In this experiment a simple current balance will be used to measure the force on a current-carrying wire in a magnetic field. The magnetic field is produced by a solenoid, and from the magnitude of the force on the wire the number of turns in the solenoid will be calculated.

**Equipment**

- 5 A Power Supply,
- Helmholtz Coils
- 500 mA Power Supply,
- 5A Current shunt,
- 2 Digital Multimeters
- Electronic weight scale,
- 100-turn triangular coil with balance arm.

**Method**

The torque balance is shown schematically in Figure 1. The balance arm is a thin rectangular insulator upon which a 100-turn triangular coil is mounted. The coil is balanced by a weight resting on the pan of electronic scale. A small counterweight (a short piece of wire) is hung from the hook near the small coil to provide a gravitational torque \( \tau_g \), about an axis through the attachment point of the main weight, and will be counter-balanced by the magnetic torque \( \tau_m \) produced when current flows in the 100-turn coil in the presence of the horizontal magnetic field near the center of the Helmholtz coils.

The torque on a coil of \( N \) windings, of area \( A \) and carrying a current \( I \), mounted in a magnetic field \( B \) (assumed constant over the coil's area) is given by:
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\[ \tau_m = \mu \times \mathbf{B} = NI A \times \mathbf{B}, \]

where \( \mu \) is the total magnetic moment of the coil.

A pair of Helmholtz coils produces the magnetic field \( \mathbf{B} \). The distance between the Helmholtz coils is approximately equal to the radius \( R \) of the coils, and the \( \mathbf{B} \) field near the center is very uniform with magnitude given by:

\[ B = 8\mu_0 N_H I_H / (5^{3/2} R), \]

where \( N_H \) is the total number of windings in a single Helmholtz coil, \( I_H \) the current through the coils, and \( \mu_0 \) the magnetic permeability of the vacuum.

\( \mathbf{B} \) is adjusted by varying \( I_H \) (in magnitude and flow direction!) until the magnetic torque precisely counterbalances the gravitational torque from the piece of wire used as weight, as indicated by the electronic scale.

Q1. In what direction does the gravitational torque point? Use the right-hand rule in the vector product \( \tau_g = \mathbf{L} \times \mathbf{F}_g \). In what direction must the magnetic torque point in order to compensate the gravitational torque?

Procedure

Adjust the balance so that it is precisely horizontal and positioned such that the small coil is precisely at the center of the Helmholtz coils where the field will be most uniform. Turn on the electronic scale (hold down the "ON" button until the display lights up) The scale should "zero" itself automatically at start-up. Make sure the scale units are grams ("g" on the display); if not, click the left button momentarily until "g" is displayed (if you hold this button down longer, the scale will turn off). Observe the zero reading for a few minutes: you may see small fluctuation due to air currents, table vibrations, etc.. Therefore, keep these fluctuations small by moving slowly and carefully during the measurements.

Measure the radius of the Helmholtz coils and register the number of windings for later use in calculating \( \mathbf{B} \). Also, measure the dimensions of the small coil to determine the coil's area and magnetic moment.

The scale is used to measure torque applied by forces acting on the far side of the balance arm. To calibrate the scale for torques, first measure a standard gram mass on the scale, which should thus read exactly 1.00 g. Then, hang the 1-g weight off the hook near the small coil and record the scale's reading: it should read about 7-8 g, reflecting the effect of the lever arm ratio. Measure and record the total length of the lever arm; this information can now be used to convert scale readings in grams to torques by masses hung from the hook.

Q2. What is the numerical value in SI units of the gravitational torque produced by the 1-g mass hung from the hook? What is the corresponding scale reading?

Now, turn on the small power supply and adjust the current in the small 100-turn coil to precisely 500 mA, as read by the digital ammeter. This may cause the scale to read a value different from zero; if so, re-zero the electronic scale.
Q3. What could be the cause of a non-zero scale reading when the small coil is powered up?

You have been provided with several lengths of thin wire to use as weights on the small hook. Hang one of these on the hook and record the scale reading to measure the gravitational torque from this piece of wire.

Now, with the small wire still in place, turn on the large power supply of the Helmholtz coils. This will create a magnetic torque on the small coil. Turn up the current until the magnetic torque exactly balances the gravitational torque; i.e. until the scale reads zero. Note, that you may have to reverse the current in the Helmholtz coils by exchanging the leads! Repeat the full procedure a few times to be sure that the scale’s zero and the small coil’s current have remained constant.

Repeat the above with the four other pieces of wire as weights.

Q4. Plot the magnetic torque $\tau_m$ determined from your data using equations 1 and 2, as a function of the gravitational torque $\tau_g$. Be sure to show appropriate error bars for each point.

Q5. Discuss the significance of your plot. What does it prove?