Year 1 Laboratory Manual
Investigating the Faraday Effect

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November 6, 2021

*You should reference this work as:'S. P. D. Mangles (Ed.) Year 1 Laboratory Manual: Investigating the Faraday Effect', Imperial College London, 2021

1. Investigating Faraday's Law

1.1 Introduction

In 1831 Faraday performed what looks like a very simple experiment with a coil and a bar magnet shown in Fig. 1.1. Faraday observed that a changing magnetic field induces an electric field. This changing magnetic field can be produced by the motion of a permanent bar magnet through a coil and results in a voltage appearing across the ends of a coil. We can express Faraday's findings in the simple expression

$$\varepsilon = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{1.1}$$

where ε is the induced electromotive force (voltage) and $\mathrm{d}\Phi/\mathrm{d}t$ is the rate of change of magnetic flux through a single loop. This equation is Faraday's law of induction.

The consequences of Faraday's experiments are profound; in particular the equivalence of moving either the magnet and coil, which ultimately led Einstein to the foundation of Special Relativity some 74 years later*. Einstein's work goes beyond what we will cover in this lab experiment but the experiment you are about to perform puzzled some of the finest minds of the 19th century and ultimately led to one of the landmark achievements of physics.

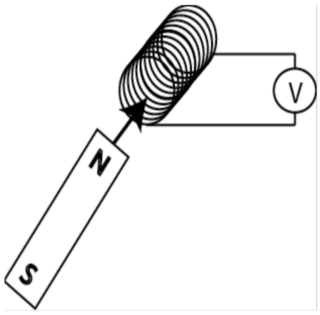

Figure 1.1: Schematic diagram of Faraday's classic experiment.

1.2 Experimental Procedure

Electromagnet and coil

While Faraday originally used a very simple experiment to demonstrate equation 1.1, here you will make a more controlled experiment. The moving magnet will be replaced by a time varying magnetic field produced by passing a current through a coil of wire. When a current is passed through such a coil, called a solenoid, a magnetic field is generated inside the coil. The magnetic field inside the coil is uniform and the filed lines are parallel with the axis of the coil. The magnetic

*Introduction to Electrodynamics, D.J.Griffiths, 3rd Ed, Addison Wesley (1999).

field inside a long solenoid is given by

$$B = \frac{\mu_0 N I}{L} . \tag{1.2}$$

Here, B is the magnetic field strength (i.e. the magnetic flux per unit area), N is the number of loops in the solenoid, I is the current in the solenoid, L is the length of the solenoid and $\mu_0 = 1.257 \times 10^{-6}$ H m^{-1} is the permeability of free space. The magnetic flux inside the coil is therefore

$$\phi = BA , \tag{1.3}$$

where A is the area of the circular coil cross-section.

Since the magnetic flux generated by our solenoid is proportional to the current, we can use a signal generator to supply the coil with an alternating current to control $d\Phi/dt$: an alternating current can be used to generate an alternating magnetic field.

Because we need to pass an appreciable current through the large, primary coil, the output of the signal generator is fed into an amplifier and then passed into the coil via an 18 Ω resistor. *

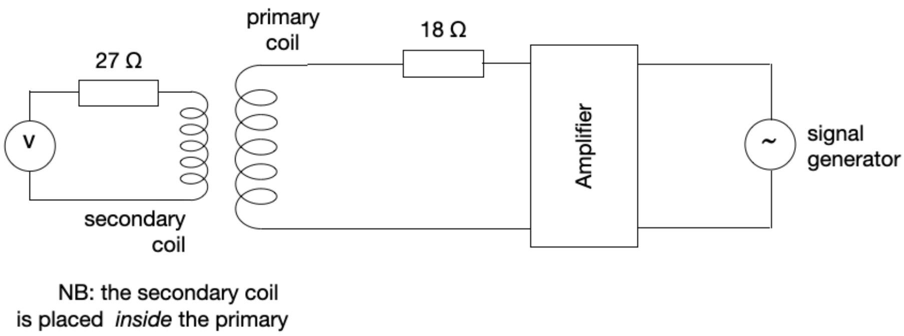

Figure 1.2: Concentric coil arrangement with the primary coil driven using a periodic signal supplied by the function generator.

Circuit setup:

1. Configure the signal generator on the scope to output a 500 Hz, zero offset and 2 V amplitude sine wave. You can verify the amplitude output of the signal generator is correct using channel A of the scope.
2. With the amplifier set to zero (turn the dial all the way to the left), connect the signal generator to the input of the amplifier using the coaxial cable.
3. Connect channel A of the scope to the output of the amplifier and slowly increase the amplification using the dial on the front of the amplifier until the amplitude of the signal reaches approximately 5 V without the sine wave becoming distorted.
4. Connect your amplifier in series with the grey primary coil and 18 Ω resistor.
5. Connect channel A of the scope to measure the voltage drop over the 18 Ω resistor *only*.
6. Connect the pink secondary coil in series with the 27 Ω resistor.
7. Connect channel B of the scope to measure the voltage drop over the 27 Ω resistor and insert the secondary coil into the primary coil so that the signal measured by channel B is maximised.

*The amplifier and resistor are required since the output impedance of the signal generator is too high (600 Ω) to drive any appreciable current through the coil. For reference, the output impedance of the amplifier is about 4 Ω, so can drive a load of roughly similar impedance efficiently.

The signal generator can generate three different waveforms

1. sinusoidal
2. triangular
3. square

Each coil has a resistor in series with it. By measuring the voltage drop across this resistor we are measuring the current in the resistor (as $V = IR$). Because the resistor and coil are in series, this is also a measurement of the current in the coil.

For each of the input waves observe the output from the secondary coil. Record the voltage waveform measured in the secondary coil produced for each case.

Question: Do you think that the voltage waveforms you are what you expect from Faraday's Law?

1.3 Investigating the efficiency

Two coils with a common core and a different number of turns act as a transformer. Transformers can be used to step-up or step-down the voltage. For an ideal transformer the voltage change will be directly proportional to the number of turns, following

$$\frac{V_P}{V_S} = \frac{n_P}{n_S}, \tag{1.4}$$

where V_P and V_S are the (peak) voltages at the primary and secondary coils respectively, n_P and n_S are the number of turns per unit length in each coil.

While you can increase the output voltage just by having a favourable ratio of turns, transformers cannot be used to magically generate energy; the power input and power output can at best be equal, meaning the output current will decrease correspondingly if the output voltage increases. In fact, there will inevitably be power losses and geometrical effects associated with any transformer, so the input and output powers are described by

$$\epsilon P_P = P_S \tag{1.5}$$

or

$$\epsilon V_P I_P = V_S I_S, \tag{1.6}$$

where I_P and I_S are the current in the primary and secondary coils, and ϵ denotes the *efficiency* of the transformer, a dimensionless number smaller than one. *

In this experiment, you will investigate the efficiency of the two coils acting as a transformer. We now need to measure both the current in each coil (which can be done as in the previous part of the experiment) and a direct measurement of the voltage drop across each coil.

Use a sine wave as your input and measure the values of RMS voltage and current at the coils (not the output of the amplifier).

Use equation 1.6 to calculate the efficiency of the transformer. Why is the value so low?

Insert the ferrite core into the smaller coil. Investigate the effect of inserting this ferrite core into your two coils and measure the corresponding efficiency. What is the observed effect?

*While not crucial for this calculation since you take a ratio, it is important to remember that, for alternating current, the power P is actually calculated using the Root Mean Square (RMS) values of current and voltage, where $V_{RMS} = V/\sqrt{2}$ and $I_{RMS} = I/\sqrt{2}$.

Air is a paramagnetic material with a magnetic susceptibility of 3.6×10^{-7}. The Ferrite core is Nickel-Zinc which is a ferromagnetic material with a magnetic susceptibility of between 20–15000.

Investigate different paramagnetic, diamagnetic and ferromagnetic materials online, note down their magnetic susceptibilities, and consider how inserting these materials into the core would affect the efficiency of the system. What would be the best possible material to use for your transformer and why?

Simulating Faraday's Law

Using Faraday's law, create a simple simulation of the current you would expect in the secondary coil for a given current in the primary coil. This code should have the following input variables:

- Number or primary coils
- Number of secondary coils
- Frequency of a sinusoidal input voltage
- Amplitude of a sinusoidal input voltage

Your code should produce a graph of both the primary and secondary coil currents.

If you have time you could develop your code to produce a graph of current in the secondary coil for square, triangle and arbitrary current waveforms in the primary coil.

You may find it useful to include an option to adjust the secondary coil voltage to take into account the efficiency of the system.

In the experiment you measured the voltage drop across each series resistor, which is directly proportional to the current in each coil. How do the curves your code produces compare to the current you measured in the coils?