Physics SL

Internal Assessment

Research question: How does changing the density of turns in a solenoid affect the magnetic field it generates?

Name: José Raúl Pastrana Martínez

Candidate number: 006047-0097

Session: May 2016

Teacher: Dr. Anthony Schultz

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Introduction

The objective of this investigation is to discover the way in which the magnetic field of a solenoid increases when the density of the turns of the solenoid is increased. First of all, a solenoid is a long coil of wire with a center of empty space. When connected to a battery, causing electric current to flow through, a magnetic field is generated within and around it. This field is uniformly concentrated in the solenoid's center and weak around it, as each turn of the coil contributes with its own magnetic field, superimposing with the other fields in the center.

Design

The experiment involves measuring the magnetic field produced by a solenoid – after electric current is passed through it– at different degrees of coil tightening, or turn density, and analyzing any existing relationship, such as a proportionality.

Variables

The independent variable, n, is the turn density, of how many turns are in a given length of the solenoid (hence, density). This is measured in the number of turns per given unit length.

The dependent variable, B, is the magnitude of the interior magnetic field of the solenoid that each one of the densities produces, expressed in mT (mili-tesla) units and measured with a magnetic field sensor.

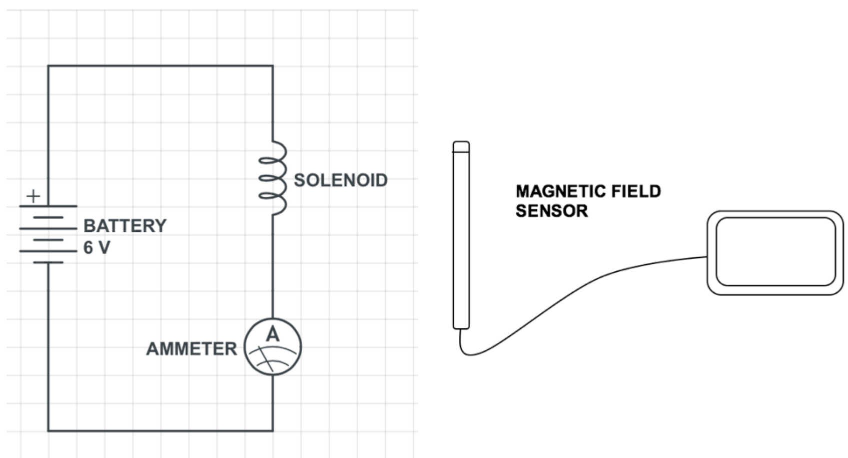
The control variables include using the same electric current, generated by the same battery, as well as using the same solenoid, magnetic field sensor and ammeter to make measurements.

Experiment

The experiment requires an insulated copper wire uniformly coiled into a solenoid with the ends sandpapered off to introduce the electric current; a 6-volt battery to generate the current; a magnetic field sensor to measure the field generated; an ammeter to measure the current going through the circuit to relate it to the measurements of the magnetic field; a ruler to measure the changing densities; and a marker to keep track of the last loop of a unit length.

The procedure is the following: first, the ammeter should be properly wired, connected to the solenoid and set to 20mA (mili-amperes), then, the remaining ends of the solenoid and the ammeter should be connected to the battery, effectively creating a circuit. Following this, the current and the magnetic fields must be measured, which, since the circuit is un-switched –causing it to get hot really fast– must be quickly done to avoid harm and depleting the battery, which must be disconnected after the measurements of each full trial. The current must remain constant during the whole experiment, and in an attempt to keep it this way it will only stop flowing after each experimental trial –as the equipment must be taken care of. Additionally, it will be measured continuously to make sure it does not vary, which must be accounted for in case it does. The magnetic field will be measured in the interior of the solenoid, as there is where it is the strongest, by introducing the magnetic field sensor within the solenoid. To change the turn density, the coil must be tightened around the magnetic field sensor, increasing the number of turns per unit length. Then, the magnetic field emitted by that new density must be measured and recorded. The tightest the coil can get without having turns overlap each other is at 19 turns per centimeter, and these turns can be separated from each other by expanding the coil. The coil will start expanded at a density of only one turn per centimeter, and it will be compressed by two turns for every magnetic field measurement, until it becomes the tightest it can get (19 turns per centimeter). After every measurement is recorded and the circuit is disconnected, the process will be repeated two times to reduce any possible errors.

Diagram of experiment



Raw data

After doing several trials to determine the best way to set up the circuit and measure the magnetic field, it was discovered that the battery had been depleted to a voltage of 5.75V. Hence, all of the following data comes from from that voltage.

	Magnetic field B (mT) ±0.100mT			
Turn density n (turns per centimeter)	1st trial T_1	2nd trial T_2	3rd trial T_3	Average T_{avg}
1	0.056	0.136	0.078	0.090
3	0.395	0.258	0.246	0.300
5	0.558	0.512	0.469	0.513
7	0.615	0.712	0.835	0.721
9	0.844	0.943	0.951	0.913
11	0.955	1.128	0.981	1.021
13	1.101	1.233	1.254	1.196
15	1.308	1.415	1.448	1.390
17	1.444	1.539	1.558	1.514
19	1.545	1.658	1.636	1.613

The average magnetic field, calculated to reduce error and uncertainty among trials by smoothing them out, is obtained in the following way: $T_{avg} = \frac{T_1+T_2+T_3}{3}$, for example, the first row: $T_{avg} = \frac{0.056+0.136+0.078}{3} = 0.090$. Figures are rounded to three decimal places.

Magnetic field uncertainty

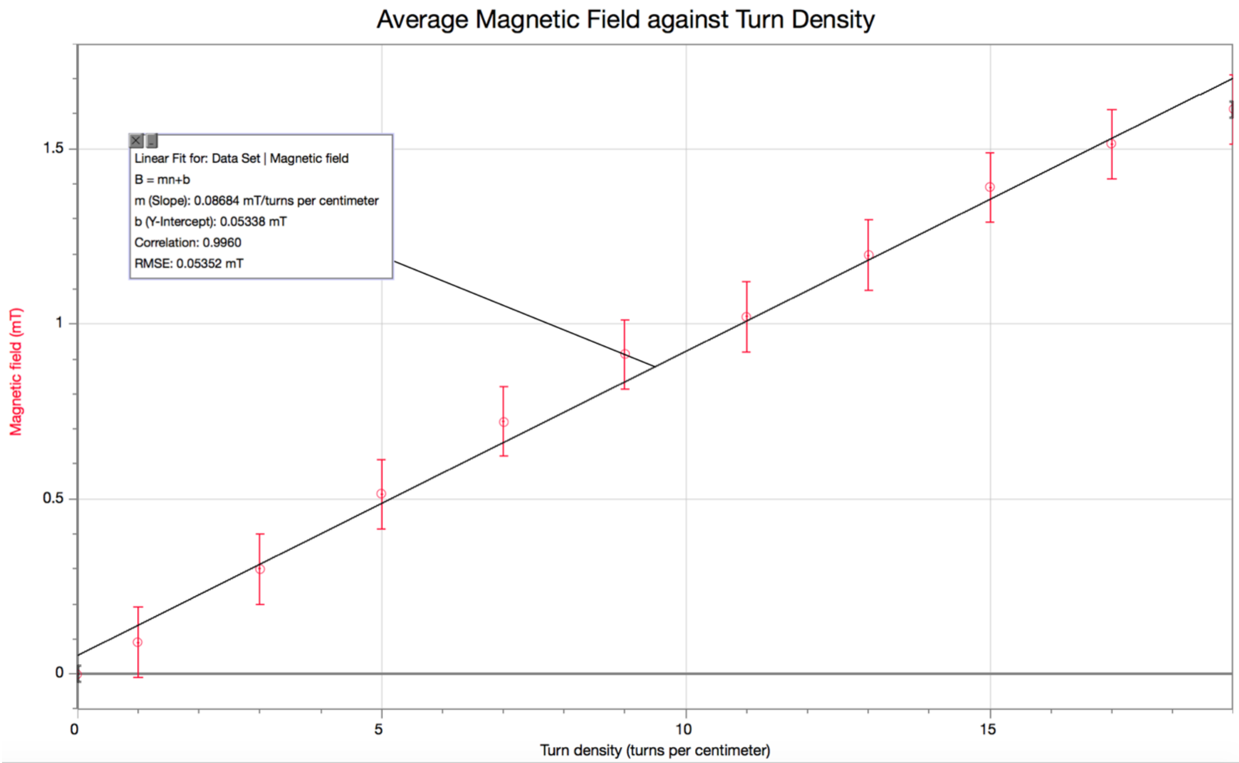
The magnetic field has an uncertainty of ±0.100mT, as the sensor spiked up to that level. This is mainly due to the sensibility of the instrument to any possible interference and the not perfectly stable current going through the circuit that generated the field.

Regarding the electric current, it decreased significantly in between trials because the voltage of the battery was decreasing as measurements took place. The voltage decreased from 5.75V to 4.81V after all three trials were made. This was mainly due to keeping the circuit connected during each one of them in an effort to keep the current constant, even though the measurements were done as fast as possible. As for the current, it was 2.05mA when T_1 started, 1.96mA when T_2 began, and 1.80mA when T_3 started. Even though the change was of 0.25mA, it will be regarded as irrelevant because that fraction of amperes does not have that great of an impact on magnetic field.

Processed data

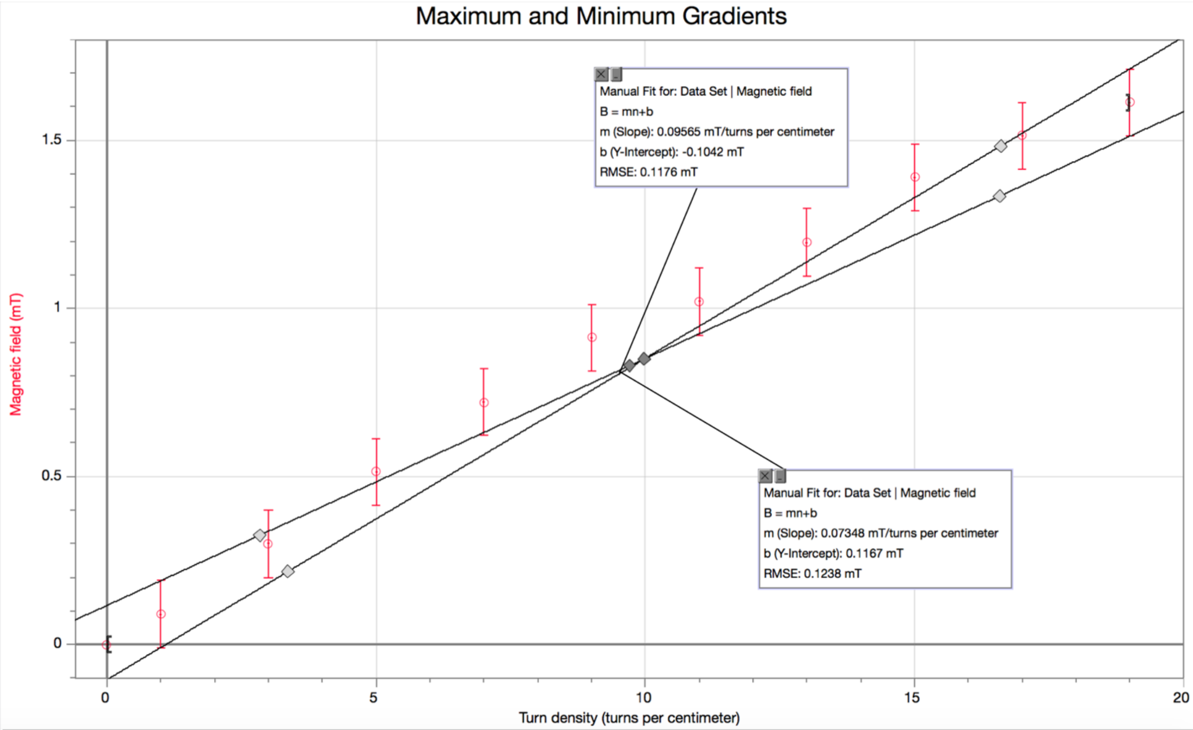
The calculated magnetic field average, T_{avg}, carries with the uncertainty that each trial had, ±0.100mT, as it was calculated with it. In this way, the data used for graphing is the turn density, n, in units of turns per centimeter, and the average magnetic field measured, T_{avg} (but expressed as magnetic field B), in units of mili-tesla.

Graphing data	
Turn density n (turns per centimeter)	Average magnetic field T_{avg}, or B_{avg}, (mT) ±0.100mT
0	0
1	0.090
3	0.300
5	0.513
7	0.721
9	0.913
11	1.021
13	1.196
15	1.390
17	1.514
19	1.613



As the graph shows, there is a linear and proportional relationship between turn density and magnetic field, with a really high correlation of 0.9960. As the gradient illustrates, this means that the magnetic field increases approximately 0.0868 mT per every turn in a centimeter.

Graphing the uncertainty to calculate it better:



From this graph, it can be seen that the maximum gradient is about 0.0957 and the minimum 0.0735. The gradient of the line of best is approximately 0.0868. Therefore:

The uncertainty above the line of best fit is $0.0957 - 0.0868 \approx +0.009$.

The uncertainty below the line of best fit is $0.0735 - 0.0868 \approx -0.013$.

The gradient and its uncertainty are thus 0.089 ± 0.011 to three significant figures.

Analysis

As the data revealed, magnetic field in a solenoid is directly proportional to turn density. This can be proved by Ampere's Law: $B = \mu nI$, where B is the magnetic field, n is the number of turns per unit length, and I (current) and μ are constants.

Conclusion

As evidenced by the data, changing the turn density of a solenoid has a direct proportional impact on its magnetic field by the section affected. The line of best fit's gradient means that, in this case, the magnetic field increases as the turn density increases by a proportionality factor of about 0.089 mT per turn of wire in a centimeter, with an uncertainty of ± 0.011 mT per turn.

Evaluation

Even though the correlation between the turn density and magnetic field in a solenoid was found to be directly proportional, there is enough uncertainty and error to consider modifying to improve the quality of the investigation. One of them is the interference of the magnetic field sensor, which allowed an uncertainty margin of a full 0.1mT. Also, the instability of the circuit caused difficulties to the data collection from the ammeter's readings, which were constantly changing. If both of these problems were observational errors rather than due to the instruments, then a solution could be to run more trials to smooth inaccuracies out, only minding a proper calibration when using instruments to avoid systematic error and more care and time being put on the measurements to avoid random error. For instance, an error with the magnetic field measurements might had been due to an improper handling of the coil and sensor, in which turns could have slightly overlapped each other when measuring their field, increasing it erroneously.

Another problem was the fast depletion of the battery, which was supposed to be of 6V but in reality was of less than 5.75V, which led to a weaker (and decreasing) electric current, which in turn led to a debilitated magnetic field.

Other inaccuracies include the negligible resistance of the ammeter in the circuit and the also negligible resistance of the solenoid, which cased a 0.06V loss in the circuit.

Improvements

One improvement to be made could be using a different magnetic field sensor, to compare and reduce interferences. If not, fixing the stability of the circuit would solve the problem, it only has to be switched. Also, to solve the easily drainable battery problem, resistors could be incorporated in the circuit, improving its stability and flow of electric current at the same time.

Another improvement could be analyzing the relationship between the battery's voltage and the circuit's electric current, which is responsible for the solenoid's magnetic field.

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