

# Twin-flex EMC experiments

## 1 Objectives

In undergraduate laboratories, experiments involving signal generators, cables and oscilloscopes frequently show anomalies that are left unexplained. An EMC educational cable experiment, based on [1], highlights some interesting metrological problems. The original intention of the experiment was to demonstrate the large coupling between the variously terminated cable loops. A desire to make good measurements, correlated with theory, quickly demands deeper understanding.

Field theory provides an excellent initial model for the coupling; lumped circuit element models are helpful for second order effects. EMC design principles, good measurement practice, field theory and model optimisation are seen.

The objective of this practical is to demonstrate crosstalk between pairs of parallel wires due to magnetic field, electric field, and common wire coupling. The theoretical prediction thereof, using Maxwell's equations, will be presented and compared to measured results.

Firstly, the magnetic field coupling between two parallel wire loops will be predicted theoretically, using formulations from [2]. From Ampere's law, the magnetic field associated with the current flow in a conductor can be calculated. Having determined the magnetic field, the electromotive force (EMF) induced in the secondary circuit can be calculated using Faraday's law. A practical experiment will be conducted and the results compared to the theoretical predictions. It will be shown that magnetic field coupling is associated with low impedance circuits (low voltage, high current).

The second part of this practical will show the effects when two circuits have a common ground wire. Any practical conductor has a finite resistance and, although seemingly insignificant, a voltage drop due to current flow could couple significantly to the secondary circuit - hence 'common resistance'. It will be shown that this phenomenon is dominant at lower frequencies (where magnetic coupling is low) and associated with low impedance circuits (low voltage, high current), because the conductor resistance becomes negligible in high impedance circuits.

The last part of this practical will show the difference between E and B field coupling between two wire pairs.

Various publications [3- 6] chart our developing understanding of this "simple" practical.

## 2 Equipment needed for this practical

1. Sinusoidal signal generator (10 kHz to 1.0 MHz)
2. Oscilloscope (20 MHz is adequate)
3. Two pieces of appliance cord of length 2m
4. One  $47\Omega$  resistor, one  $10\Omega$  resistor (check these values in the lab), and 3 x  $10K\Omega$  pots
5. A PC running MATLAB and a calculator

### 3 Experiment 1: Magnetic field (inductive) coupling between closely spaced, parallel wires (loops)

#### 3.1 Procedure

##### 3.1.1 General description

The experiment configuration is shown in Figure 1. It shows two loops placed flat on a non-conducting surface, parallel and touching. The signal generator is connected to  $R_1$  ( $R_1 = 10\Omega$ ) through one of the pieces of appliance cord, forming loop 1. Loop 2 is formed by soldering  $R_2$  ( $R_2 = 47\Omega$ ) to one end, and a short circuit on the other end of the second piece of appliance cord as shown. An oscilloscope probe is connected over  $R_2$  to  $V_2$ .

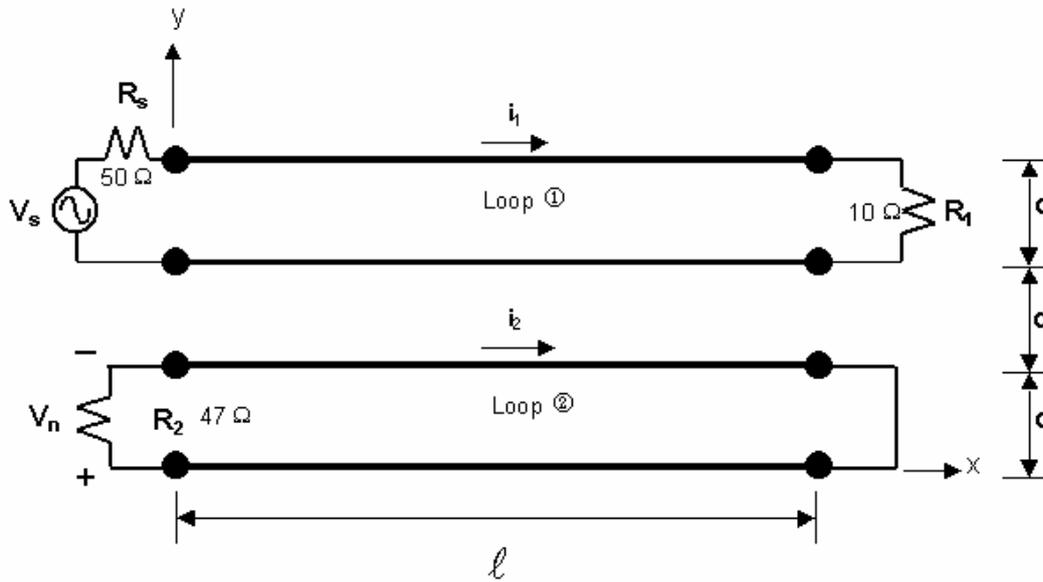


Figure 1: Configuration of expt.1

##### 3.1.2 Theoretical prediction

Referring to Figure 1, the voltage excited across  $R_2$  due to current flow in loop 1 is to be determined. The current flowing in loop 1 is:

$$i_1 = \frac{V_s}{Z_{loop1}} \quad (1)$$

where

$$Z_{loop1} = R_s + R_1 + 2 \times \ell \times R_\ell + j\omega L_{self} \quad (2)$$

$R_\ell$  is the resistance per unit length of the copper conductor, and can be found from the cross-sectional area of the conductor by treating the individual strands as a single solid strand:

$$R_\ell = \frac{1}{\sigma\pi\Delta^2} \quad (3)$$

where  $\sigma$  is the conductivity of copper ( $\approx 5 \times 10^7 S/m$ ) and  $\Delta$  is its radius.

$L_{self}$  is the external self-inductance of the loop. The internal self-inductance is ignored, as it is much smaller. The self-inductance is found by ignoring the effects at the ends of the loop, and assuming that the current flows in thin conductors at  $y = 0$  and  $y = d$  (the conductors drawn vertically in Figure 1 can be neglected). A magnetic field circulates around these conductors and passes through the xy-plane at right angles.

$$\begin{aligned} L_{self} &= \frac{\int \bar{B} \cdot d\bar{a}}{i} \\ &= \frac{\mu_0 \ell}{2\pi} \ln \left| \frac{(d - \Delta)^2}{\Delta^2} \right| \end{aligned} \quad (4)$$

Using Faraday's law, the EMF in loop2 can be found as

$$EMF_{Exp1} = -j\omega\mu_0 i_1 l \cdot \ln \left[ \frac{(d + \Delta)(3d - \Delta)}{(2d + \Delta)(2d - \Delta)} \right] \quad (5)$$

Note that the  $V_s$  voltage of eqn (1) must be measured as an OC value (ie. loop disconnected). However, when comparing phases of loop 1 and 2 on an oscilloscope, the loaded  $V_s$  value must be computed which will modify  $i_1$  in eqn (1) accordingly. The EMF measured in loop2 can be determined from the voltage over  $R_2$ .

$$v_2 = \frac{EMF}{Z_{loop2}} \cdot R_2 \quad (6)$$

$Z_{loop2}$  is the resistance and self-inductance of loop 2.

A study of the theory shows that:

1. The magnetic field coupling is directly proportional to frequency and current in the first loop (more coupling as the frequency and/or current increases).
2. As the equation contains an area integral, it can be seen that the coupling increases with an increase in area of the victim loop.
3. The coupling is inversely proportional to the separation of the loops.

### 3.1.3 Instructions

The theoretical equations have been implemented numerically on PC in MATLAB. To do the practical measurements:

- Set the OC amplitude on the signal generator to 10Vp-p (more than this will load the generator unnecessarily)
- Connect the signal generator to loop 1 and attach channel 1 of the oscilloscope to this point.
- Measure the voltage across  $R_2$  using the oscilloscope. Measure at discrete frequencies between 10 kHz and 1 MHz.
- Record the magnitude and relative phase values of channels 1 and 2 for entry into the Matlab program.

## 4 Experiment 2: Magnetic field (inductive) coupling between closely spaced, parallel wires (loops) using a common ground wire

### 4.1 Procedure

#### 4.1.1 General description

The experiment configuration is shown in Figure 2. It shows two loops placed flat on a non-conducting surface, parallel with respect to each other. Both loops use the same ground conductor. The signal generator is connected to  $R_1$  ( $R_1 = 10\Omega$ ) through one of the pieces of appliance cord, forming loop 1. Loop 2 is formed by soldering one conductor of the second length of flex to loop 2, using a resistor  $R_2$  ( $R_2 = 47\Omega$ ) at one end (see Figure 2). The other conductor of the second piece of cord is left unconnected. The oscilloscope probes are connected across  $R_2$  measuring  $V_2$ .

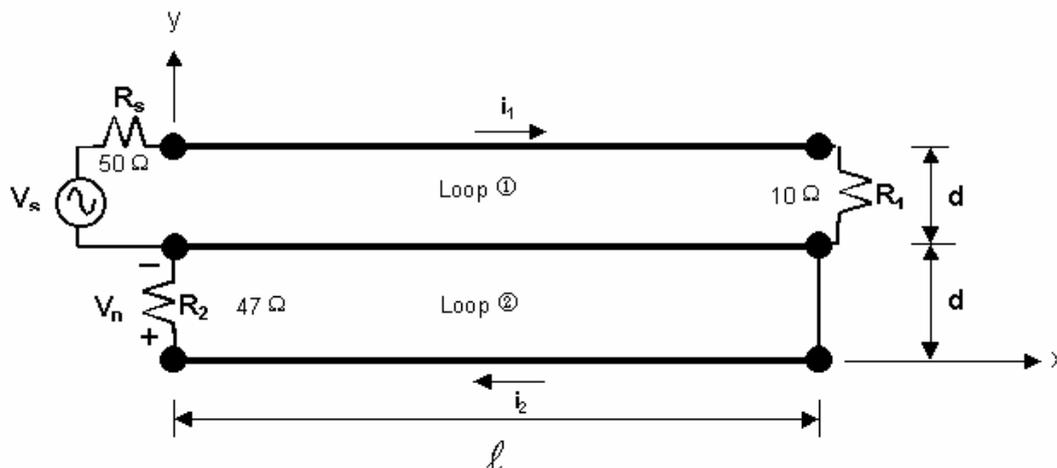


Figure 2: Set-up for Experiment 2

#### 4.1.2 Theoretical prediction

Referring to Figure 2, the voltage excited across  $R_2$  due to current flow in loop 1 is to be determined. In this configuration, both magnetic field and common resistance coupling occur.

Determination of the equation for the EMF in the second loop due to magnetic field coupling, is done as in experiment 1, with the integration limits suitably altered. Note the same practical considerations in using  $i_1$  as a reference value:

$$EMF = -jf\mu_0 i_1 \ell \ln \left| \frac{(2d - \Delta)\Delta}{(d + \Delta)(d - \Delta)} \right| \quad (7)$$

Once again, this EMF gives rise to a current in loop2, which is measured as a voltage over resistor  $R_2$ .

$$v_2 = \frac{EMF}{Z_{loop2}} \cdot R_2 + \frac{\ell R_\ell i_1}{\ell R_\ell + R_2 + j\omega L_{self}} \cdot R_2 \quad (8)$$

The second term in (8) is resistive coupling caused by the voltage drop along the centre conductor.

### 4.1.3 Instructions

1. The theoretical equations have been implemented numerically on PC in MATLAB
2. To do the practical measurements:
  - Set the OC amplitude on the signal generator to 10Vp-p.
  - Connect the signal generator and the oscilloscope channel 1 to loop 1 and measure the voltage across  $R_2$  using the oscilloscope. Measure at discrete frequencies between 10 kHz and 1 MHz
  - Record the magnitude and relative phase values of channels 1 and 2 for entry into the Matlab program.

## 5 Experiment 3: Electric field (capacitive) coupling between closely spaced, parallel wires (demonstration)

### 5.1 Procedure

#### 5.1.1 General description

The configuration for the first part of this experiment is the same as for experiment 1 (see Figure 1), the only difference being the replacement of  $R_1$  with a 10K $\Omega$  variable resistor. This configuration will be referred to as ‘configuration 1’.

The configuration shown in Figure 3 is used in the second part of this experiment. It shows two loops placed on a non-conducting surface, parallel with respect to each other (NB: Place the appliance cord vertically, in contrast to the flat placement of experiments 1 and 2). The signal generator is connected to  $R_1$  ( $R_1$  is a 10K $\Omega$  pot) through one of the pieces of appliance cord, forming loop 1. Loop 2 is formed by soldering  $R_2$  ( $R_2$  is a 10K $\Omega$  pot) and  $R_3$  ( $R_3$  is a 10K $\Omega$  pot) to the ends of the second piece of appliance cord as shown. The oscilloscope probes are connected across  $R_2$  measuring  $V_2$ . This configuration will be referred to as ‘configuration 2’.

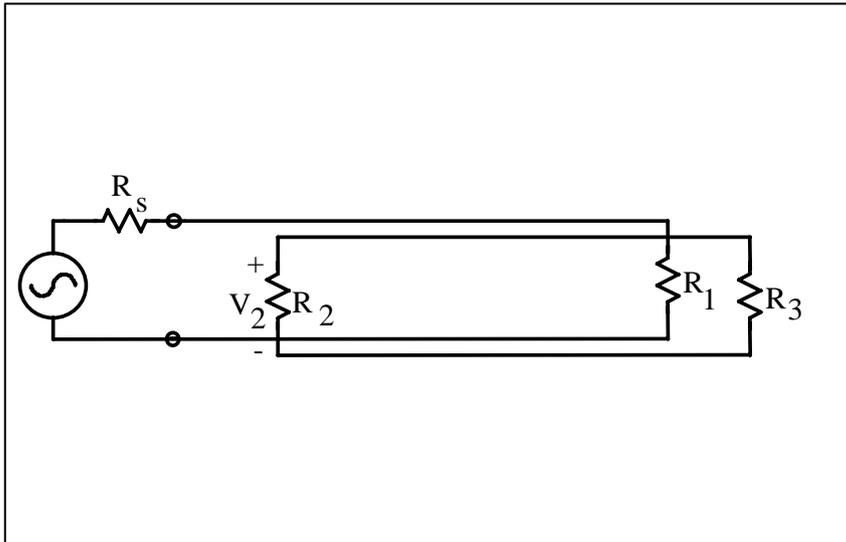


Figure 3: Configuration 2 of expt.3

### 5.1.2 Instructions

- Using configuration 1, set the amplitude on the signal generator to 10Vp-p and the frequency to 1MHz.
- Connect the signal generator to loop 1 and measure the voltage across  $R_2$  using the oscilloscope. Observe the voltage change across  $R_2$  as the value of  $R_3$  is changed. Explain the result.
- Now, using configuration 2, set  $R_3$  to its maximum value. Vary the value of  $R_1$ , while observing the voltage across  $R_2$ . Explain the result.
- With  $R_1$  and  $R_3$  set to their maximum resistance values, vary the frequency on the function generator while observing the voltage across  $R_2$ . Explain the result.

## 6 References

- [1] CLAYTON PAUL, "Crosstalk in cables", in IEEE EMC Education Manual, August 1992.
- [2] H A HAUS & J R MELCHER, "Electromagnetic Fields and Energy", Prentice Hall, 1989.
- [3] L H BECKER, "Crosstalk in cables", HF Electronics EMC Experiment 1, August 1995.
- [4] T E W STUART and H C READER, "Apparently simple low frequency measurements: An EMC View", IEEE/SAIEE Symposium on Communications and Signal Processing, COMSIG '98, Cape Town, Sept. 1998, paper AP-19.
- [5] H C READER, T E W STUART, M BEMMELMANS, "Metrology in Electromagnetics: Simple Problems", Millennium Conference on Antennas and Propagation, Davos, April 2000, ESA (European Space Agency), SP-444 Proceedings, Session 3P7, paper 0527.