[APP03] Magnetic field measurement with a smartphone

1.Objectives：

To measure the magnetic field of earth and at the center of the coil carrying electric current I with a smartphone.

2. Introduction：

The first documented observation of electric-current-induced magnetic field is made by a physicist in Copenhagen, Demark, in 1820: Hans Christian Oersted found that when a compass needle is placed near a wire, the needle deflects as soon as the two ends of the wire are connected to the terminals of a battery and the wire carries an electric current. Later Biot and Savart introduced a formula from experimental phenomena to find the strength of a magnetic field at any arbitrary position around a current-carrying wire. First, a current I flowing in any path can be considered as many infinitesimal current elements of Idl. The moving charges on each infinitesimal current segment will generate an infinitesimal magnetic field in space. The magnetic field at an arbitrary point in space should be a vector summation of all the infinitesimal magnetic fields. Figure 1 shows one infinitesimal magnetic field dB produced at point P from the position of dl. The small magnetic field dB is perpendicular to both dl and r, and r is a displacement vector from the position of dl to point P. Therefore, the Biot-Savart Law can be expressed as:

$$dB = \frac{\mu_0}{4\pi}\frac{Id\boldsymbol{l}\times\boldsymbol{r}}{r^3} \tag{1}$$

The multiplication sign in the above equation means “cross product”. Using SI unit system μ_0 = $4\pi\times10^{-7}(T\cdot m/A)$ Again, the displacement vector r is from the position of dl to point P. The summarized magnetic field B is then obtained by integral over the path in question carrying an electric current, I. That is

$$\boldsymbol{B} = \frac{\mu_0}{4\pi}\int\frac{Id\boldsymbol{l}\times\boldsymbol{r}}{r^3} \tag{2}$$

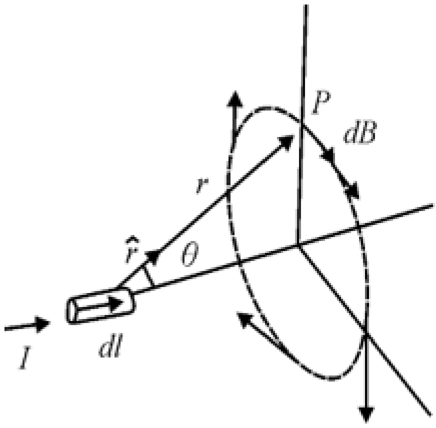


Figure 1

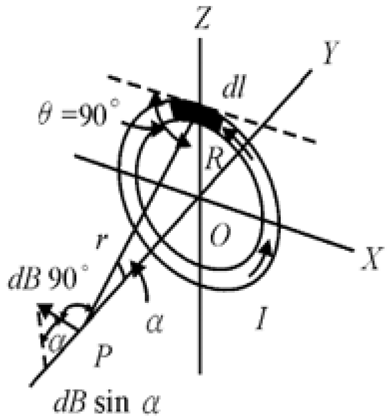


Figure 2

Now, consider a circular loop of radius R carrying electric current I, such as Figure 2. Assuming the plane of the circle is on plane X-Z, point P is at an arbitrary position on the symmetrical axis of the loop. The distance between P and the ring center, O, is y and the one from P to an arbitrary infinitesimal segment, dl, on the loop is r. From Equation (1) we know that dl will generate a magnetic field dB at point P and dB is perpendicular to both dl and r. Because dl and r are normal to each other, Equation (1) is written into

$$dB = \frac{\mu_0 I dl \sin 90°}{4\pi r^2}$$

Let α represent the angle between r and Y axis. An arbitrary dB can be decomposed into two vector components, one parallel to y axis and the other perpendicular to y axis. Because of circular symmetry, each and every vertical componet will find its counter part in its exact opposite direction to cancel out each other. So the value of B from Equation (2) is:

$$B = \int dB \sin\alpha = \frac{\mu_0}{4\pi}\frac{I \cdot \sin\alpha}{r^2}\int dl \tag{3}$$

In the above integration, α、I、r are constants, so the integral should be

$$B = \frac{\mu_0 \cdot I \cdot R \cdot \sin\alpha}{2r^2}$$

At point O, the ring center, α=90° and r = R, therefore

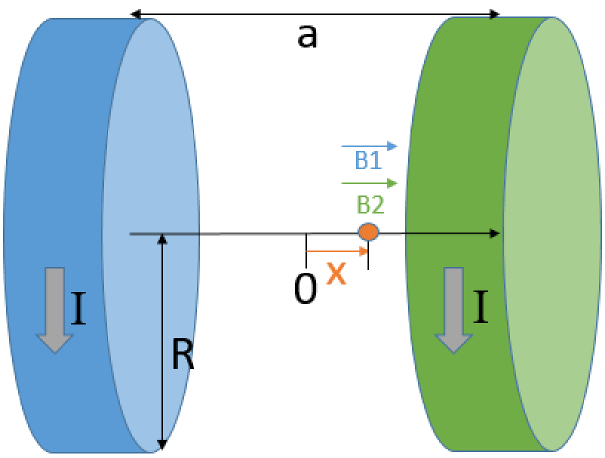
$$B = \frac{\mu_0 I}{2R} \tag{4}$$

If a coil consists of N circular wire rings on a round hoop, each ring will generate roughly the same value of magnetic field. Collectively, the total magnetic field at the center of the coil is:

$$B = \frac{\mu_0 NI}{2R} \tag{5}$$

When we place two identical N turn circular coils in parallel and the distance between two coils is equal to the coil radius R, that is a simple Helmholtz coil. A Helmholtz coil is a device for producing a region of nearly uniform magnetic field B_h. It consists of two identical circular coils that are placed symmetrically, one on each side of the experimental area along a common axis, and separated by a distance equal to the radius R of the coil. Each coil carries an equal electrical current flowing in the same direction. Assume that the center of the intermediate area of the two coils is taken as the origin of x. Then the magnitude of the magnetic field at x is

$$B_h = B_1 + B_2 = \frac{\mu_0 \mathrm{N} \mathrm{I} R^2}{2[(R^2 + \left(\frac{a}{2} + x\right)^2]^{3/2}} + \frac{\mu_0 \mathrm{N} \mathrm{I} R^2}{2[(R^2 + \left(\frac{a}{2} - x\right)^2]^{3/2}} \tag{6}$$



R: The radius of a coil

μ_0: Permeability

a: The distance between 2 coils

Figure 3

When a=R at x=0, B_h is

$$B_h = \frac{8\mu_0 \mathrm{NI}}{\sqrt{125}\mathrm{R}} \tag{7}$$

Inside the central area, the magnitude of the magnetic field is within 1% of its central value.

Helmholtz coils and solenoids are often used to provide the uniform magnetic field required for the experiment. We use this uniform magnetic field as a known magnetic field to correct the magnetic sensor of the smartphone.

3. Materials：

Smartphone、Circular coil、Multimeter、Variable resistor、DC power supply

4. Procedure：

(1) Calibration

1. First of all, you have to find out where the magnetic sensor is inside the smartphone. Open the APP and use the magnet to move over the smartphone to find a point where the magnetic field reading was the highest. This position is where the magnetic sensor is located.
2. Connect the DC power supply, variable resistor, multimeter and 2 coils in series as shown in Figure 4.

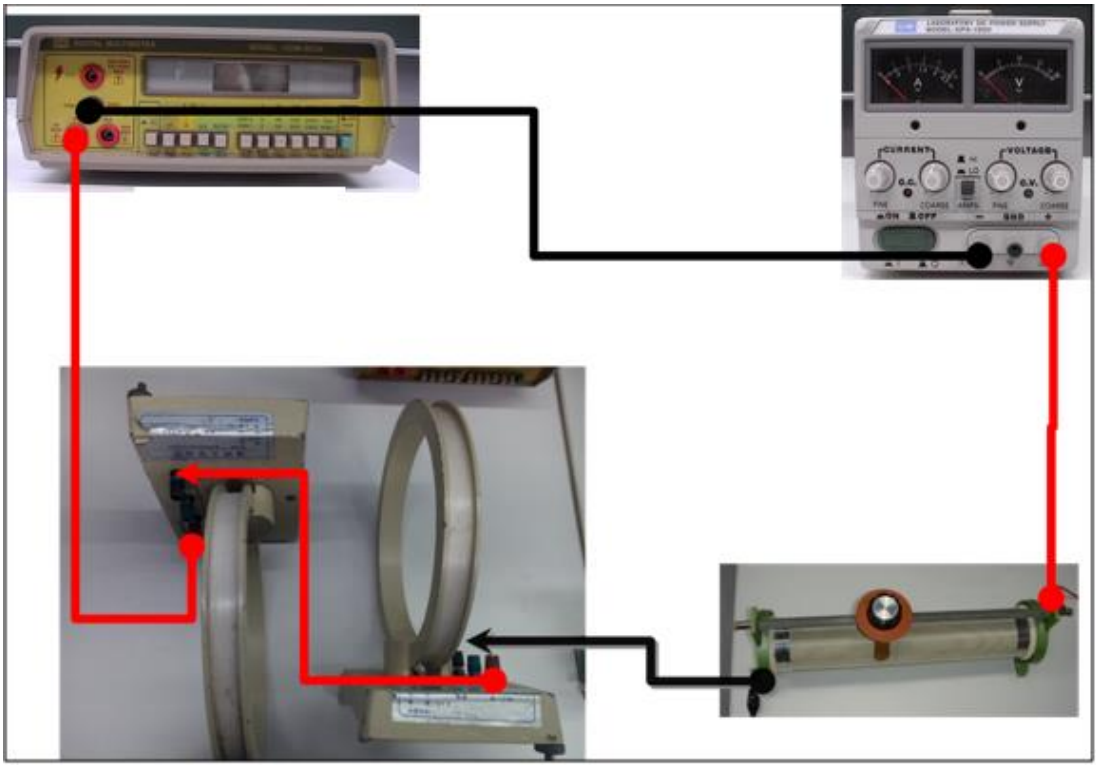


Figure 4

3. Place two coils as shown in Figure 5. Make sure the distance between two coils is equal to 77mm (the radius of a coil) and the surface of a coil is parallel to the other one.

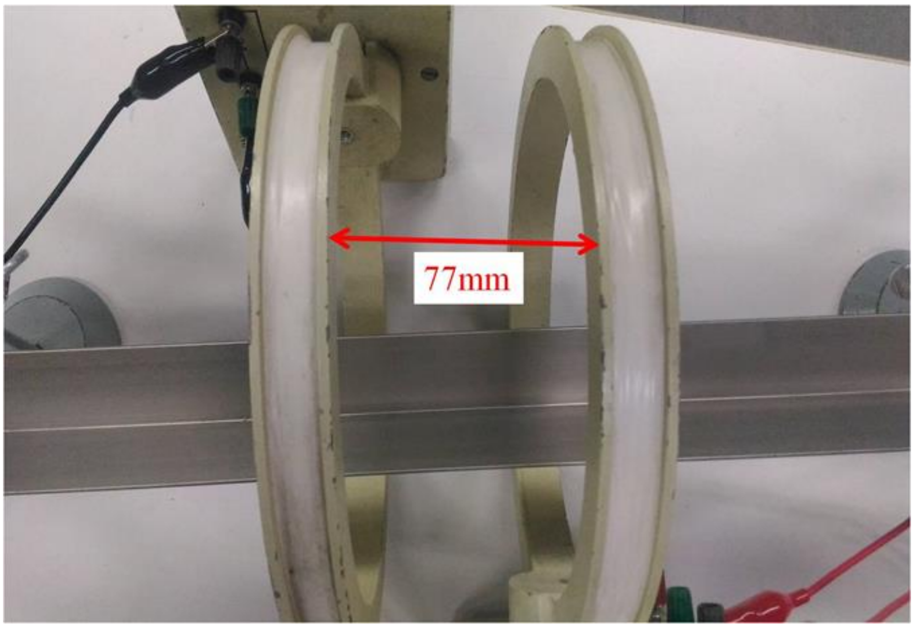
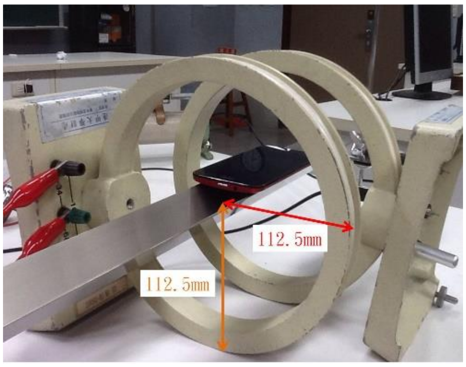


Figure 5

4. Place the smartphone on the platform and place the magnetic sensor approximately at the center of the coil as shown in Figure 6 and 7.



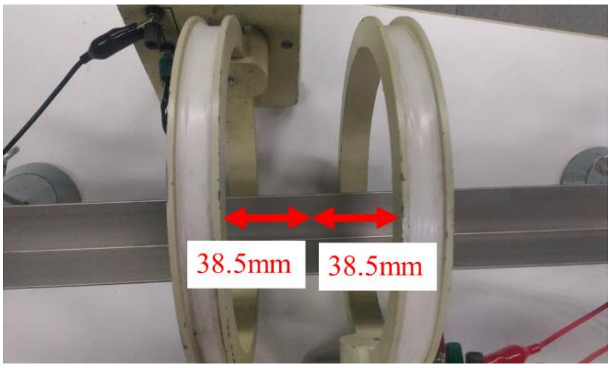


Figure 6

Figure 7

5. Adjust the angle of the smartphone relative to the coil surface and verify that the coil surface is perpendicular to the smartphone magnetic sensor. Open the APP and zero out the background magnetic fields. When two coils carry an equal electrical current flowing in the opposition direction, move the smartphone to find the position with the smallest magnetic field as shown in Figure 8. This position is the center point of Helmholtz coil. When two coils carry an equal electrical current flowing in the same direction, we can obtain a uniform magnetic field in this region.

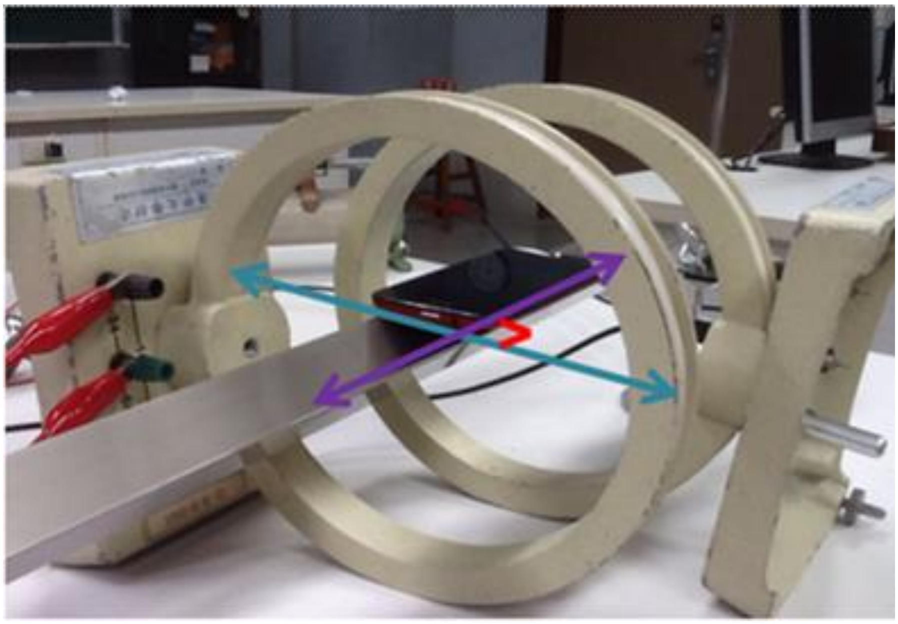


Figure 8

6. Turn off the power and zero out the background magnetic fields. Turn on the power. When two coils carry an equal electrical current flowing in the same direction, record the measured magnetic field.
7. Change the current and repeat the measurement of the magnetic field.
8. Compare the experimental value with the theoretical value to obtain the calibration coefficient of the magnetic sensor.

(2) Measurement – the magnitude of the magnetic field at the center of the coil

1. Remove one coil in the circuit. Move the smartphone to the center of the other coil still in the circuit. Adjust the angle of the smartphone relative to the coil surface, and confirm that the coil surface is perpendicular to the magnetic sensor of the smartphone. Open the APP and zero out the background magnetic fields. Turn on the power, move the smartphone up and down, left and right to find the position with the smallest magnetic field. Then move the smartphone axially to find the position where the magnetic field is the largest, which is the center point of the coil.
2. Turn off the power and zero out the background magnetic fields. Turn on the power then record the measured magnetic field. Change the current and repeat the measurement of the magnetic field.
3. Calculate the experimental value of permeability μ_0 and compare it with the theoretical value to calculate the percentage error.

(2) Measurement – the magnitude of the magnetic field of the earth

1. Find a place with less magnetic field interference. Open the APP to measure the Earth's magnetic field and compare it with the theoretical value to calculate the percentage error.

5. Questions：

(1) Why the magnitude of the magnetic field at the center of the coil is the largest comparing to other positions in the axial direction?

(2) When measuring the Earth's magnetic field, why can't we use the function of eliminating the background magnetic fields or need to find a place without magnetic field interference?

(3) Please draw the location of the magnetic sensor on the smartphone and record your smartphone model and calibration coefficient.

(4) What is the relationship between the current and the magnitude of the magnetic field, when the number of coil turns remains the same?