The University of Scranton

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Electromagnetics Laboratory
Hall Effect

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Abstract

This experiment demonstrates the procedures, theory, and experimental background of the Hall Effect. In this experiment, the magnetic field will be mapped for the region in and around the pole pieces of an electromagnet, along the axis of symmetry of the solenoid. Several electrical parameters, including conductivity, density of charge carriers, charge carrier mobility, and the Hall Coefficient for the solenoid will also be determined.

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1 Introduction

This project will examine the usage of magnetometers and their use in the Hall Effect.

This experiment demonstrates the procedures, theory, and experimental background of the Hall Effect. In this experiment, the magnetic field will be mapped for the region in and around the pole pieces of an electromagnet, along the axis of symmetry of the solenoid. Several electrical parameters, including conductivity, density of charge carriers, charge carrier mobility, and the Hall Coefficient for the solenoid will also be determined.

1.1 Equipment

- Electromagnet
  - U-Core
  - Pair of colored pole pieces
  - 2 coils, 250 turns each
- 20 Volt/10 Ampere DC power supply
- DC power supply
- 3 digital multi-meters
- RFL Model 505 Gaussmeter
- Meter stick and Vernier Caliper
- Hall Effect Apparatus
- Large 650 turn solenoid
- Hall sensor

1.2 Hall Effect Theory and Background

The Hall effect comes about due to the nature of the current in a conductor. Current consists of the movement of many small charge carriers, typically electrons, holes, ions, or all three. Moving charges experience a force, called the Lorentz force, when a magnetic field is present that is perpendicular to their motion. When such a magnetic field is absent, the charges follow approximately straight, 'line of sight' paths between collisions with impurities, phonons, etc. However, when a perpendicular magnetic field is applied, their paths between collisions are curved so that moving charges accumulate on one face of the material. This leaves equal and opposite charges exposed on the other face, where there is a scarcity of mobile charges. The result is an asymmetric distribution of charge density across the Hall element that is perpendicular to both the 'line of sight' path and the applied magnetic field. The separation of charge establishes an electric field that opposes the migration of further charge, so a steady electrical potential builds up for as long as the charge is flowing. It shall be noted that in the classical view, there are only electrons moving in the same average direction both in the case of electron or hole conductivity. This cannot explain the opposite sign of the Hall effect observed. The difference is that electrons in the upper bound of the valence band have opposite group velocity and wave vector direction when moving, which can be effectively treated as if positively charged particles (holes) moved in opposite direction than the electrons do.

For a simple metal where there is only one type of charge carrier (electrons) the Hall voltage V_H is given by:

$$V_H = \frac{-IB}{ned} \tag{1}$$

where I is the current across the plate length, B is the magnetic flux density, d is the depth of the plate, e is the electron charge, and n is the charge carrier density of the carrier electrons.

The Hall coefficient is defined as:

$$R_H = \frac{E_y}{j_x B} \tag{2}$$

where j is the current density of the carrier electrons, and E_y is the induced electric field. In SI units, this becomes

$$R_H = \frac{E_y}{j_x B} = \frac{dV_H}{IB} = \frac{-1}{ne} \tag{3}$$

As a result, the Hall effect is very useful as a means to measure either the carrier density or the magnetic field. Figure 1 shows the Hall Effect in a simplified manner.

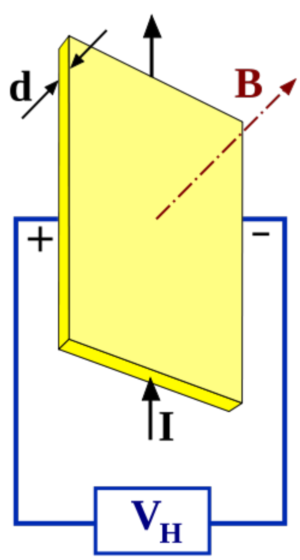

Figure 1: Schematic diagram of the Hall Effect

One very important feature of the Hall effect is that it differentiates between positive charges moving in one direction and negative charges moving in the opposite. The Hall effect offered the first real proof that electric currents in metals are carried by moving electrons, not by protons. The Hall effect also showed that in some substances (especially p-type semiconductors), it is more appropriate to think of the current as positive "holes" moving rather than negative electrons. A common source of confusion with the Hall Effect is that holes moving to the left are really electrons moving to the right, so one expects the same sign of the Hall coefficient for both electrons and holes. This confusion, however, can only be resolved by modern quantum mechanical theory of transport in solids.

It must be noted though that the sample inhomogeneity might result in spurious sign of the Hall effect, even in ideal van der Pauw configuration of electrodes. For example, positive Hall effect was observed in evidently n-type semiconductors.

Simplistically, the Hall Effect operates by an inducted current across a piece of metal in a magnetic field.

2 Procedure

The electromagnet was assembled to have a strong homogeneous field by placing the flat ends of the pole pieces facing one another. A variable DC voltage source was connected to the apparatus using the wall-mounted variable voltage controller. This large wall mounted unit was chosen because it could provide currents up to and surpassing 20 amps.

Next, the gaussmeter was calibrated following the manufacturers detailed instructions. In summary, the gauss probe was calibrated to the magnetic charge of free space within the room, to take into account the electromagnetic interference from several other experiments that were occurring several feet away. EMF interference from these experiments, particularly an antenna and waveguide experiment could possibly skew data, so it is important that the meter be calibrated to the average background noise. Next the gaussmeter was placed in between the magnetic poles and the experiment was ready to begin.

First, the magnetic field as a function of magnet current over the range of 0-10 Amps was recorded. 3 distinct trials were run, at decreasing lengths of air gap between the magnetic poles.

Hall Voltage V_H was measured as a function of transverse current I, with constant magnetic field strength.

3 Discussion and Apparati Calculations

The following calculations were performed based upon the specifications of the equipment:

3.1 Electromagnet

Based upon usage trial with the electromagnet, the maximum admissible constant current is 5 Amps. However, the magnet can be loaded for brief periods of time to nearly 4 times this value. When the electromagnet is loaded to 20 Amps, the current could only be open for several seconds at a time before the apparatus must be shut down and cooled, as the temperature of the apparatus approaches 125°C.

3.2 Leybold Hall Effect Apparatus

The measured length of the piece of silver in the Leybold apparatus was 0.0646 m $\times$ 0.02 m ($l \times w$). The band thickness was described in the apparatus literature to be 5×10^{-5}m, but was calculated to be 0.7mm. Possible reasons for this inconsistency may arise from improper storage of the apparatus, or the purchase of an incompatible model.

The transverse current (I_{max}) was calculated to be 22 Amps, using the information given in the lab manual.

3.3 Solenoid Coil

Referencing the literature from the solenoid manufacturer, the resistance of the large solenoid coil was found to be 3Ω.

4 Data

The following data was collected:

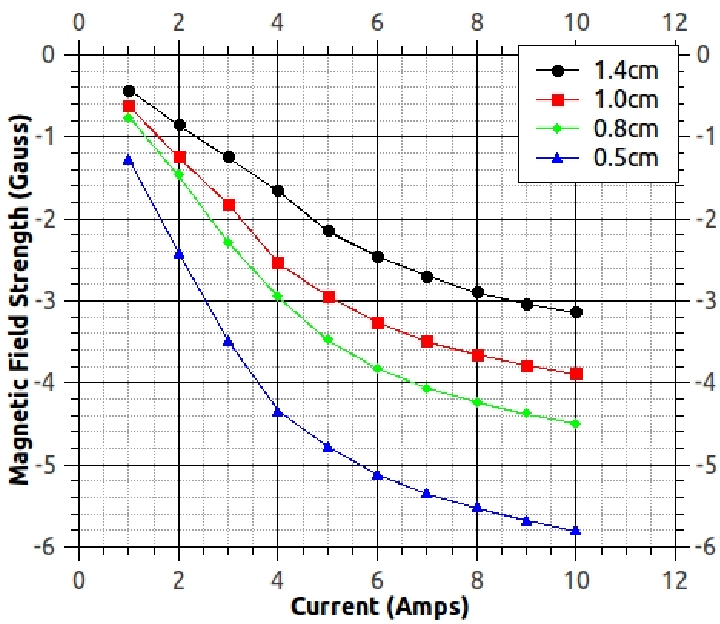

Figure 2: Magnetic Field and Distance Calibration Curve

I_{coil} Amps $\rightarrow$	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Separation of 1.4cm	-0.426	-0.847	-1.244	-1.655	-2.14	-2.45	-2.70	-2.89	-3.03	-3.14
Separation of 1.0cm	-0.621	-1.245	-1.813	-2.54	-2.94	-3.26	-3.49	-3.65	-3.78	-3.89
Separation of 0.8cm	-0.764	-1.463	-2.28	-2.95	-3.47	-3.82	-4.06	-4.23	-4.37	-4.50
Separation of 0.5cm	-1.20	-2.52	-3.41	-4.06	-4.52	-4.79	-5.08	-5.18	-5.31	-5.43

Table 1: Observed Gauss Values (in kG) for Hall Effect Calibration Curve

I_{coil}	10	12	14	16	18	20
ΔV	6.4	6.9	7.1	8.3	8.0	7.9

Table 2: Observed Values for Hall Voltage with Δ_gI=10A, V_{out}=2.4V

I_{coil}	10	12	14	16	18	20
ΔV	10.2	10.7	11.3	11.6	12.0	12.1

Table 3: Observed Values for Hall Voltage with Δ_gI=15A, V_{out}=1.33V

I_{coil}	10	12	14	16	18	20
ΔV	22.3	23.9	24.8	26.4	27.1	26.5

Table 4: Observed Values for Hall Voltage with Δ_gI=20A, V_{out}=1.13V

5 Contemporary Applications of the Hall Effect

Hall effect sensors are readily available from a number of different manufacturers, and may be used in various sensors such as rotating speed sensors (bicycle wheels, gear-teeth, automotive speedometers, electronic ignition systems), fluid flow sensors, current sensors, and pressure sensors. Common applications are often found where a robust and contactless switch or potentiometer is required. These include: electric airsoft guns, triggers of electro-pneumatic paintball guns, go-cart speed controls, smart phones, and some global positioning systems.

The Motorola Droid, Droid 2, and the HTC Incredible cell phones have a built-in Hall Effect sensor to detect when the phone is placed in a charging dock. This allows the cell phone to launch actions based upon the inducted Hall Voltage. For example, the Droid would launch a desk clock style application when placed in a desk dock, and launch a navigation application when placed in a car mounted dock, due to the differing voltages associated with the docks. The output to the phone system is proportional to both the applied magnetic field and the applied sensor voltage. If the magnetic field is applied by a solenoid, the sensor output is proportional to the product of the current through the solenoid and the sensor voltage. As most applications requiring computation are now performed by small but powerful digital processors instead of large inductors, the remaining useful application is in power sensing, which combines current sensing with voltage sensing in a single Hall effect device.

By sensing the current provided to a load and using the device's applied voltage as a sensor voltage it is possible to determine the power dissipated by a device.

Hall sensors can detect stray magnetic fields easily, including that of Earth, so they work well as electronic compasses: but this also means that such stray fields can hinder accurate measurements of small magnetic fields. To solve this problem, Hall sensors are often integrated with magnetic shielding of some kind. For example, a Hall sensor integrated into a ferrite ring can reduce the detection of stray fields by a factor of 100 or better (as the external magnetic fields cancel across the ring, giving no residual magnetic flux). This configuration also provides an improvement in signal-to-noise ratio and drift effects of over 20 times that of a bare Hall device. The range of a given feedthrough sensor may be extended upward and downward by appropriate wiring. To extend the range to lower currents, multiple turns of the current-carrying wire may be made through the opening. To extend the range to higher currents, a current divider may be used. The divider splits the current across two wires of differing widths and the thinner wire, carrying a smaller proportion of the total current, passes through the sensor.

The principle of increasing the number of windings a conductor takes around the ferrite core is well understood, each turn having the effect of multiplying the current under measurement. Often these additional turns are carried out by a staple on a PCB.

A variation on the ring sensor uses a split sensor which is clamped onto the line enabling the device to be used in temporary test equipment. If used in a permanent installation, a split sensor allows the electric current to be tested without dismantling the existing circuit.

Hall effect devices used in motion sensing and motion limit switches can offer enhanced reliability in extreme environments. As there are no moving parts involved within the sensor or magnet, typical life expectancy is improved compared to traditional electromechanical switches. Additionally, the sensor and magnet may be encapsulated in an appropriate protective material.

Commonly used in distributors for ignition timing, the Hall Effect sensor is used as a direct replacement for the mechanical breaker points used in earlier automotive applications. Its use as an ignition timing device in various distributor types is as follows. A stationary permanent magnet and semiconductor Hall effect chip are mounted next to each other separated by an air gap, forming the Hall effect sensor. A metal rotor consisting of windows and tabs is mounted to a shaft and arranged so that during shaft rotation, the windows and tabs pass through the air gap between the permanent magnet and semiconductor Hall chip. This effectively shields and exposes the Hall chip to the permanent magnet's field respective to whether a tab or window is passing though the Hall sensor. For ignition timing purposes, the metal rotor will have a number of equal-sized tabs and windows matching the number of engine cylinders. This produces a uniform square wave output since the on/off (shielding and exposure) time is equal. This signal is used by the engine computer or ECU to control ignition timing. Many automotive Hall effect sensors have a built-in internal NPN transistor with an open collector and grounded emitter, meaning that rather than a voltage being produced at the Hall sensor signal output wire, the transistor is turned on providing a circuit to ground though the signal output wire.

The sensing of wheel rotation is especially useful in anti-lock brake systems. The principles of such systems have been extended and refined to offer more than anti-skid functions, now providing extended vehicle handling enhancements.

Some types of brushless DC electric motors use Hall effect sensors to detect the position of the rotor and feed that information to the motor controller. This allows for more precise motor control in environments that do not allow the possibility of sparking circuits.

Applications for Hall Effect sensing have also expanded to industrial applications, which now use Hall Effect Joysticks to control hydraulic valves, replacing the traditional mechanical levers. Such applications include; Mining Trucks, Backhoe Loaders, Cranes, Diggers, Scissor Lifts, etc.

A Hall effect thruster (HET) is a relatively low power device that is used to propel some spacecraft, once they get into orbit or farther out into space. In the HET, atoms are ionized and accelerated by an electric field. A radial magnetic field established by magnets on the thruster is used to trap electrons which then orbit and create an electric field due to the Hall effect. large potential is established between the end of the thruster where neutral propellant is fed and the part where electrons are produced, so electrons trapped in the magnetic field cannot fall down the potential, and thus are extremely energetic allowing them to ionize neutral atoms. Neutral propellant is pumped into the chamber and is ionized by the trapped electrons. Then positive ions and electrons are ejected from the thruster as a quasineutral plasma, creating thrust.

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