

# FARADAY'S LAW and THE AC GENERATOR

## REFERENCES

E. Hecht - Physics: Calculus (Brooks/Cole Publishing Company ,1996)

D. Halliday, R. Resnick, J. Walker - *Fundamentals of Physics, vol.2, 4<sup>th</sup> edition* (J. Wiley & Sons Inc., 1993)

## INTRODUCTION



A large fraction of the electrical power used by the world today is obtained by converting the rotational energy of a turbine into electrical energy. This is usually done by having the turbine turn a coil of wire inside a region where there is a strong magnetic field. The production of an electric current in this manner is explained by Faraday's Law, one of the most important laws of Electricity and Magnetism.

In this experiment you will examine several quantitative aspects of Faraday's Law. The apparatus consists of a rectangular coil of wire that can be rotated at a steady angular frequency in the uniform magnetic field generated by two stationary coils. Both the rotating coil's angular frequency and the strength of the magnetic field can be varied. The electro-motive force (*emf*) generated in the rotating coil can be measured and compared with the predictions of Faraday's Law.

## THEORETICAL BACKGROUND (see also References, above).

### (a) Production of Magnetic Field by currents

One of the fundamental laws of Electricity and Magnetism states that the flow of electric current (in wires, for example) produces a magnetic field. The magnitude and direction of the field depend on the magnitude and spatial distribution of the current. The *magnetic field induction*,  $\vec{B}$ , produced at the center of a single coil of wire is directly proportional to the current: its magnitude is given by

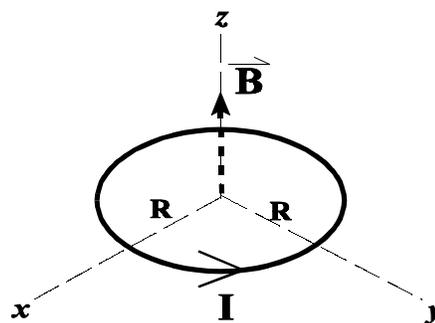
$$(1) \quad \mathbf{B} = \mu_0 \frac{\mathbf{I}}{2R}$$

where:  $\mathbf{I}$  is the current

$\mathbf{R}$  is the coil radius

$\mu_0$  is the permeability of the vacuum

The direction of this field is at right angles to the plane of the coil, along its axis; if you curve the fingers of your right hand in the direction of the current flowing in the coil, your thumb will point in the direction of the magnetic field. In the diagram, the coil lies in the  $x$ - $y$  plane.



The Helmholtz coil arrangement used in this experiment consists of two similar coils, each of radius  $R$  and  $N$  turns, placed parallel to one another at a distance  $R$  apart. Over a reasonably large central region of the Helmholtz coils, the value of  $B$  along the axis will be fairly uniform, and is given by :

$$(2) \quad B \approx 0.72 \mu_0 \frac{NI}{R}$$

(the factor of 0.72 comes from geometrical factors in the expression for the field from either coil.)

### (b) Electromagnetic Induction

The term electro-motive force (*emf*) is used to describe the voltage that is produced in a coil of wire which is moving relative to an external magnetic field.

*N.B. in spite of the confusing nomenclature, an emf is NOT a force!*

According to Faraday and Henry, the *emf* induced in a coil depends on:

- the rate of change of  $B$  through the coil
- the rate of change of the perpendicular area of the coil penetrated by the magnetic field lines.

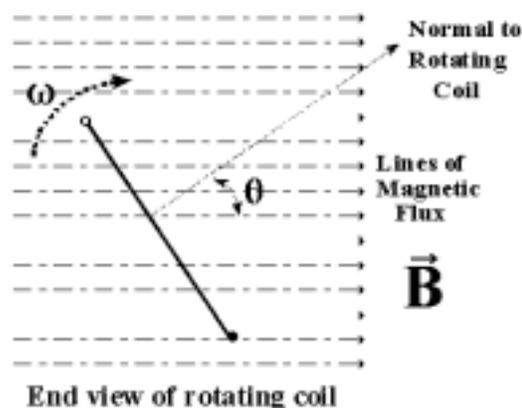
*Faraday's Induction Law* gives the value of the induced voltage (in volts) in a coil with  $n$  turns and area  $A$ . The electro-motive force across the coil will be proportional to the rate of change of magnetic flux through it:

$$E = -n \frac{\Delta\Phi}{\Delta T} \quad (3)$$

with

$$\Phi = BA \cos \theta \quad (4)$$

where  $\Phi$  is the *magnetic flux* through the coil and  $\theta$  is the angle between the normal to the rotating coil and the direction of the magnetic field.



*(N.B. the negative sign in equation (3) represents the fact that the induced magnetic field opposes the change causing it; this is known as Lenz's Law).*

## EXPERIMENT

A coil with area  $A$ , consisting of  $n$  turns is rotated with constant angular velocity  $\omega$  (frequency of rotation,  $f = \omega / 2\pi$ ) in a uniform magnetic field having magnetic induction  $B$ . The axis of rotation is perpendicular to the lines of magnetic field.

In this case  $\theta = \omega t$  so that the induced voltage is given by:

$$E = -n \frac{\Delta\Phi}{\Delta t} = -n \frac{\Delta(BA \cos\theta)}{\Delta t} = -nBA \frac{\Delta(\cos\theta)}{\Delta t} = (nBA\omega) \sin(\omega t) \quad (5)$$

This is a sinusoidal alternating voltage with a peak voltage of  $E_m = (n B A \omega)$  (6)

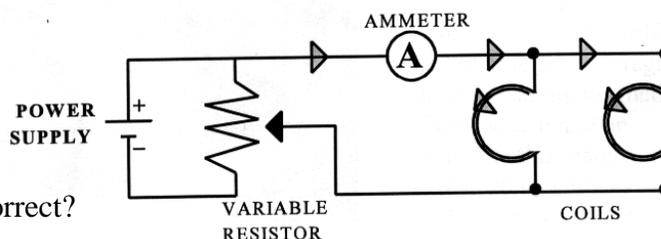
For the rotating coil,  $n = 4000$ , and the value of  $A$  is noted on the coil itself;  $B$  is given by (2).

Thus the variation of  $E_m$  with  $\omega$  (or  $f$ ) and  $B$  (or  $I$ ) can be investigated.

## METHOD

Build a circuit for the two Helmholtz coils to include the DC power supply, the variable resistor and a digital ammeter.

Connect up the coils so that their magnetic fields add. How would you check that the connection of the coils is correct?



**CAUTION! - You can obtain currents of up to 6 A in this circuit, so start off at low current (resistor maximum) and take care! Use the 10 A input on the meter. You will blow a fuse if you use the 2 A input.**

Connect the analogue AC voltmeter across the rotating coil. Note that the analogue voltmeter, since it averages over the alternating values of the emf, displays root-mean-square (rms) values:

$$E_{\text{rms}} = E_m / \sqrt{2} \quad (7)$$

First take readings of  $E$  with no current in the Helmholtz coils. How do you explain any non-zero value you observe? Then carry out sequences of measurements to investigate the variation of the peak voltage  $E_m$  ---

i) as a function of the rotation frequency  $f$  and

ii) - as a function of the current  $I$  in the Helmholtz coils.

You should take at least 10 data points spread over the available values of  $I$  and  $f$ .

Plot the two dependencies. Then, from the slopes of these graphs or otherwise, determine the value of  $\mu_0$ . Identify the sources of error in this experiment - in particular, what is the contribution of any non-zero value of  $E$  when the current in the Helmholtz coils is zero?

### Possible extension

Using the same apparatus, design an experiment to measure the geomagnetic field, and, if you have time, take a few measurements.