In part I of this experiment, the voltage induced in a coil of wire by a changing magnetic flux will be observed. In part II, the magnetic field along the axis of a current loop will be precisely measured.

**Equipment**

- Oscilloscope,
- Set of induction coils, and large loop coil,
- Oscillator,
- Probe coil with amplifier,
- DC power supply,
- Tap Switch,
- Galvanometer,
- Bar magnet,
- Magnetic compass.

**Method**

In part I, a galvanometer G is connected to the terminals of an induction coil (the larger of the pair) as shown below. A magnetic field is produced by a bar magnet (Fig. 1a) or by a second coil set up inside the larger coil (Fig. 1b). The currents induced in the larger coil as the field changes are observed with the galvanometer.

The magnetic field produced by a current loop will be measured with a probe coil. The dependence of the magnetic field on the distance $x$ will be compared with the formula derived in the textbook. The basic setup is shown in Figure 2. The large coil, which is connected to an oscillator (function generator), produces a time-varying magnetic field. This field induces a voltage in the small probe coil proportional to the strength of the field. An oscilloscope is used to measure the signal induced in the probe coil.
A coil carrying an AC current $i = i_0 \sin(\omega t)$ of (angular) frequency $\omega$ produces a time-varying magnetic field. The field along the coil axis is given by:

$$B(x) = \mu_0 N_0 i_0 a / [2(a^2+x^2)^{3/2}] \sin(\omega t) = \mu_0 N_0 i_0 / [2a(1+x^2/a^2)^{3/2}] \sin(\omega t) = B_0(x) \sin(\omega t),$$

where

$$B_0(x) = [\mu_0 N_0 / (2a)] (1+x^2/a^2)^{-3/2}, \quad (1)$$

and $x$ is the distance from the measuring point to the center of the large coil, $a$ is the coil radius, $N$ is the number of turns of the large coil, and $\mu_0$ is the permeability constant of free space.

The voltage induced in the probe coil at position $x$ is:

$$V(t) = \text{emf} = N_{\text{probe}} A_{\text{probe}} dB/dt = N_{\text{probe}} A_{\text{probe}} \omega B_0(x) \cos(\omega t) = V_0(x) \cos(\omega t),$$

where

$$V_0(x) = N_{\text{probe}} A_{\text{probe}} \omega B_0(x) \quad (2)$$
is the amplitude of the induced voltage at position $x$. This amplitude is measured by the oscilloscope. $N_{\text{probe}}$ and $A_{\text{probe}}$ are the number of turns and the cross-sectional area of the probe coil, respectively. From equations (1) and (2), we obtain:

$$V_0(x) / V_0(0) = (1+x^2/a^2)^{-3/2}, \quad (3)$$

$$V_0(0) = N_{\text{probe}} A_{\text{probe}} [\mu_0 N_0 \omega / (2a)], \quad (4)$$

where $V_0(0)$ is the induced voltage amplitude at position $x = 0$. Taking the natural log of both sides in (3), we find:

$$\ln\{V_0(x) / V_0(0)\} = -(3/2) \ln(1+x^2/a^2). \quad (5)$$

**Procedure**

1. **Induction**

   1. Move the North pole of a bar magnet in and out of a coil connected to the galvanometer (see Figure 1a). Record your results. Repeat with the South pole.
Q1. What effect does a changing magnetic field have on the coil?
Q2. Which end is the "north" pole?
Q3. For all cases considered above, draw a diagram in your notebook to show clearly and unambiguously the directions of windings in the coils, the directions of magnetic fields, and the directions of induced currents. Explain all your observations as completely as you can using Faraday's law of induction and Lenz's Law.

II. Magnetic Field of a Loop

1. Turn on the oscillator and set the frequency at 5 kHz. Do not change the frequency after starting your measurements. Turn on the power switch for the probe coil amplifier.
2. Place the center of the probe coil (C) in the center of the large coil (A), and record the position of the probe on the meter stick. This corresponds to the \( x=0 \) position. Measure the amplitude of the induced voltage with the oscilloscope. This voltage is \( V_0(0) \) in equation (5).
3. Move the probe coil along the meter stick and observe the amplitude change on the oscilloscope. Change the oscilloscope scale when necessary to obtain high sensitivity. Be sure the vertical sensitivity control of the oscilloscope is in the "calibrated" position. As you move the probe, take a reading every time the voltage changes by 5 or 10% from its previous value.
4. Measure the diameter of the large coil.
5. Be sure to turn off all apparatus when you are finished, especially the battery-powered probe coil amplifier.

Q4. Plot the data such that \( \ln\left\{ V_0(x) / V_0(0) \right\} \) is on the y-axis and \( \ln \left( 1+\frac{x^2}{a^2} \right) \) is on the x-axis, where \( x \) is the position of the probe coil relative to the center of the large coil. \( V_0(x) \) is the amplitude at position \( x \), \( V_0(0) \) is the amplitude at position \( x = 0 \), \( a \) is the radius (not the diameter!) of the large coil. Obtain the slope from the plot.

Q5. If the theory leading to equation (5) is correct, what should the slope of your plot be?

Q6. Discuss your results.