Calibration of a Hall Effect Gaussmeter and an Investigation of its Properties

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Abstract

A gaussmeter is constructed using an integrated Hall effect device in order to measure the strengths of magnetic fields. The instrument is calibrated using uniform magnetic fields generated by Helmholtz coils. The data from the calibration is analyzed to determine linearity and sensitivity with respect to the Hall voltage output. The Hall voltage is determined to be linearly proportional to the magnetic field strength in the range of 0.1 mT to 3 mT; however, nonlinearity beyond that range is found to be significant. The sources of nonlinearity are determined to be most likely either material or geometrical. Finally, the sensitivity in the instrument is found to be 5.6 V/T, which is significantly different from the manufacturer-advertised sensitivity of 13 V/T. Potential causes for the discrepancy are explained. The implications of all of the above on the effectiveness of the gaussmeter are discussed.

Introduction

The Hall Effect refers to the phenomenon whereby a potential difference develops across a current-carrying conductor in a magnetic field[1]. This fact was discovered by Edwin Hall in 1879[1]. At the time, the prevailing knowledge was that mechanical forces (as a result of magnetic fields) act on conductors as a whole, but not directly on the currents within[1]. To the contrary, Hall hypothesised that a magnetic field would cause currents to “tend towards” one side of the conductor. He observed that placing a current-carrying strip of gold leaf in a magnetic field produced a voltage difference perpendicular to both the current and the magnetic field, with a magnitude proportional to each[1].

The Hall Effect can also be understood by considering the Lorentz force on the charge carriers in a conductor[2]. This force is given by the following equation:

$$\bar{F} = q_0\bar{E} + q_0\bar{v} \times \bar{B} \tag{1}$$

where *F* is the force, *qo* is the charge, *E* is the electric field, *v* is the velocity, and *B* is the magnetic field[2]. In the presence of a magnetic field, the charge carriers in the conductor are pushed to one side, producing an electric field perpendicular to the current, up to the point at which the electric force cancels the magnetic force. The potential that remains across the conductor once the Lorentz force becomes equal to zero again is defined as the Hall voltage.

As the Hall voltage is dependent on magnetic field strength, Hall effect devices can be used to detect the presence and strength of a magnetic field. However, the Hall voltages for most conductors are generally too small to be usefully detectable[3]. For this reason, in current technologies, an integrated Hall effect device is often used. Integrated circuits allow the Hall element to be combined with other circuit elements that not only amplify the signal, but also maintain a constant current through the Hall element, and even compensate for temperature variation[3].

In addition to directly detecting magnetic fields, integrated Hall effect devices have important applications in other areas where magnetic fields are often indirect indicators of other variables of interest. They are found in many different technologies today, including computers and cars, where they are used to determine linear position, angular position, velocity, rotation and current[3].

One relatively straightforward way to use a Hall effect device in order to measure magnetic field is to build a gaussmeter. A Hall effect gaussmeter can be used to determine the magnetic field from the following equation[4,5]:

$$V_H = SB + V_0 \qquad (2)$$

where V_H is the Hall voltage, S is the sensitivity, B is the magnetic field strength, and V_0 is the initial voltage. Hall effect gaussmeters are both simple to use and cost-effective, as most commercial Hall devices cost under $2 USD[2]. Despite the low cost and simplicity of the gaussmeter, there are most likely limitations surrounding its use as a magnetic field strength detector. The purpose of this experiment is firstly to build and calibrate a Hall effect gaussmeter using an integrated Hall effect device, and secondly to determine under what conditions a Hall effect gaussmeter can effectively measure magnetic field strength.

Method

In order to perform this experiment, we built a Hall effect gaussmeter using an integrated Hall effect device[6]. The device that we used is model A1302 from Allegro Microsystems, LLC, which has a manufacturer-advertised sensitivity of 1.3 mV/G (13 V/T)[5]. It contains a linear amplifier and a CMOS A output structure, and has a temperature range of -40 to 125 degrees Celsius[5]. A 9 V battery supplied the voltage to the circuit, and a voltage regulator decreased the voltage to the Hall effect device to 5 V. The entire apparatus was contained on a circuit board; however the Hall effect device itself was remotely attached so that the magnetic fields measured would be less likely to affect the rest of the circuitry. The circuit diagram below outlines the general structure[6].

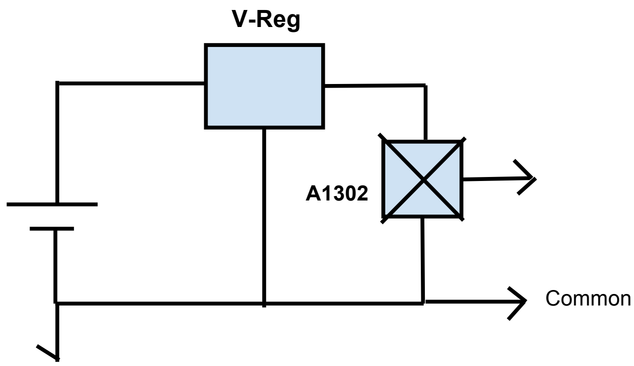

Figure 1. Diagram of Hall effect gaussmeter circuit.

In order to calibrate the gaussmeter, we built two Helmholtz coils. An ideal Helmholtz coil is formed from a pair of identical coils of wire connected in series, where the distance between them is equal to their radius. The magnetic fields from each coil then add constructively, producing a uniform magnetic field at the center of the Helmholtz coil setup[7]. The strength of the magnetic field at the center point can be calculated using the Biot-Savart law, which simplifies to the equation:

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}, \tag{3}$$

where *B* is the magnetic field strength in Tesla, μo is the permeability of free space, *n* is the number of loops, *I* is the current, and *R* is the radius of the coils[7]. The magnetic field strength produced can therefore be varied by altering the current through the Helmholtz coil. Additional notes on the theory of Helmholtz coils and their role in this experiment can be found in the Appendix.

Two sets of Helmholtz coils were built, each with twenty loops. Coil A had a thick wire gauge, and a radius of 0.0174 m. Unfortunately, the thicker gauge wire was more difficult to wrap into circular loops, which resulted in a less than ideal coil with non-uniform loop radii. However, due to the thickness of the wire, the wires generated very little heat when current was applied to them. Coil B had a thin wire gauge and a radius of 0.0153 m. The thin wires generated noticeably more heat when current was run through them; however the wire loops were much more uniform, producing a nearly ideal Helmholtz coil.

The Helmholtz coils were then each connected to a current output machine that was able to produce steady currents ranging from 0 A to 2.5 A with an accuracy of +-0.005 A. The current was increased in increments of 0.1 A from 0 A to 2.5 A using the current output machine in order to vary the magnetic field in each coil setup. The Hall effect sensor was held in place at the center point of the coils, and the voltage reading from the gaussmeter was recorded at each current increment. The uncertainty in the magnetic field strength for both coils was derived from a digital uncertainty in the current output machine as well as the uncertainty in measuring the radius of the coil. Although there was an uncertainty associated with the gaussmeter itself, it was negligible in comparison to the uncertainty associated with the magnetic field strength, as the relative uncertainty in the voltage reading was at least 1000 times smaller than the relative uncertainty in the magnetic field strength.

The data was analyzed for linearity, and models were created for the data from each coil.

Results

The voltage output from the Hall effect gaussmeter showed a linear relationship to the magnetic field strength for coil A. This was determined by a linear model, represented by the red line, for the following set of data points, in blue, which resulted in a minimized chi square of 1.008.

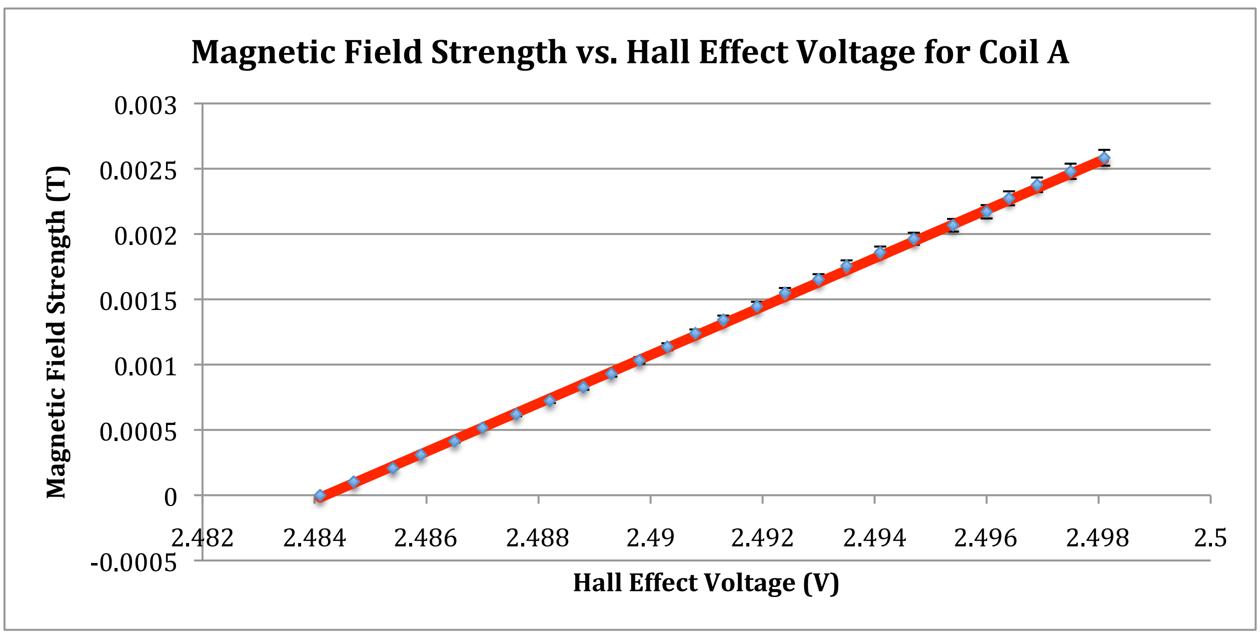

Figure 2. Magnetic field strength vs Hall effect voltage: results for coil A showing data points in blue and and linear model in red. Chi square of 1.008.

The graph of the residuals for this model showed points that were randomly scattered about the x-axis, with around ⅔ of the errors bars crossing the x-axis. A power law fit was also performed on this data; the chi square was 0.561 with a power of 1.04.

Coil B was able to produce higher magnetic field strengths due to its smaller radius. The Hall effect voltage from the gaussmeter shows a linear relationship to the magnetic field at lower field strengths. The residuals graph clearly shows the deviation that occurs at higher magnetic field strengths, as the data points start to form a linear pattern in the second half of the graph. This "hockey stick" pattern shows undoubtedly that the data points no longer conform to the original linear model.

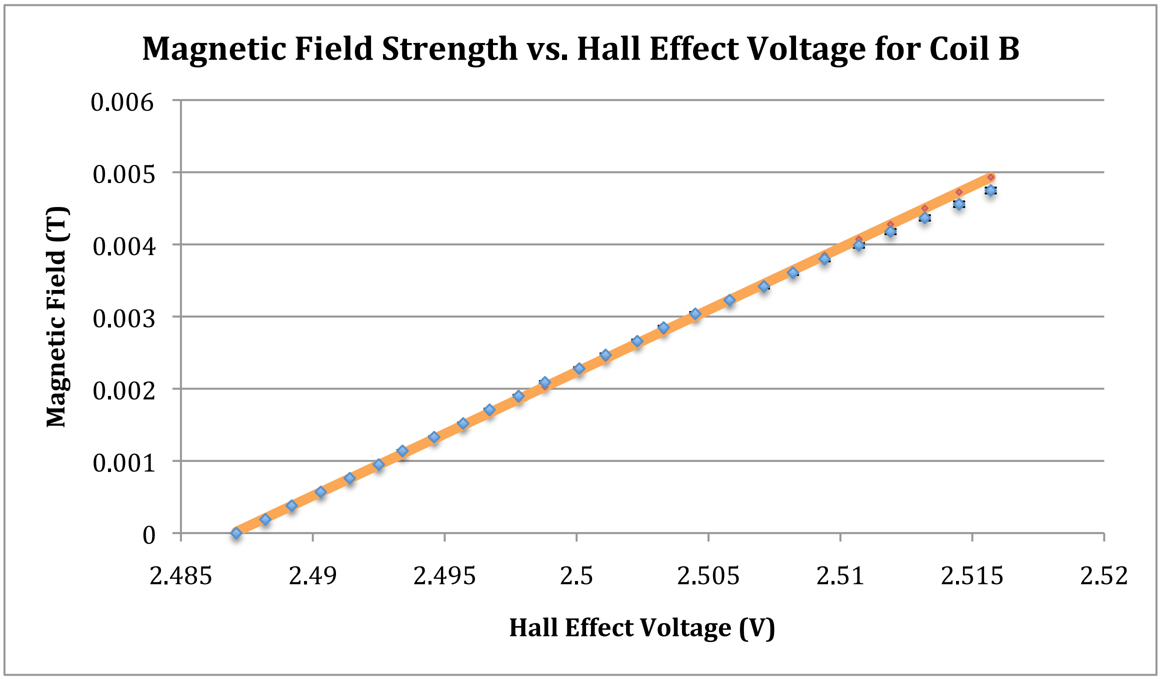

Figure 3. Magnetic field strength vs. Hall effect voltage: results for coil B, showing linear model in orange, and data points in blue. Chi square of 6.448

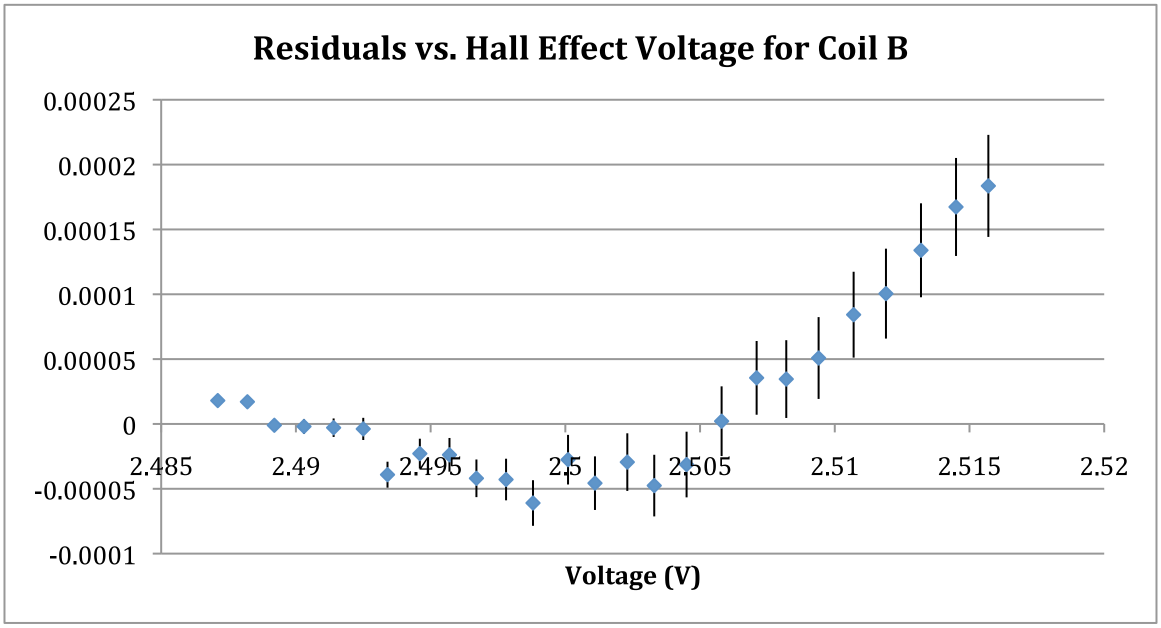

Figure 4. Residuals vs. Hall effect voltage for Coil B. Chi square for model is 6.448

A power law fit for the data from coil B was conducted and resulted in a power of 0.971 and a chi square of 3.299. Although the power law fit had a lower chi square, compared to the linear model, the "hockey stick" pattern was also evident in the graph for the residuals for the power law fit, which shows that this model likewise does not fit the data well.

Due to the deviation present in both the linear model graph and the graph of the residuals, two partial fits were conducted. The first partial fit conducted was simply to remove the data points that did not fit into the linear model, as identified by the points that make up the "hockey stick" pattern in the residuals graph. This partial fit resulted in the exclusion of 10 data points, and it provided a significantly lower chi square of 1.147, which indicates a strong linear relationship between the Hall effect voltage and the magnetic field strength for the remaining data points. A power law fit was also conducted with this partial data set and resulted in a chi square of 1.039 with a power of 0.994.

We noticed that the point where the data began to significantly deviate from the linear model for coil B was close to the high end of the range of magnetic field strength for coil A. Therefore we conducted another partial linear fit where all the data points with a magnetic field strength higher than the coil A's range were excluded. This fit resulted in 12 data points being excluded, and a chi square of 1.081. This partial fit confirmed the linear relationship from the data from coil A. The power law fit for this data set had a chi square of 1.054 with a power of 0.997.

Finally, a partial power law fit was conducted on the last 10 data points from coil B that showed deviation from the linear model. The slope of the graph was 0.90276, and the chi square was 0.0660.

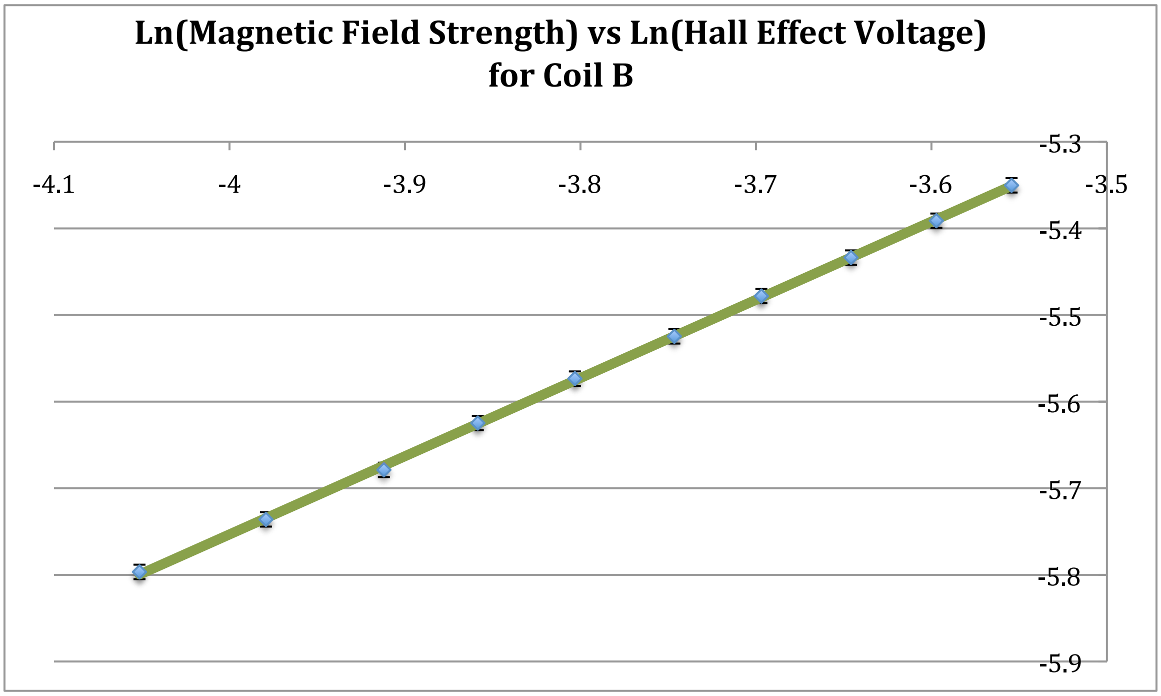

Figure 5. Partial power law fit for last 10 data points from coil B. Data points in blue, model in green. Slope of graph is 0.90276 and chi square is 0.0660.

Discussion

A. Linearity Analysis of Coil A

The Hall effect gaussmeter shows a clear linear relationship to the magnetic field strength for coil A. Indicators of an excellent fit include the fact that the chi square is 1.008, which is very close to one, as well as the fact that the residuals are randomly scattered about the x-axis, and that ⅔ of the errors bars on the residuals pass through the x-axis. The maximum magnetic field strength used was 2.584 mT, therefore we can conclude that the Hall effect voltage varies proportionally to the magnetic field strength up to that field strength. This strong agreement with the linear theory behind its operation shows the Hall effect gaussmeter to be effective at measuring magnetic field strength for small magnetic fields.

B. Linearity Analysis of Coil B

Due to the second partial fit for the data from coil B, where data points with a magnetic field strength higher than those from coil A are eliminated, we are confident that the Hall effect device output voltage is proportional to the magnetic field strength at least up to a magnetic field strength of 2.584 mT. Adding the information gathered in the first partial fit for coil B, we can conclude that the Hall Effect device remains linearly proportional to magnetic field strength provided the magnetic field strength is less than or equal to 3.038 mT.

The partial power law fits consistently have a lower chi square than the partial linear fits, however the powers are both very close to 1 (within 0.01) for both fits, suggesting a mostly linear fit. It is interesting to note that the powers in the partial fits for the power law converge to 1 as the chi square also approaches 1. Therefore one can reasonably come to the same conclusion reached from coil A's data; that is, the data being modeled is linear at lower magnetic field strengths.

Finally, the partial power law fit for the last 10 data points from coil B indicated that the data was not linear at higher magnetic field strengths. The slope of 0.9, while still close to 1, is significantly different compared to the previous power law slope values of 0.99. However, a slope of 0.9 does not seem to suggest an alternative proportionality, only a rather poor linear fit. Therefore, we can only conclude that the Hall effect device no longer maintains a clear linear relationship to magnetic field strength at values above 3 mT.

The implications of all of the above is that the relationship between Hall effect voltage and magnetic field strength becomes more nonlinear past a certain magnetic field strength. The data seems to remain loosely linear, with a power of 0.9, however this is still significantly less linear than below magnetic field strengths of approximately 3 mT.

In a paper published in 1988, Popovic and Halg outline the following theory for the nonlinearity of integrated Hall Effect devices[4]. The non-linearity for a sensor is defined to be:

$$\mathbf{NL} = (V_{\mathrm{H}} - V_{\mathrm{H0}})/V_{\mathrm{H0}}. \tag{4}$$

where NL is defined to be the nonlinearity, (V_H - V_{Ho}) is defined to be the deviation from the linear model, and V_{Ho} is the model[4]. Three types of nonlinearity are explained in the paper by Popovic and Halg: material, which is linked to properties of charge carriers; geometrical, which is due to short-circuiting within the sensor; and junction field-effect, which occurs when the plate thickness varies slightly with the Hall voltage produced[4]. The source of nonlinearity can be inferred from a plot of the nonlinearity values against the magnetic field. If the source of the nonlinearity is either material or geometric, the nonlinearity will be proportional to the square of the magnetic field strength[4]. On the other hand, if the nonlinearity is linearly proportional to the magnetic field strength, then it is likely that the source of the nonlinearity is the junction field-effect[4].

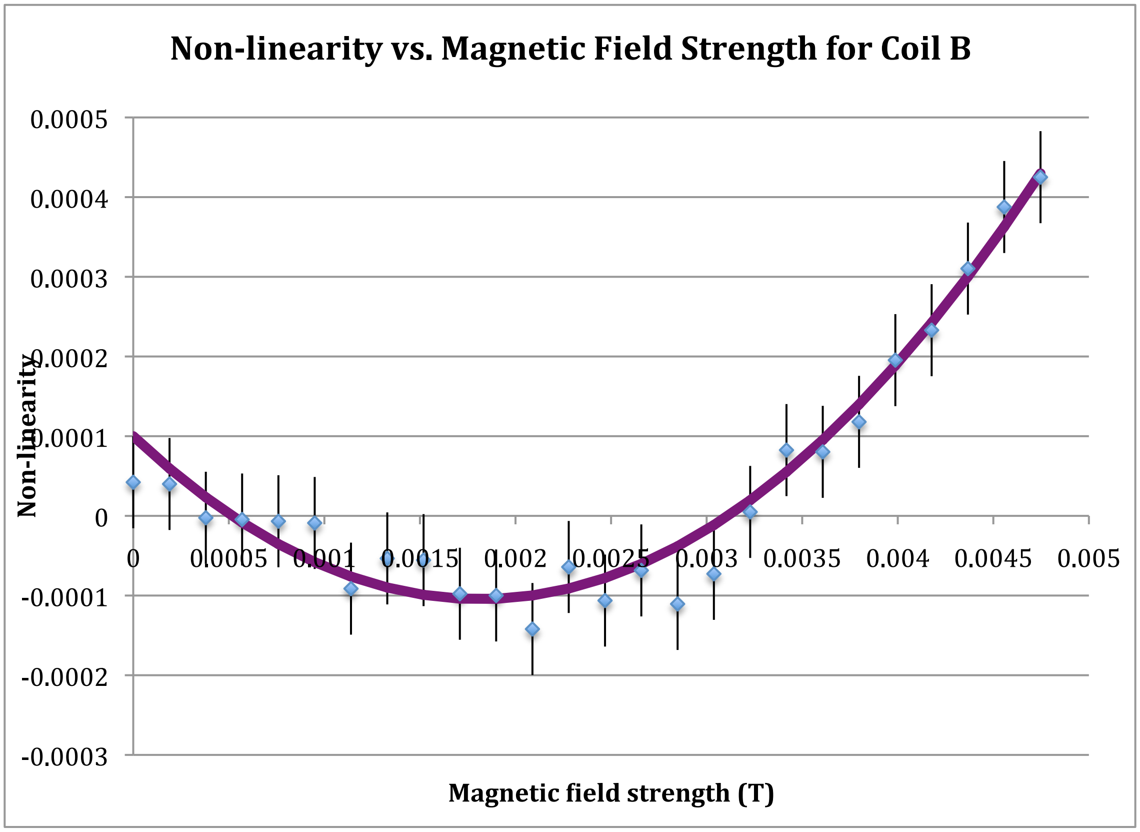

Figure 6. Graph of nonlinearity vs. magnetic field strength for coil B: data points in blue, quadratic model in purple. Chi square 0.312.

Above is a graph of the nonlinearity for the data from coil B with the quadratic model $y = 62.142x^2 - 0.2255x + 0.0001$. This model results in a chi square of 0.312. We also conducted a linear fit to the nonlinearity values, however the model was qualitatively unsuitable, and the chi square was 4.050. As a result of these chi squares, we can conclude that the dominant source of nonlinearity for our particular Hall effect device was originating from either material or geometrical effects, or a combination of the two. This seems likely as Popovic and Halg describe the junction field-effect as being most prominent in devices with a sensitivity of around 500 V/T, a value that is 100 times the sensitivity of our particular device[4].

C. Analysis of Sensitivity

The sensitivity of a commercial Hall effect sensor is normally defined as depending on the Hall voltage produced divided by current and magnetic field strength[4]. However, we define sensitivity to depend only on the Hall voltage divided by magnetic field. The term for current is unnecessary, as the current supplied to the device is made constant by the nature of the integrated circuit. This definition also allows comparison between our data and the manufacturer-advertised sensitivity, as the latter is defined in the same manner. For our analyses, we are considering the sensitivity to be equal to the slope of the best linear fit to the graph of Hall voltage vs. magnetic field strength for low magnetic field strengths.

Our experimentally determined sensitivity values are 5.4 V/T for coil A and 5.6 V/T for coil B. As the t-score for these two values is 1700, we can infer that coil A is actually producing a weaker magnetic field than predicted by the equation, which is likely due to its non-ideal design[7] (see the Appendix for more detail). The sensitivity of coil A as derived from our graph of V vs. B is therefore lower than it should be. We will then take our official experimental sensitivity value to be the value of the sensitivity obtained from the measurements done with coil B, which is 5.6 V/T.

The manufacturer-advertised sensitivity for this design of Hall effect device is 13 V/T, which is significantly different from our experimentally determined sensitivity. One possible explanation for this difference is that the particular Hall effect sensor that we used for our gaussmeter simply happened to be an outlier with respect to its sensitivity. If manufactured Hall effect devices follow a gaussian distribution with respect to sensitivity values, then our device could have had a lower sensitivity than advertised just as a result of random chance. Alternatively, prior use of the Hall effect device before data collection could have altered the sensitivity, as mechanical stress to the circuit or exposure to high magnetic field strengths can affect the sensitivity of a Hall effect device[8,9]. However this seems unlikely due to the large difference in the predicted and experimental sensitivity values. Finally, it has been shown that the sensitivity of Hall effect devices can drift over time, often due to moisture absorption[9]. Therefore, it is possible that our particular Hall effect device initially had a sensitivity closer to the manufacturer's specifications, but the sensitivity decreased over time. The device was purchased a month before the data collection took place, and it is unknown when it was actually manufactured. While this seems to explain the change in sensitivity, in order to determine if the sensitivity drift does indeed occur at significant levels in a relatively short amount of time, we would need to investigate further and perform long-term experiments where we periodically re-calibrate the device.

All three possibilities for the source of the difference in sensitivity from the manufacturer's value have the same implications for the use of the gaussmeter. When performing experiments with the Hall effect gaussmeter, a simple calibration graph using a Helmholtz coil that is as close to ideal as possible should be created in order to determine the particular device's sensitivity, as the sensitivity of the Hall effect device is not something that can necessarily be trusted from the manufacturer's specifications. The calibration need not be as involved as our experiment; since the gaussmeter is quite linear under magnetic field strengths of 3 mT, simply taking one data point close to 0.1 mT magnetic field strength and a second data point close to 3 mT should provide the sensitivity. However, due to the variation in our results, we would not recommend using a Hall effect gaussmeter without performing at least some kind of calibration in order to determine the sensitivity before using it for an experiment.

D. Analysis of Difference in Initial Voltage

The initial voltage for each data set (2.4841 for coil A and 2.4871 for coil B) was significantly different, as the t score for the two values is 37, which strongly suggests that the two values are distinct. This means that there should be some factor that caused the initial voltages to be different. The coils were set up at the same time in the same room, approximately 0.3 m apart.

There may have been an external magnetic field that varied in the two different locations, causing the observed variance. One source of this difference could be minor variations in the earth's magnetic field, which affected the initial voltage outputs, however this is unlikely due to the proximity of the coils to each other, as well as the fact that the earth's magnetic field is weaker than the sensitivity of the gaussmeter. A potential second external magnetic field source could be various magnetic influences near the set-up of the experiment such as magnetized metal in the table or nearby magnets that we were unaware of. Depending on the strength of these magnetic fields, the short distance between the coils could have caused the initial voltage to be slightly different. Finally, the initial voltage can be changed from mechanical stress[8]. It is possible that in the movement during the data collection from coil A to coil B, something in the Hall effect device was changed from slight mechanical stress. Mechanical stress can also originate from moisture absorption over the long term[9]. The implications of this are simply that before each use, a zero point for the Hall effect gaussmeter should be determined before it is used to measure the magnetic field strength.

Conclusion

The Hall effect gaussmeter can be used as an effective tool for measuring magnetic field strength. However, there are many limitations which must be imposed upon the measuring process in order to maintain accurate results. The Hall effect gaussmeter is capable of measuring fields in the range of 0.1 mT to 3 mT; otherwise the magnetic field strength is either undetectable, or the Hall effect voltage no longer maintains a linear relationship to the magnetic field strength. Additionally, before each set of data is taken, the initial voltage at zero magnetic field strength must be determined, as this value seems to change significantly. Finally, the sensitivity of the device must be ascertained by a short calibration before measurements can be taken, as the actual sensitivity might be significantly different from the manufacturer's specifications.

Overall, building and using a Hall effect gaussmeter may be straightforward and cost-effective for simple measurements in the correct range of magnetic field strength. If a larger range of magnetic field strength is required, a more sophisticated instrument would produce fewer complications in the interpretation of data.

Appendix

Our main reason for using Helmholtz coils to calibrate our gaussmeter was to maximize the uniformity of the magnetic field produced in the volume occupied by our Hall effect device. At the center of an ideal Helmholtz coil configuration, both the 1st and the 2nd derivatives of magnetic field with respect to on-axis position are equal to zero, resulting in a significantly more uniform field than in a solenoid of similar dimensions[10]. Configurations involving three or four coils are able to produce fields that are even more uniform, but we deemed these to be overly complex for the purposes of our experiment, as potential errors in construction would likely outweigh any benefit[10]. Due to the small radii of our own coil setups, which were necessary in order to generate magnetic fields of detectable strength, we had some difficulty in placing our Hall effect device exactly at the center. However, the magnetic field in the general region should have been sufficiently uniform to negate any slight deviations from the correct position.

We must also take into account the fact that both of our coils are non-ideal to differing degrees, while the equation that we relied on in order to calculate the magnetic field is a simplification for an ideal case. Therefore, our derived uncertainties in magnetic field (based on uncertainties in the current and coil radii) are likely inadequate. In order to more accurately determine the magnetic fields produced by our coils, we would need to calibrate them using DC fields, which is beyond the scope of our experiment[7]. In addition, the equation for the non-ideal magnetic field, which is significantly more complex, includes multiple variables for which we were unable to obtain data, such as the exact cross-sectional area of the wire used[7]. However, we can still infer the effect of non-ideal behaviour on our data through comparison with other researchers' experiments, as well as between coil A and coil B data. D.E. Kirtley calibrated a Helmholtz coil with similar dimensions to Coil B, and found that the differences between the actual and theoretical magnetic field were very nearly negligible for currents up to 3A, so we therefore believe it likely that Coil B essentially behaves as an ideal coil[7]. On the other hand, Coil A is noticeably non-ideal, which would probably decrease the magnetic field's strength and uniformity. In comparing our Coil A and Coil B data sets, a non-ideal design for coil A does seem to be the best explanation for the lower sensitivity value. However, as the data is still linear, and the difference in sensitivities is not particularly significant compared with the manufacturer advertised sensitivity, we do not believe that non-ideal Helmholtz coil construction at all impedes our ability to assess the effectiveness of our gaussmeter.

Acknowledgements

We came across the inspiration for this paper while perusing the internet. An article from a website titled "Magnet Man" that described the design and procedure for building a Hall effect gaussmeter caught our attention. It was this article that provided us with the initial idea for our experiment, and which guided the construction of the actual gaussmeter. Therefore we thank Rick Hoadley, a.k.a. Magnet Man.

We would also like to thank Dr. Mark van Raamsdonk for explaining the Hall Effect to us on our first encounter with Magnet Man's website.

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