Laboratory Exercise 5 – THE OSCILLOSCOPE

Introduction

The aim of this exercise is to introduce you to the oscilloscope (often just called a 'scope), the most versatile and ubiquitous laboratory measuring instrument. The oscilloscope is used to display and analyse electrical signals, either repetitive waveforms or transient pulses, which are changing too fast to be recorded by simple analogue meters like the AVO or by digital instruments such as the DMM. For many years oscilloscopes used *cathode-ray tubes* and *analogue* circuitry that swept a narrow beam of electrons across a fluorescent screen, as in a TV. These cathode-ray oscilloscopes, or CROs, use the signal to be analysed to control vertical movement of the electron beam. This produces a display that is effectively a graph of voltage (vertically) versus time (horizontally).

Analogue 'scopes need repetitious signals to produce the display. However, like so many electronic devices they are increasingly being replaced by *digital* 'scopes that can capture even a single pulse and display it from a memory. The use of computerised digital electronics also makes it possible for the display to be much more versatile and informative, with sophisticated mathematical treatment of the digital data available if needed. The use of thin liquid-crystal displays rather than bulky cathode-ray tubes makes 'scopes much more compact and lighter, and also allows inexpensive use of colour for the displays.

The horizontal axis of the display usually represents time, but sometimes it is useful for it to be controlled instead by a second time-varying voltage. We will not investigate this so-called *XY* mode. Note that instructions for the oscilloscope can be found at the end of this section.

Main features

Most 'scopes have similar basic features. They differ mainly in the speed of signals that they can handle, the number of parameters you can adjust, and the additional facilities that are offered. Because the data in modern 'scopes is digital, it can be stored and transferred to PCs by various methods for printing or adding to documents; indeed many of the more expensive digital 'scopes actually *are* PCs 'underneath', and this for example allows access to their data via the internet.

Digital 'scopes such as those in our laboratory can display signals from a few millivolts to a hundred volts, at frequencies up to about 60 MHz. More expensive models can work at up to a few GHz (1 GHz = 10^9 Hz). You do not need any detailed knowledge of the internal circuitry of an oscilloscope in order to use it effectively, but the main functions need explanation. We have provided separate notes describing how to do the things required for this experiment. However, our 'scopes also have clear instruction manuals, as well as built-in help (in a wide variety of languages!) on-screen via the **help** button.

The *horizontal* axis is controlled by a **timebase** circuit which drives the display in the horizontal (*X*) direction at a constant rate, adjustable by a front-panel knob at the right. Selection of the *XY* display mode (see below) turns the timebase off and allows the display to be driven horizontally by one of the input voltage signals. Note, oscilloscopes cannot be used as ammeters directly.

Most oscilloscopes can display two or more signals, or **channels**. The signals are applied at front-panel sockets to internal **amplifiers** whose gain is adjustable by knobs; these are used to give convenient *vertical* deflections on the screen. Thus the 'scope is also like voltmeter. The signal displays can be moved up and down, even off the screen. You can display either or both traces, and if there are two signals then they can also be added or subtracted algebraically if desired to produce the display.

The amplifiers must have a stable gain at low and high frequencies if the 'scope is to be used for measuring voltages accurately. Each input channel has three modes for connection: AC, DC, and GROUND. The GROUND selection connects the channel to earth, allowing you to see the position of zero volts input. The AC setting introduces a capacitor in series with the input and is used to eliminate any DC component, so that a small time-varying signal can be displayed in the presence of a large DC offset without driving the trace off-screen. The DC setting should be used for low frequency signals. For high frequencies, the 60 MHz limit of our models limits them to signals longer than about 20 ns.

The third important circuit handles **triggering**. Its task is to synchronise the timebase with the arrival of a repetitive signal, so that at every sweep this appears in the same position on the screen. This has many complex features but we shall use only the simplest ones.

The display is **triggered** whenever the trigger signal exceeds a voltage that you can set. The source of this trigger signal can be either the channel 1 or channel 2 input signal, or a separate EXTERNAL signal fed into an adjacent socket. Every 'scope has an AUTOMATIC trigger mode, displaying a timebase even when no trigger signal is present so that you can see what might be there. NORMAL mode requires a signal to trigger the timebase. Finally, you can choose the slope (increasing or decreasing voltage) and the magnitude of the triggering signal.

Part A: Getting familiar with the 'scope and function generator

Displaying simple waveforms

This is a short exercise to familiarise you with basic use of the 'scope. Sinusoidal, square, and triangular waves are available from the function generator; their frequencies can be varied from 0.03 Hz to 3 MHz and their amplitudes adjusted up to about 20 volts **peak-to-peak**, i.e. from maximum positive (+10 V) to maximum negative (–10 V) with respect to earth.

Figure 1 Sine wave

• Using a breadboard connect the output of the function generator to the channel-1 input of the 'scope, making sure that the signal (red) leads, and earth are connected. Select sine waves — the square wave button should be out. Adjust the 'scope controls to obtain a stable waveform on the screen.
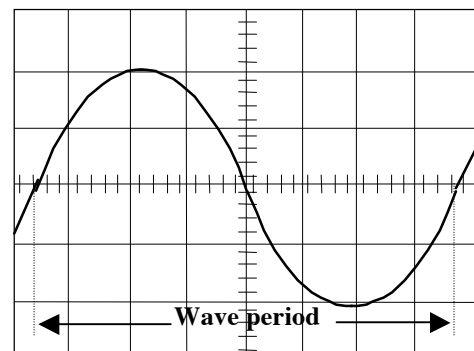
• Now try adjusting the controls on the oscilloscope and function generator to see what they do[1]. Vary the frequency by factors of 10 between 10 Hz and 1 MHz, and compare the indicated frequencies on the function generator dial with the exact frequencies measured automatically by the 'scope. Do the respective calibrations agree over the whole frequency range? With care you should be able to check this to an accuracy limited only by the frequency dial on the function generator. You should compare what you see on the 'scope to the digital meter on the function generator.

• Also, at one frequency learn how to use the 'scope's **cursor** features. Use the horizontal cursors to measure the period (figure 1) of the waveform, convert this to frequency, and compare with the 'scope's automatic measurement and the function generator's digital meter measurement. Then compare the amplitude as measured by the vertical cursors, and compare

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[1] Don't be afraid of *trying controls to see what they do* — this is really the only way to learn how to use a 'scope. Some of the buttons, knobs and menus will take a while to get the knack of, but once the general mode of operation is understood things will start to seem much easier.

with the automatic measurement. (The cursors are mainly meant for measuring the spacing of features that are *not* measured automatically by the 'scope.)

• Next, compare the calibration of the amplitude knob of the function generator with the amplitude measured by the 'scope (that of the oscillator is not intended to be very precise).

• Switch the trigger mode to NORMAL triggering and change the trigger amplitude. Study what happens when you change the trigger level or signal amplitude.
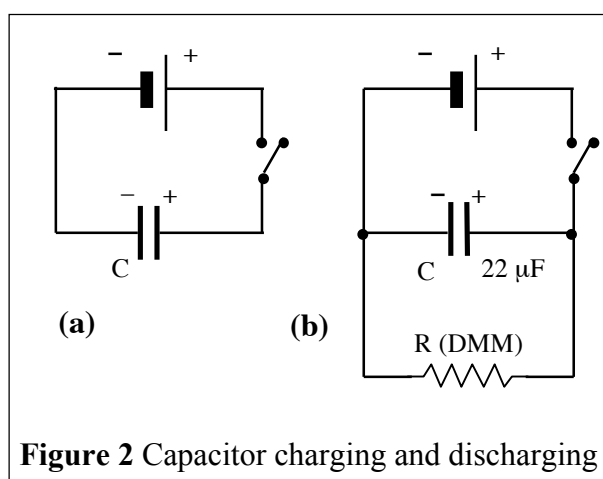
Comparing frequencies: direct display of waveforms

• An 'unknown' sine wave from an oscillator is available on the signal circuit terminals above your bench. Feed this signal (care with signal and earth connections again!) to channel 2. Trigger the timebase on this 'unknown' signal and, viewing both signals together on the screen, adjust your oscillator to match the 'unknown', getting as stationary a display as possible. Use the 'scope to measure the amplitude and the frequency of the 'unknown' waveform.

Part B: *RC* circuits

In exercise 2 you measured the input resistance of a DMM. In this exercise we show another way to do it which leads on to a demonstration, using the oscilloscope, of the effect of **capacitance** on electrical signals, and some more about the relative **phase** of wave trains.

A capacitor is a device that stores electric charge. Suppose a capacitor is charged, as in figure 2(a), by momentarily closing a switch connected to a battery. When the switch is opened again there is nowhere for the charge to go so it stays on the two plates of the capacitor, maintaining a voltage difference *V* between them. The capacitance *C* is the charge stored divided by the voltage: $C = Q/V$. But if a resistance *R* is placed across the capacitor, as shown in figure 2(b), the charge can leak through *R* from one plate to the other, discharging the capacitor. The larger *R* the

Figure 2 Capacitor charging and discharging

slower the leak, and the larger *C* the more charge there is to transfer. So it is not surprising that both the charge on the capacitor and the voltage across it decrease with time *t* according to the exponential law:

$$Q = Q_0 e^{-t/RC} \qquad and \qquad V = V_0 e^{-t/RC}$$

where the product *RC*, the **time constant**, is a measure of how rapidly charge and voltage decrease. We'll use this to measure the input resistance of a DMM.

Input resistance of a DMM

• On the breadboard make the simple circuit of figure 2(b), using a 22 μF capacitor and using the DMM as the resistor, set to measure voltage. Use a desk-top power supply connected to the breadboard with wires. The value of *R* is then the input resistance of the meter. The capacitor *must* be connected the right way round — the polarity is marked on it by a vertical line indicating +.

• Depress the switch and make contact for a few seconds, long enough to charge the capacitor up through the internal resistance of the battery. Release the switch and immediately start to

record the voltage as a function of time, every 15 seconds initially and then every minute after two or three minutes, until the voltage has fallen to less than a tenth of its initial value.

• Plot log V versus t and deduce a value for R from the slope of your graph (see exercise 4 to remind yourself how to do this). Comment on any unusual features of your graph.

Using the oscilloscope to measure time constants

The oscilloscope can be used to measure time constants as short as microseconds or less.

• Connect up the RC circuit of figure 3, and apply a square-wave of frequency about 50 kHz. Use the 'scope to observe, on channel 1, the voltage applied to the capacitor and, on channel 2, the current that flows into or out of the capacitor. Remember, the 'scope does not measure current directly, so instead measure the voltage across a 1 kΩ resistor. Just as previously, the positive-going and negative-going edges of the waves charge up the capacitor, which then discharges through the resistor R (the parallel input resistance of the 'scope is much too large to have any effect).
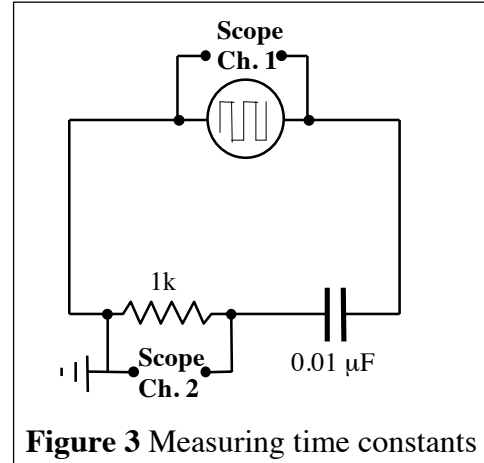
Figure 3 Measuring time constants

• Measure the time $t_{1/2}$ for this current, measured as the voltage across R, to fall to half its peak value. By taking logs of $V_0/2 = V_0 \exp(-t_{1/2}/RC)$ we see that $t_{1/2} = \log_e 2\ (RC)$. Does the value of RC obtained in this way agree with simply multiplying the known values of $R{\times}C$?

The RC circuit as a frequency filter

- High Pass Filter
• Raise the oscillator frequency to about 1 Mhz and notice that there is now too little time for the capacitor to discharge appreciably, and so the very short-period waves pass across unhindered. Switch to sine waves, and the input and output wave trains should still look the same.

• Now reduce the frequency; as you do so two effects will begin to appear: (a) The *amplitude of the output decreases*, becoming zero at very low frequencies since the capacitor remains completely discharged, with virtually no current flow, when the applied voltage is changing sufficiently slowly. For this reason the RC circuit is called a **high pass filter**, letting through only high frequencies. The frequency at which the output amplitude falls to $1/\sqrt{2}$ of its high frequency value is by convention called the **cut-off frequency**. It can be shown that the cut-off frequency is $1/(2\pi RC)$. (b) The *output signal begins to lag behind the input*. The capacitor causes a phase shift between voltage and current. Since this is a series circuit, the current must necessarily be the same everywhere in the circuit. Therefore the voltage across the capacitor will lag that current by at most 90° at very low
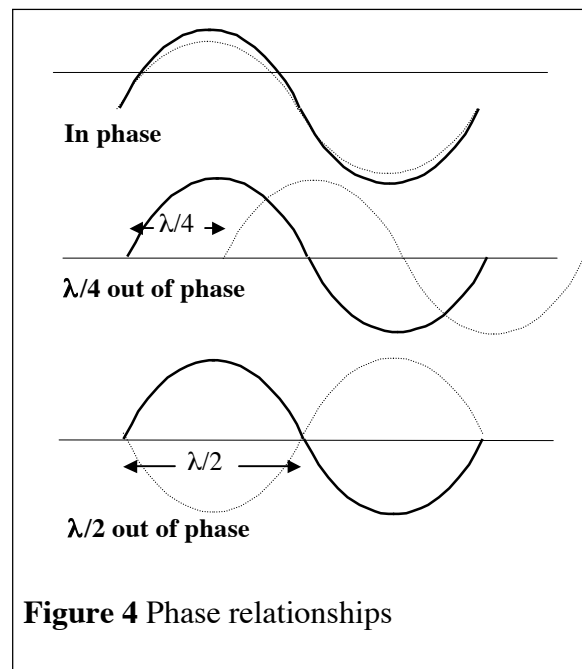
Figure 4 Phase relationships

frequencies, while at the same time the voltage across the resistor will be in phase with the current. This lag is called a **phase shift** (figure 4).

• Make a plot of the voltage across Ch. 2, the resistor, as a function of the logarithm of the frequency f: $\log f$.

• Measure the cut-off frequency and compare it with $1/(2\pi RC)$. Measure the phase shift at this frequency, converting your result to degrees.

- Low Pass Filter

Similarly to the high pass filter, you will now study the **low pass filter**, which lets through only low frequencies. Swap the resistor with the capacitor in your circuit.

• Make a plot of the voltage across Ch. 2, the capacitor, as a function of the logarithm of the frequency f: $\log f$.

• Measure the cut-off frequency and compare it with $1/(2\pi RC)$. Measure the phase shift at this frequency, converting your result to degrees.

Part C: *RLC* circuits

An **RLC circuit** consists of a resistor (R), inductor (L) and a capacitor (C) connected in series or in parallel.

An inductor is a circuit element consisting of a coil of wire on a core material made of ferrous or non-ferrous material. An inductor resists changes in the flow of electric current through it, because it generates a magnetic field that acts to oppose the flow of current through it, which means that the current cannot change instantaneously in the inductor. This property makes inductors very useful for filtering out residual ripple in a power supply, or for use in signal shaping filters. They are frequency-dependent devices, which means that their inductive reactance, or "effective resistance" to AC decreases as the frequency gets lower, and increases as the frequency gets higher. This property makes them useful in tone controls and other filters. Note that this is opposite to what happens with the capacitors.

RLC circuits can be used to select a certain narrow range of frequencies from the total spectrum of waves. There are two fundamental parameters that describe the behaviour of *RLC circuits*: the **resonant frequency** and the **damping factor**. We define ω as the angular frequency (ω $=2\pi f$), where f is the frequency. The resonant angular frequency ω_0 is given by $\omega_0 =1/\sqrt{(LC)}$. The damping factor $\Delta\omega$ is given by $\Delta\omega =R/2L$ for the circuit considered in the following exercise.

Connect up a circuit as in figure 5 and apply sine waves of frequency f.

The self resistance of the inductor should be used in series with the resistor. However, we will assume that the resistance of the inductor is so small with respect to the resistance in the circuit to be neglected.
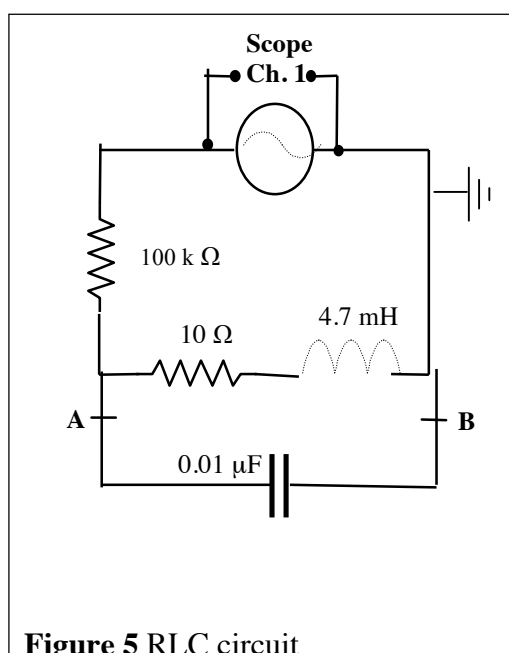
Figure 5 RLC circuit

• Make a plot of the variation of the voltage across A and B versus the angular frequency ω.

• Measure the maximum ω_0 of the distribution and compare it to $1/\sqrt{(LC)}$.

• For $\omega_0 \pm \Delta\omega$ the measured voltage is $1/\sqrt{2}$ of the output voltage. Measure $\Delta\omega$ and compare it to $R/2L$.

Change the sine waves to square waves of angular frequency ω_0. You should still observe a sine wave across A and B. Vary the frequency and note that you still observe a *good* sine wave for frequencies in the range $\omega_0 \pm \Delta\omega$ (**narrow pass filter**).

• Store and print the voltage across A and B for $\omega=\omega_0$, $\omega=\omega_0+\Delta\omega$ and $\omega=\omega_0-\Delta\omega$, This experiment shows that a square wave can be represented as a sum of sine and cosine waves (Fourier transforms).