B5b: Magnetic Force & Fields

Introduction:

It is impossible to picture our modern life without a number of household appliances: microwaves, refrigerators, air conditioners, etc. You might be surprised to find out that in the heart of operation of most of them lies physics phenomena associated with the magnetic fields and the magnetic forces. Magnetic fields and magnetic forces play an important role in the operation of electro generators and transformers, without which production of electricity and a large scale power grid would not be possible, eliminating many modern conveniences. They are also at the basis operation for MRI machines - instruments that drastically changed medical diagnostics.

Magnetic phenomena are numerous and complex, but all of them have the same fundamental nature: interaction between moving charged particles. In this experiment, you will explore one of the basic interactions: magnetic force acting on a current carrying wire due to the magnetic field of a permanent magnet. The focus will be on exploring the magnetic field surrounding a permanent magnet. A single wire loop is positioned in the gap between two plates that are a part of an external permanent magnet. As current is applied to the wire the net force on the wire will move it from its original zero position. As the current through the wire is changed the wire's displacement correspondingly changes. By keeping track of these displacements, along with some additional measurements, it becomes possible to calculate the magnitude of the magnetic field for the permanent magnet.

To construct a more detailed picture of the magnetic field than just its magnitude, it is necessary to utilize a magnetic field sensor, which provides both field strength and field direction when placed near a magnetic source. By sampling both field strength and direction for multiple regions around the magnet a more complete 3 dimensional representation of the magnetic field can be developed. Also the magnetic field measure in the region between the plates can be compared to the field calculated during Part I.

Apparatus:

- variable gap magnet
- power supply (10 amp)
- magnetic field sensor (with computer)
- digital multimeter (contained within power supply)
- wire loop with non-conducting mount
- support stands
- hook-up wire

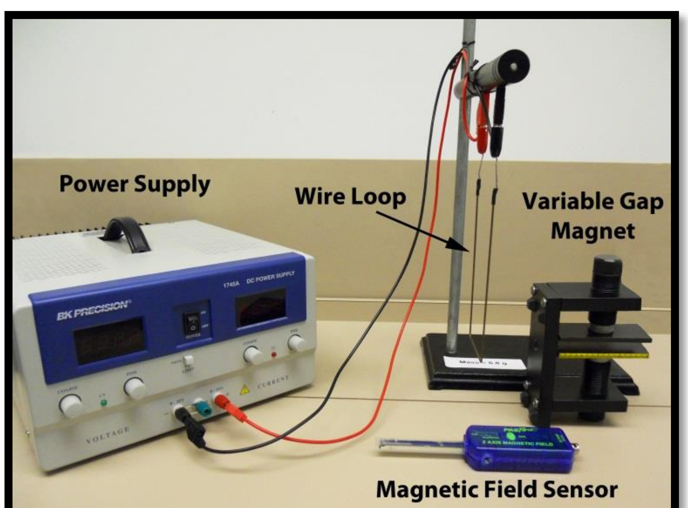


Figure 1

Discussion:

For a complete discussion of the relationship between an electromagnet wire being displaced by a magnetic field, the current running through that wire, and the displacing magnetic field, it will be necessary to consult a physics textbook.

Please read/review the following section **"Magnetic Force on a Current Carrying Wire"**

This section can be found in either: Cutnell & Johnson. **Physics**, *Chapter* **21** *section* **5**

or

James Walker. **Physics**, *Chapter* **22** *section* **4**

Both textbooks provide an equation for the magnetic force acting on an electromagnetic wire in the presence of magnets, obtained by drawing on the concept that any charge moving through a magnetic field experiences a magnetic force. Since that charge cannot leave the wire, the wire itself must ultimately be displaced by an angle θ from its stationary position. This equation, a consequence of the Lorentz Force Law, is as follows:

$$F = ilB_{ext}\sin\varphi$$

Where i is the current passing thru the wire, l is the length of the wire that passes thru the variable gap magnet, B_{ext} represents the magnetic field of the variable gap magnet, and φ is the angle between the current and the magnetic field of the variable gap magnet. For this experiment, the magnetic field and the current will always be perpendicular, with $\varphi = 90°$, resulting in the following equation:

$$F = ilB_{ext}$$

Unfortunately, for this experiment, it is impossible to simply utilize the Lorentz Force Law directly to calculate the variable gap magnets' combined magnetic field. This impossibility results because it is not possible to measure the magnetic force being experienced by the electromagnetic wire directly.

However, by applying Newton's 1st Law to the system of this experiment, it does become possible to find an experimentally viable equation for B_{ext}. Newton's 1st law states that an object at rest tends to remain at rest. From this statement, one may infer that the sum of forces acting upon an object that is at rest will be zero; the forces must cancel each other out.

This definition, when applied to an rigid object that can rotate about a single point (such as the electromagnetic wire being used in this experiment), can be stated similarly for the torques acting on the rotating object. Please recall that torque, $\vec{\tau}$, can also be represented as the cross product of the lever arm, $\vec{R}$, and the force causing the torque, $\vec{F}$:

$$\vec{\tau} = \vec{R} \times \vec{F}$$

Converting this cross product notation from vector to scalar notation, it can be seen that the magnitude of the torque is given by:

$$\tau = RF\sin\theta$$

Where the angle θ is the displacement experienced by the rigid body undergoing rotation, and τ, R, and F are defined as the respective magnitudes of the terms from the previous equation.

From the ideas of torques acting on a rigid rotating body, it becomes possible to state Newton's first law in terms of the torques acting on a rigid, rotating body[i]:

$$\sum \tau = \sum (RF \sin \theta) = 0$$

Before considering the sum total of all the torques acting collectively, things may be simplified by defining the torques individually. To this avail, please consider the 3 dimensional and 2 dimensional Force Diagrams of the experiment offered in **Figure 2** and **Figure 3**. From **Figure 3** it becomes clear that there are only 3 forces acting on the electromagnetic wire in this experiment: the weight of the wire, $\vec{W}$, the magnetic force introduced at the beginning of this handout, $\vec{F}_m$, and the tension, $\vec{T}$, that exists between the rigid wire and its pivot point.

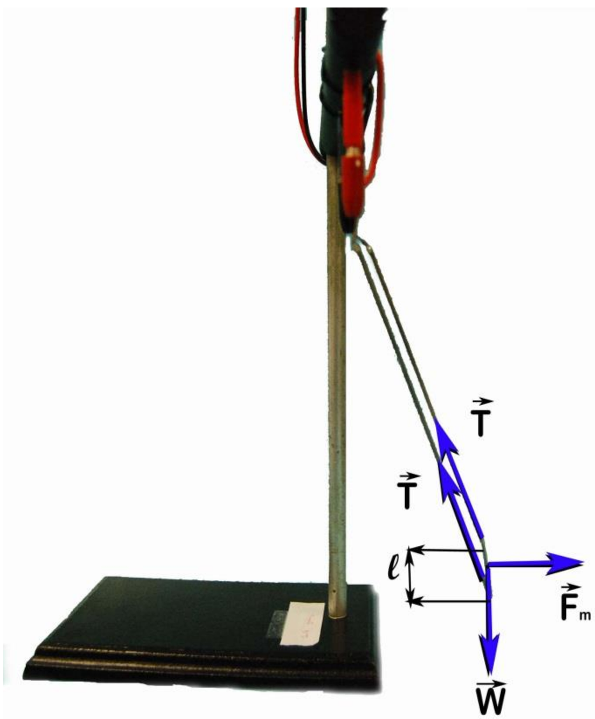


Figure 2

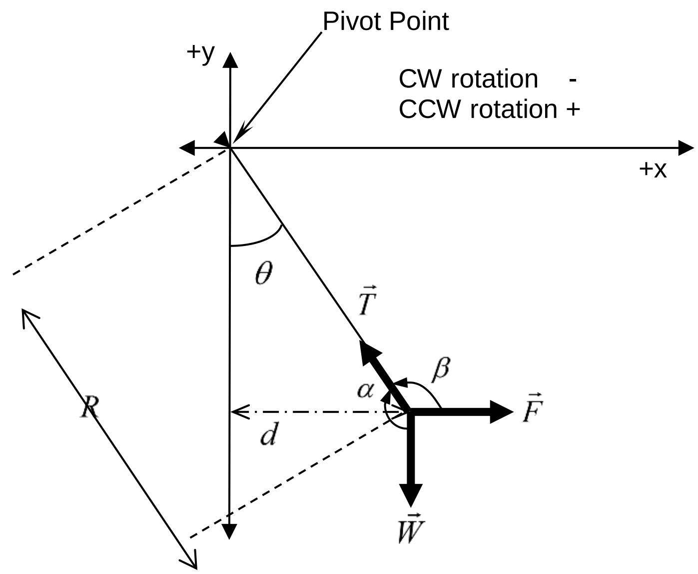


Figure 3

First consider the torque due to the weight of the wire, $\vec{W}$, which, from the formula for the magnitude of torque given above, is given by:

$$\tau_{\vec{W}} = -Rmg \sin \alpha$$

Where R is the radius of the wire, m is the mass of the wire, g is the accepted value for gravity (9.792m/sec^2), and α is the angle between the force, $\vec{W}$, and the wire itself. More will be discussed regarding α shortly. The negative sign is present because the angle is enacted in a clockwise direction.

The next torque to consider would be the torque due to the magnetic force, $\vec{F}_m$, experienced by the wire:

$$\tau_{\vec{F}_m} = RilB_{ext} \sin \beta$$

Where R is the radius of the wire, i is the current flowing thru the wire, l is the length of the wire passing thru the variable gap magnet, B_{ext} is the magnetic field of the variable gap magnets, and β is the angle between the force, $\vec{F}_m$, and the wire itself (which is positive since the β is enacted in a counterclockwise direction).

The final force that might create any torque, as evinced in the force diagram of **Figure 3**, is the tension of the wire's connection to the pivot point. Since the tension is actually being enacted the full length of the wire, and culminates at the pivot point itself, the angle between the $\vec{T}$ and the wire is $180°$, giving the following equation and eliminating any torque due to tension:

$$\tau_{\vec{T}} = T\sin(180) = 0$$

Thus, referring back to Newton's first law in terms of torque, the equation can be given as:

$$\sum \tau = \tau_{\vec{F}_m} + \tau_{\vec{W}} = RilB_{ext}\sin\beta - Rmg\sin\alpha = 0$$

It isn't feasible, though, to directly measure or directly approximate either of the angles α or β. To account for this requires that several different trigonometric identities and geometric proofs regarding the congruency of angles formed by parallel and perpendicular lines be used in order to determine things in terms of θ, the angle the wire magnet is displaced from its rest position, an angle that can be easily determined through physical measurements.

$$\sin\alpha = \sin\theta$$

$$\sin\beta = \sin(90+\theta) = \cos\theta$$

$$\tan\theta = \frac{\sin\theta}{\cos\theta}$$

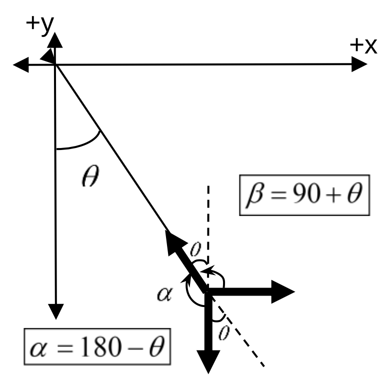


Figure 4

In light of these first two trigonometric identities, the sum of the torques may be expressed as:

$$\sum \tau = RilB_{ext}\cos\theta - Rmg\sin\theta = 0$$

Beginning to solve the previous equation for the unknown value, B_{ext}, gives:

$$ilB_{ext}\cos\theta = mg\sin\theta$$

Using the final trigonometric identity then gives:

$$ilB_{ext} = mg\tan\theta$$

And, if one also takes into account that the angle that the wire will be displaced is very small, and that for small angles the following is true:

$$\tan\theta \approx \sin\theta$$

Then the equation becomes:

$$B_{ext} = \frac{mg}{il}\sin\theta$$

If one then further considers the 2 dimensional representation of the experiment presented in **Figure 3**, then it should become clear that:

$$\sin\theta = \frac{d}{R}$$

The resulting expression from the sum of the torques and Lorentz Force Law thus becomes:

$$\boxed{B_{ext} = \frac{mg}{lR}\left(\frac{d}{i}\right)}$$

The above equation will be used to calculate the magnetic field being produced between the two plates of the magnets used in **Part I** of the experiment. That magnetic field will then be checked against the magnetic field directly measured in **Part II** of the lab.

Procedures:

This lab consists of two sub-experiments, both of which are designed to measure the magnetic field produced between two magnetic plates, albeit through differing methods. In **Part I**, the magnetic field will be measured via indirect means, by determining the displacement of the wire due to the magnetic force (as highlighted in the **Discussion** section). For **Part II**, the magnetic field will be measured for all of the areas surrounding the permanent magnetic, by using a magnetic field sensor and computer data collection software. Please see a lab instructor before beginning **Part I**.

PART I

1. First, adjust the gap between the magnetic plates, if necessary, so that there is a one centimeter gap between them.
2. Next, measure the length of the wire that will actually be in the magnetic field of the magnet, length (l) (see **Figure 2**).
3. Measure the radius (R) of the wire loop from the bottom of the plastic holder (see **Figure 2**).
4. Determine the effective mass of the wire (m). **DO NOT REMOVE THE WIRE FROM ITS NON-CONDUCTING MOUNT.** ***Please see a lab instructor if there are any issues with finding the mass.***
5. Position the wire loop, centered on one of the dash marks according to the scale provided on the magnets, in between the magnetic plates. This is your zero position and should be in the middle of the scale.
6. Confirm that the power supply is connected to the wire. Confirm the current knob and voltage knob are set to the minimum, and then turn the power supply on. Once the power supply has been turned on, **PLEASE DO NOT TOUCH THE WIRE**. Adjust the voltage knob so that it is about a fourth of the way towards maximum.
7. Slowly adjust the current on the power supply until the wire loop has a displacement of ***5 mm*** from its zero position & record the current.
8. Do five measurements, each time recording the current needed to create displacements of an additional ***5 mm***. (The distance between each of the larger dash marks is ***5mm.***)
9. After completing 5 trials, zero out the current, turn the power supply off, and then reverse the positive and negative connections of the wire to the power supply.
10. Turn the power supply back on and do another five measurements, each time recording the current for the negative displacements using ***5 mm*** increments in the opposite direction as the first set of five measurements.(*As an aside, consider that the current is being displaced in the negative direction, and that the current itself is negative, since the polarity of the connections has been reversed*).
11. Once all the data has been collected for the first set of ten measurements, zero the current, turn the power supply off, and disconnect the wire from the power supply. Allow the wire to re-stabilize for 5 minutes before reconnecting and beginning the next trial. While waiting for the wire to dissipate any heat, it is recommended that calculations be begun to find the magnetic field for this first set of trails.
12. Repeat steps 5 thru 10 for the second set of ten measurements.
13. Calculate the magnetic field for each data point. Calculate the mean and standard deviation for the magnetic field for each trial.

PART II

1. Measure the magnetic field using the computer magnetic field sensor. ***Please see the lab instructor for details about the computer magnetic field sensor.***
2. Using the magnetic field sensor's data construct a picture of the magnetic field around the magnet.

Experiment B5b: Magnetic Force & Fields

Student Name____

*Lab Partner Name*____

*Lab Partner Name*____

Physics Course____

Physics Professor____

Experiment Start Date__________________________________

Lab Assistant Name	*Date*	*Time In*	*Time Out*

Experiment Stamped Completed

Data Sheets: B5b: Magnetic Force & Fields

NAME: ____________________ DATE: __________________

length =________________ *Radius* =_______________ *mass* =_________________

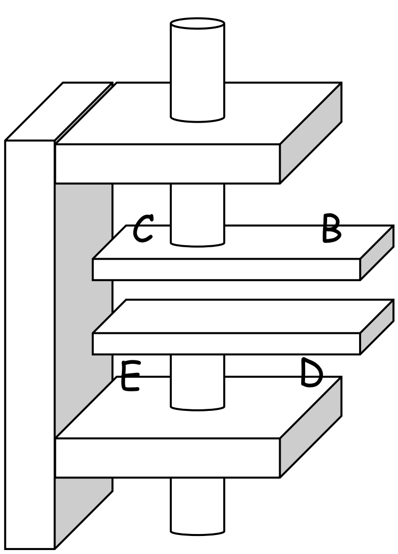
d displacement (mm)	trial 1		trial 2	
	i current (A)	*B* Magnetic Field (T)	*i* current (A)	*B* Magnetic Field (T)
5				
10				
15				
20				
25				
-5				
-10				
-15				
-20				
-25				
	Mean______________ Std. Dev.___________		Mean______________ Std. Dev.___________	

Data Sheets: B5b: Magnetic Force & Fields

NAME: ____________________ DATE: __________________

		magnitude (T)	direction (Front View)
between plates	A		
above plates outside	B		
above plates inside	C		
below plates outside	D		
below plates inside	E		
2 cm. right of plates	F		
2 cm. left of plates	G		

Side View



Front View