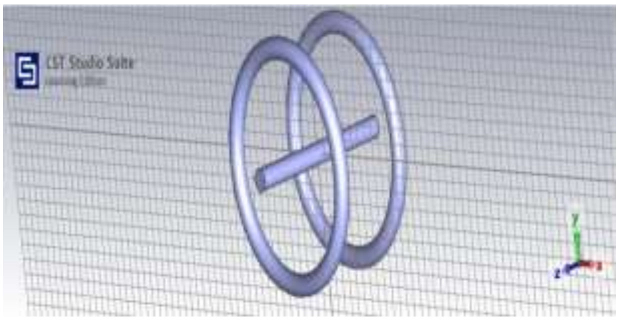


***Figure 11.*** *Modelling the coils*

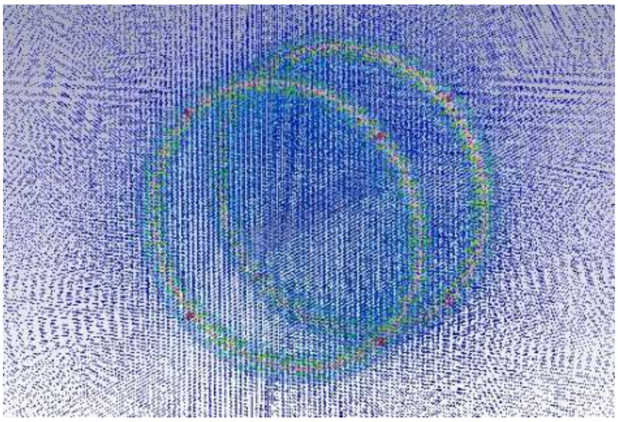

***Figure 12.*** *Visual representation of the magnetic field*

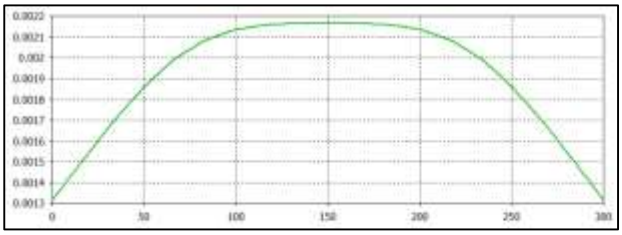


***Figure 13.*** *Plot of magnetic field versus z, generated by the software.*

## 4.4.Software data analysis

We see that the graph fits perfectly with the theoretical prediction made with Python. In the space between the two coils the magnetic field is homogeneous which is shown by the straight horizontal line.
It is worth noting that the magnetic field values in this graph are given in Tesla (T and not mT).
However, no drop is seen as given by the experiment. This is because in the modeling we have placed the coils at a distance of exactly equal to $R$.

## 5. Conclusions

The analysis of the experimental measurements proved that the Biot-Savart Law very accurately describes the magnetic field generated by two identical coils in the Helmholtz configuration, so this law applies to this case.
The same conclusion can be reached by using software applications such as CST Studio, which we used during this work.
This means that this application is able to generate results very similar to those we obtain by experiment. This allows the student to develop an understanding of the physical problem without having to perform the experiment, and only by modelling it. This is no less valuable than the experiment, since the student practically sees how the apparatus is assembled in the laboratory, I would even say that without understanding it, it will be very difficult to model the apparatus.
For this reason, I would prefer the use of computers for practical work with didactic purposes. The only downside to using these apps is that they don't show the difference between reality and theory as well as experiment. So, without the experiment, we would not be able to see the differences that we saw in the graphs derived from the experimental measurements. Also, we can't talk about uncertainty as the software applications are designed to give perfect results that are predicted by theory.
Such applications can also be used for modelling new problems, thus opening the way for real research. Such applications have long been used by engineers for practical predictions and are quite effective.

## Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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