locktronics

Simplifying Electricity

Aircraft Maintenance - Electrical Fundamentals 4

Contents

Developed by Mike Tooley in conjunction with Matrix Technology Solutions Ltd

Worksheet 1

AC measurements
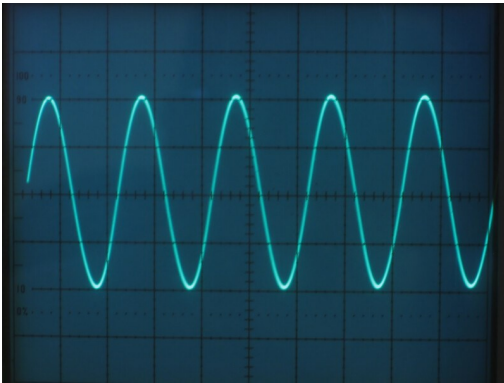
The ability to make accurate measurements of alternating current and voltage is an important skill. In reality, AC measurements are not quite so easy to make as DC.

First of all, here's a brief introduction to some of the quantities and terminology that you will need to get to grips with:

AC voltage and current

When measuring alternating voltage and current, we usually use *root-mean-square* (RMS) values. These are the effective value of an alternating current. They are the DC equivalents that would produce the same heating effect if applied to a resistor.

It is sometimes useful to use the *peak* or *peak-to-peak* value of an AC waveform as they are easy to measure using an oscilloscope (see the picture).
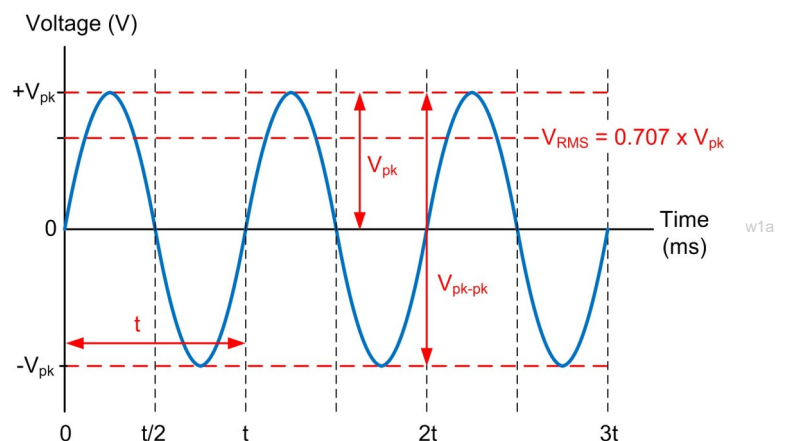
Frequency

The frequency of a repetitive waveform is the number of cycles of the waveform which occur in one second. Frequency is expressed in hertz, (Hz), and a frequency of 1Hz is equivalent to one cycle per second. Hence, a signal frequency of 400Hz means that 400 cycles of it occur every second.

Periodic time

The periodic time (or period) of a signal is the time taken for one complete cycle of the wave. The relationship between periodic time, t, (in s) and frequency, f, (in Hz) is:

$$t = 1 / f \quad \text{or} \quad f = 1 / t$$

For example, the periodic time of a 400Hz AC signal is 2.5ms.

Waveforms

Waveforms show us how voltage or current signals vary with time. Common types of waveform include sine (or sinusoidal), square, triangle, ramp (which may be either positive or negative going), and pulse. In this module we are concerned only with the most basic of waveforms, the sine wave. This waveform is used for all aircraft AC power supplies.

Waveforms are viewed and measured using an oscilloscope, either a conventional type or a virtual instrument (like Picoscope).
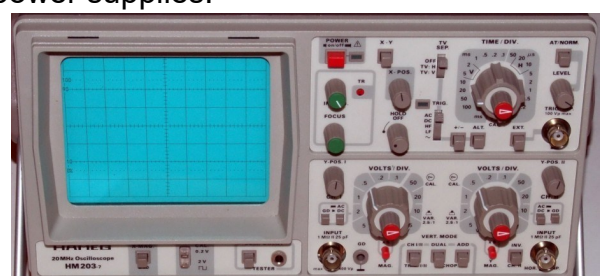
Worksheet 1
AC measurements

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Over to you:

- Connect an oscilloscope to display the output of a signal or waveform generator.

- Adjust the signal generator to produce a sine wave output at 100 Hz. and set the amplitude of the signal so that the display on the oscilloscope is exactly 2 V peak-peak.

- Sketch the oscilloscope display on the graph paper below, and male sure that you label the voltage and time axes.

- Use the x-axis time scale on the oscilloscope to measure accurately the time for one complete cycle (i.e. the periodic time). Record this in the table.

- Set the signal generator to 200 Hz, 400 Hz, 600 Hz, 800 Hz and 1,000 Hz and at each frequency measure and record the period time in the table.

- Use the data in the table to plot a graph of periodic time against frequency. Use this to verify the relationship f = 1/t.

Frequency (Hz)	Periodic time (ms)
100	
200	
400	
600	
800	
1000	

Waveform sketch	Periodic time plotted against frequency
w1c	w1d

Oscilloscope settings:

Timebase - 1ms/div

Voltage sensitivity - ±5V/div DC

Trigger Mode - Auto

Trigger Channel - Ch.A

Trigger Direction - Rising

Trigger Threshold - 10mV
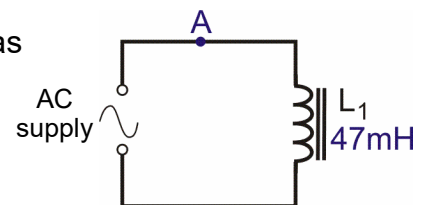
Worksheet 2
AC and inductance
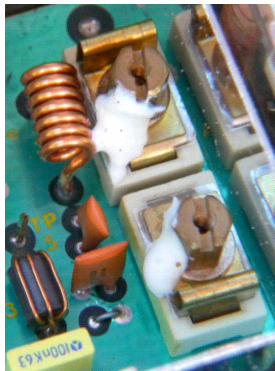
Resistors oppose electric currents. Inductors oppose *changes* to electric currents, but the mechanism is different.

An electric current flowing in the inductor, sets up a magnetic field. Increasing the current means increasing the magnetic field, and that takes energy from the current, opposing the increase. Reducing the current means reducing the magnetic field, and that releases energy which tries to maintain the current.

Inductors behave rather like flywheels on a rotating shaft. Their angular momentum tries to keep the shaft rotating at the same speed. When the shaft starts to slow down, the stored energy in the flywheel tries to keep it going. When the shaft tries to speed up, the flywheel requires energy to speed it up, and so the flywheel seems to resist the change.

Over to you:

- Connect a 47mH inductor in series with the AC power supply, as shown in the circuit diagram.

- Use enough connecting links so that the current can be measured easily at point **A**.

- Set the AC supply to output a frequency of 50Hz.

- Remove the connecting link at **A**, and connect a multimeter, set to read up to 20mA **AC**, in its place. Record the current, I, flowing at point **A** in the table.

- Remove the multimeter and replace link **A**.

- Set up the multimeter to read **AC** voltages of up to 20V and connect it in parallel with the inductor. Record the voltage, V, in the table.

- Now change the power supply frequency to 100Hz and repeat the measurements.

- Record them in the table.

- Do the same for frequencies of 500Hz and 1kHz (1,000Hz).

- Again, record these measurements in the table.

Frequency	Current I	Voltage V
50 Hz		
100 Hz		
500 Hz		
1 kHz		

So what?

- Resistors behave in a linear way. From Ohm's Law we know that if you double the current through the resistor, you double the voltage dropped across it, and so on.
  The ratio of voltage to current is called resistance.

- Inductors are more complicated. If you double the *rate of change* of current through the inductor, you double the voltage dropped across it, and so on. The ratio of voltage to rate of change of current is called **inductance L**.

- The higher the AC frequency, the faster the current changes, and so the greater the voltage drop across the inductor. In other words, the voltage dropped depends on the frequency of the AC supply. This is **not** the case with pure resistors, where the frequency has no effect.

- We describe this behaviour in terms of the **(inductive) reactance**, X_L, defined, in the same way as resistance, as $X_L = V / I$. As a result, the units of reactance are ohms.

- The inductive reactance measures the opposition of the inductor to changing current. The higher the frequency ,**f**, the greater the change in current. In fact, the formula for inductive reactance is: $X_L = 2 \pi f L$

- Using your measurements, calculate the X_L, from the formula:
  $$X_L = V / I$$
  and compare that with the value calculated using
  $$X_L = 2 \pi f L \qquad \text{where } L = 47mH$$

- Complete the following table showing your results:

Frequency	Inductive reactance from $X_L = V / I$	Inductive reactance from $X_L = 2 \pi f L$
50Hz		
100Hz		
500Hz		
1kHz		

For your records:

The opposition of an inductor to changing currents is called inductive reactance, X_L,.

It is calculated from the formula: $X_L = 2 \pi f L$ where f is the frequency of the AC signal, and L is the inductance of the inductor. It can also be obtained from the formula $X_L = V / I$, where V and I are RMS voltage and current respectively.

Inductance is measured in a unit called the henry, (H) and reactance in ohms.

Complete the following:

When the AC frequency is doubled, the inductive reactance is ………….………… .

When the AC frequency is halved, the inductive reactance is ……………..……… .

Worksheet 3
AC and capacitance

An electric current sets up a **magnetic** field inside an inductor. This then oppose changes to electric *currents*.
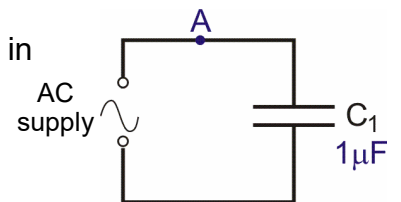
An electric current sets up an **electric** field across the plates of a capacitor. This opposes changes to the *voltage* applied to the capacitor.

Before the voltage can increase, electrons must flow onto the plates of the capacitor, increasing the electric field. This requires energy. When the voltage tries to decrease, electrons flow off the plates, reducing the electric field. These electrons try to maintain the voltage across the capacitor's plates.

Capacitors behave rather like buckets in a water circuit. They must fill up before any water flows anywhere else in the circuit. When the flow of water starts to fall, excess water flows from the bucket, trying to maintain the flow.

Over to you:

- Connect a 1μF capacitor in series with the AC supply, as shown in the circuit diagram.

- Use enough connecting links so that the current can be measured at point **A**.

- Set the AC supply to output a frequency of 50Hz.

- Remove the connecting link at **A**, and connect a multimeter, set to read up to 20mA AC, in its place.

- Record the current flowing at point **A** in the table.

- Set the multimeter to read AC voltages of up to 20V and connect it in parallel with the capacitor.

- Record the voltage in the table.

- Now change the supply frequency to 100Hz and repeat the measurements. Record them in the table.

- Do the same for frequencies of 500Hz and 1kHz (1,000Hz). Once again, record these measurements in the table.

Frequency	Current I	Voltage V
50 Hz		
100 Hz		
500 Hz		
1 kHz		

So what?

- With a resistor, when you double the *current* through it, you double the voltage dropped across it, and so on. With inductors, when you double the rate of change of *current* through it, you double the voltage dropped across it, and so on.

- Capacitors oppose a changing voltage. The faster the rate of change of *voltage*, the greater the current that must flow to charge or discharge the capacitor. The higher the frequency of the AC, the faster the *voltage* changes, and so the greater the current flowing in the circuit. In other words, the current depends on the frequency of the AC supply.

- We describe this behaviour in terms of the **capacitive reactance**, X_C, defined, in the same way as resistance, as $X_C = V / I$. As before, the units of reactance are ohms.

- The capacitive reactance measures the opposition of the capacitor to changing current. The higher the frequency ,**f**, the more rapid the change in voltage, and the greater the current flow. The formula for capacitive reactance is: $X_C = 1/(2 \pi f C)$

- Capacitors are very much a mirror image of inductors. As the frequency of the AC supply increases, an inductor offers more opposition, (i.e. the inductive reactance increases, and the current decreases) whereas a capacitor offers less, (i.e. the capacitive reactance decreases, and the current increases).

- Using your measurements, calculate the X_C, using both :

$$X_C = V / I \quad \text{and} \quad X_C = 1 / (2 \pi f C) \quad \text{where } C = 1\mu F$$

- Complete the following table with your results:

Frequency	Capacitive reactance from $X_C = V / I$	Capacitive reactance from $X_C = 1 / (2 \pi f C)$
50Hz		
100Hz		
500Hz		
1kHz		

For your records:

The opposition of a capacitor to changing voltage is called capacitive reactance, X_C, calculated from the formula: $X_C = 1 / (2 \pi f C)$ where f is the AC frequency , and C is the capacitance of the capacitor. It can also be obtained from the formula $X_C = V / I$, where V and I are RMS voltage and current respectively.

Capacitance is measured in farads (F), though most capacitors have values given in microfarads (μF).

Complete the following:

When the AC frequency is doubled, the capacitive reactance is ……………..………

When the AC frequency is halved, the capacitive reactance is ……………..………
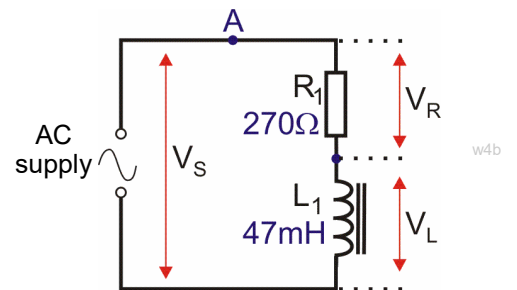
Worksheet 4

L-R series AC circuit

When an inductor and a resistor are connected in series, the pair acts as a voltage divider, but with an important difference - the way it shares the AC voltage changes with the frequency of the AC supply. The circuit is known as a series L-R circuit. As it is a series circuit, the same current flows everywhere.

The opposition to the current comes in two forms - the resistance of the resistor, which is independent of frequency, and the reactance of the inductor, which increases as the frequency increases. Together, these combine to make what is known as the impedance of the circuit.

Over to you:

- Connect a 270Ω resistor, and a 47mH inductor in series with the AC supply, as shown in the circuit diagram.

- Use enough connecting links so that the current can be measured at point **A**.

- Set the AC supply to output a frequency of 100Hz.

- Remove the connecting link at **A**, and connect a multimeter, set to read up to 20mA AC, in its place. Record the current flowing at point **A** in the table.

- Remove the multimeter and replace link **A**.

- Set the multimeter to read AC voltages of up to 20V. Connect it to measure the AC supply voltage, V_s, applied across the two components, and record it in the table.

- Measure the voltage V_L, across the inductor, and then the voltage V_R, across the resistor. Record these voltages in the table.

- Next, set the AC supply to a frequency of 1kHz. Repeat the measurements of current and the voltages across the two components, and record them in the table.

Measurement	AC frequency = 100Hz	AC frequency = 1kHz
Current at point A in mA		
Supply voltage V_S		
Voltage V_R across 270Ω resistor		
Voltage V_L across 47mH inductor		

Worksheet 4

L-R series AC circuit

So what?

- There are two effects limiting the current - the **resistance** R (270Ω) , and the **reactance** X_L.

  At the first frequency, (100Hz): $X_L = 2 \pi f L$

  $$= 2 \pi (100) \times (47 \times 10^{-3})$$

  $$= 29.5\Omega$$

- We cannot just add together resistance and reactance, because of a phase shift involved.

  The voltage across the resistor is **in phase** with the current through it.

  The voltage across the inductor is **90^0 ahead** of the current .

  We combine them using the formula for impedance, Z, which takes this into account:

  $$Z = (R^2 + (X_L - X_C)^2)^{½}$$

  In this case, there is no capacitive reactance, and so: $Z = (R^2 + X_L{}^2)^{½}$

  $$= ((270)^2 + (29.5)^2)^{½}$$

  $$= 271.61\Omega$$

- Using this value of impedance, current $I = V_S / Z$ where V_S = AC supply voltage

  so: I = ... mA   (- use your value of V_S here)

  and so the voltage across the resistor, V_R:

      = ... V   (using $V_R = I \times R$)

  and the voltage across the inductor, V_L:

      = ... V   (using $V_L = I \times X_L$)

- Check these results against your measured values.

- **At 1kHz:**

  we expect the share of the supply voltage to change. The higher frequency the greater the reactance of the inductor. As the new frequency is 10 times bigger, the reactance is 10 times bigger (i.e. 295.3 Ω) and the inductor takes a bigger share of the supply voltage.

- Repeat the above calculations at the new frequency.

- .Compare the results with your measured values.

For your records:

At a frequency f, the reactance of an inductor is: $X_L = 2 \pi f L$

and the impedance of a L-R circuit is: $Z = (R^2 + X_L{}^2)^{½}$

The (RMS) current is given by: $I = V_S / Z$ where V_S = RMS AC supply voltage.

The resulting voltage across the resistor is $V_R = I \times R$ and across the inductor $V_L = I \times X_L$

When the RMS value of supply voltage is used, all other currents and voltages will be RMS.

When the peak value is used, all other currents and voltages will be peak values too.
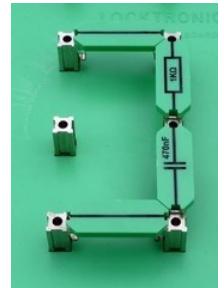
Worksheet 5
C-R series AC circuit

When an inductor and a resistor are connected in series, the pair acts as a voltage divider. The way they share the AC voltage depends on the frequency of the AC supply because the reactance of the inductor **increases** as the frequency increases.

The same is true when a capacitor and resistor are connected in series, but with an important difference - the reactance of the capacitor **decreases** as the frequency increases.

This type of circuit is known as a series C-R circuit. As before, the same current flows in all parts of the circuit.

Over to you:

- Connect a 270Ω resistor, and a 1μF capacitor in series with the AC supply, as shown in the circuit diagram.

- Use enough connecting links so that the current can be measured at point **A**.

- Set the AC supply to output a frequency of 100Hz.

- Remove the connecting link at **A**, and connect a multimeter, set to read up to 20mA AC, in its place. Record the current flowing at point **A** in the table.

- Remove the multimeter and replace link **A**.

- Set the multimeter to read AC voltages of up to 20V. Connect it to measure the AC supply voltage, V_S, applied across the two components, and record it in the table.

- Measure the voltage V_C, across the capacitor, and then the voltage V_R, across the resistor. Record these voltages in the table.

- Next, set the AC supply to a frequency of 1kHz. and repeat these measurements. Record them in the table.
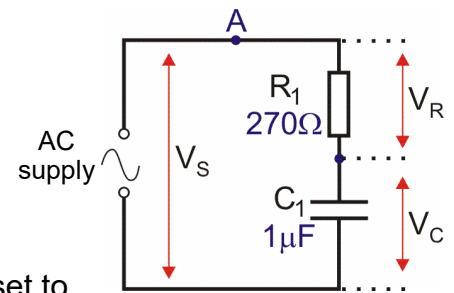
Measurement	AC frequency = 100Hz	AC frequency = 1kHz
Current at point A in mA		
Voltage V_R across 270Ω resistor		
Voltage V_C across 1μF capacitor		

Worksheet 5
C-R series AC circuit

So what?

- The treatment that follows mirrors that used for the previous worksheet.

- The two effects limiting the current are - the **resistance** (270Ω) , and the **reactance** X_C.

  At the first frequency, (100Hz): $X_C = 1 / (2 \pi f C)$

  $= 1 / (2 \pi (100) \times (1 \times 10^{-6})$

  $= 1591.5\Omega$

  The voltage across the resistor is in phase with the current through it.

  The voltage across the capacitor is 90^0 **behind** the current .

  The formula for impedance, Z, takes this phase shift into account:

  $$Z = (R^2 + (X_L - X_C)^2)^{\frac{1}{2}}$$

  In this case, there is no inductive reactance, and so:

  $$Z = (R^2 + X_C^{\ 2})^{\frac{1}{2}}$$
  $$= ((270)^2 + (1591.5)^2)^{\frac{1}{2}}$$
  $$= 1614.3\Omega$$

- Using this value of impedance, current $I = V_S / Z$ where V_S = AC supply voltage

  so: I = ... mA   (- use your value of V_S here)

  and so the voltage across the resistor, V_R:

  = ... V   (using $V_R = I \times R$)

  and the voltage across the capacitor, V_C:

  = ... V   (using $V_C = I \times X_C$)

- Check these results against your measured values.

- **At 1kHz:**

  Notice how the share of the supply voltage changes this time. The higher frequency reduces the reactance of the capacitor. As the new frequency is 10 times *higher*, the reactance is 10 times *smaller* (i.e. 159.2 Ω.) and the capacitor takes a lower share of the supply voltage.

- Repeat the above calculations at the new frequency.

- .Compare the results with your measured values.

For your records:

At a frequency f, the reactance of a capacitor is: $X_C = 1 / (2 \pi f C)$

and the impedance of a C-R circuit is: $Z = (R^2 + X_C^{\ 2})^{\frac{1}{2}}$

The (rms) current is given by: $I = V_S / Z$ where V_s = (rms) AC supply voltage.

The resulting voltage across the resistor is $V_R = I \times R$ and across the capacitor $V_C = I \times X_C$

Worksheet 6
L-C-R series AC circuit

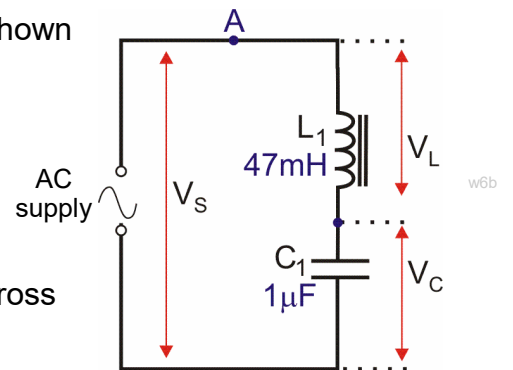At this point, circuits become very interesting!

Inductors have a reactance that increases with frequency. Capacitors have a reactance that decreases with frequency, Resistors don't care about frequency.

A series LCR circuit has all three elements, though the resistance may be that of the wire used in the inductor, rather than of a discrete resistor.

One frequency, known as the *resonant frequency*, causes the circuit to behave in an extraordinary way!

Over to you:

- Connect a 47mH inductor and a 1μF capacitor in series, as shown in the circuit diagram.

- Set the AC supply to output a frequency of **100Hz**.

- Measure the AC current, I, at **A** and record it in the table.

- Set the multimeter to read AC voltages of up to 20V.

- Connect it to measure the AC supply voltage, V_S, applied across the two components, and record them in the table.

- Change the frequency to 200Hz. Repeat the measurements and record them in the table.

- Repeat and record the measurements for each of the other frequencies listed.

| Frequency in Hz	AC supply voltage V_S in V	Current I at A in mA	Impedance Z in kΩ
100			
200			
300			
400			
500			
600			
700			
800			
900			
1000			

Worksheet 6
L-C-R series AC circuit

So what?

- Your results table may not make it obvious what is happening, partly because the output impedance of the AC supply will probably have an effect on output voltage. This will be clearer when we look at the impedance of the circuit.

- Complete the table, by calculating the impedance, Z, at different frequencies, using the formula: $Z = V_S / I$

- At low frequencies, the capacitor has a high reactance, and the inductor a low reactance.

- As frequency rises, the capacitor's reactance falls, but the inductor's reactance increases.

- There is one value of frequency, called the resonant frequency, where the combined effect of the two is a minimum. At this frequency, the impedance of the circuit is a ***minimum***.

- Plot a graph of impedance against frequency, and use it to estimate the resonant frequency. A typical frequency response curve is shown on the right.

Frequency in Hz x 100
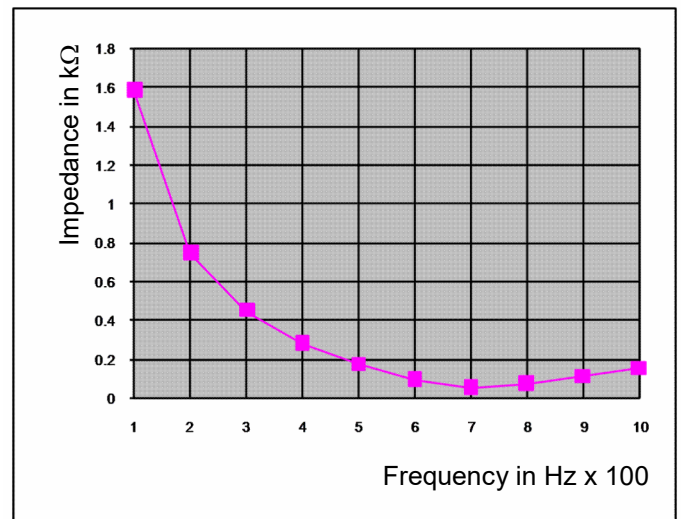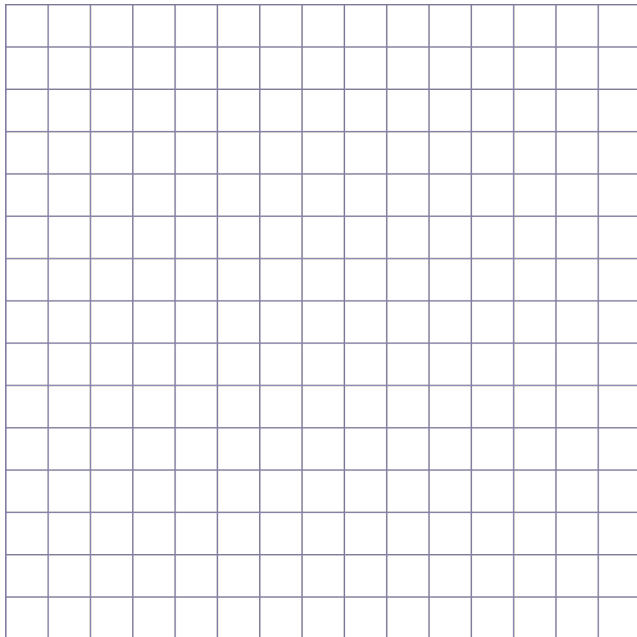
For your records:

For a series LCR circuit, the impedance is a minimum at the resonant frequency, f_R.

This can be calculated from the formula $f_R = 1 / 2 \pi \sqrt{(L \times C)}$
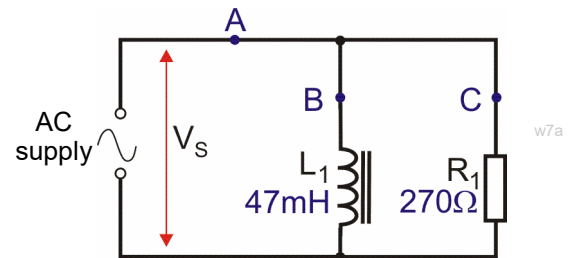
Worksheet 7

L- R parallel AC circuit

When an inductor and a resistor are connected in parallel, the pair act as a current divider, which shares the AC current in a way that changes with the frequency of the AC supply. Since the inductor and resistor are connected in parallel, they have the same voltage across them, but pass a current which depends on resistance / reactance.

Over to you:

- Connect a 270Ω resistor and a 47mH inductor in parallel with the AC supply, as shown.

- Use enough connecting links so that the current can be measured at points **A**, **B** and **C**.

- Set the AC supply to output a frequency of 100Hz.

- Measure, and record, the current flowing at point **A** .

- Do the same for the currents flowing at points **B** and **C**.

- Set the multimeter to read AC voltages of up to 20V. Connect it to measure the AC supply voltage, V_S, applied across the two components, and record it in the table.

- Next, set the AC supply to a frequency of 1kHz.

- Repeat the measurements , and record them in the table.

Measurement	AC frequency = 100Hz	AC frequency = 1kHz
Current at point A in mA		
Current at point B in mA		
Current at point C in mA		
Supply voltage V_S		

So what?

- As before, we are going to calculate the quantities you measured, so that you can compare the two. Use your value of V_S to complete the calculations below.

At a frequency of 100Hz:

Resistance of resistor R_1 = 270Ω,

and so the current through it, (at point **C**,) I_C = V_S / R = ... / 270 = ... A

Reactance X_L of inductor L_1 is given by:

$$X_L = 2 \pi f L$$
$$= 2 \pi (100) \text{ x } (47 \times 10^{-3})$$
$$= 29.5\Omega$$

and so the current through it, (at point **B**,) I_B = V_S / X_L = ... / 29.5 = ... A

The current at **A**, I_A, is found by combining these currents, but not by simply adding them. These currents are not in phase! The current, I_C, through the resistor is in phase with V_S. The current, I_B, through the inductor lags behind V_S by 90^0.

The currents can be combined using the formula: $I_A^2 = I_B^2 + I_C^2$

or: $\qquad\qquad\qquad\qquad\qquad\qquad I_A = \sqrt{(I_B^2 + I_C^2)}$

Use your results to the calculations above to calculate a value for I_A.

- Check these results against your measured values.

At a frequency of 1kHz:

- Notice how the share of the *current* changes. The reactance of the inductor is 10 times bigger (i.e. 295.3Ω.) Thus, the inductor offers a much more difficult route for the current, and so passes a much smaller current.

- Repeat the calculations at the new frequency, and check your results against the measured values.

For your records:

For a parallel combination of a resistor and inductor,
the total current I_S is given by:

$$I_S^2 = I_L^2 + I_R^2$$

where I_L = current through inductor and I_R = current through resistor.

Using the AC version of Ohm's Law:

$$I_L = V_S / X_L \quad \text{and} \quad I_R = V_S / R$$
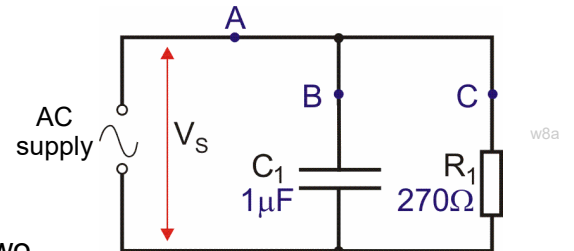
Worksheet 8
C - R parallel AC circuit

When a capacitor and a resistor are connected in parallel, they act as a current divider, sharing the AC current in a way that changes with the frequency of the AC supply.

However, in this case, when the supply frequency increases, the reactance of the capacitor *decreases*, making it an *easier* route for the current to flow though.

Over to you:

- Connect a 270Ω resistor and a 1μF capacitor in parallel with the AC supply, as shown.

- Use enough connecting links so that the current can be measured at points **A**, **B** and **C**.

- Set the AC supply to output a frequency of 100Hz.

- Measure the current at point **A**. Record it in the table.

- Do the same for the currents flowing at points **B** and **C**.

- Measure the AC supply voltage, V_S, applied across the two components, and record it in the table.

- Next, set the AC supply to a frequency of 1kHz.

- Repeat the measurements, and record them in the table.

Measurement	AC frequency = 100Hz	AC frequency = 1kHz
Current at point A in mA		
Current at point B in mA		
Current at point C in mA		
Supply voltage V_S		

Worksheet 8
C - R parallel AC circuit

So what?

- As before, we are going to calculate the quantities you measured, so that you can compare the two. Use your value of V_S to complete the calculations below.

At a frequency of 100Hz:

Resistance of resistor R_1 = 270Ω,

and so the current through it, (at point **C**,) I_C = V_S / R = ... / 270 = ... A

Reactance X_C of capacitor C_1 is given by:

$$X_C = 1 / (2 \pi f C)$$
$$= 1 / (2 \pi (100) \times (1 \times 10^{-6}))$$
$$= 1591.5\Omega$$

and so the current through it, (at point **B**,) I_B = V_S / X_C = ... / 1591.5 = ... A

Again, these currents are not in phase.

The current through the resistor is in phase with V_S.

The current, I_B, through the capacitor leads V_S by 90^0.

The current at **A**, I_A, is found by combining these currents, using the formula:

$$I_A^2 = I_B^2 + I_C^2$$

or:
$$I_A = \sqrt{(I_B^2 + I_C^2)}$$

Use your results to the calculations above to calculate a value for I_A.

- Check these results against your measured values.

At a frequency of 1kHz:

- Once again. notice how the share of the current changes. The reactance of the capacitor is 10 times *smaller* (i.e. 159.2Ω.) Thus, the capacitor offers an easier path for the current and so passes a *bigger* current.

- Repeat the calculations at the new frequency, and check your results against the measured values.

For your records:

For a parallel combination of a resistor and capacitor,

the total current I_S is given by:

$$I_S^2 = I_C^2 + I_R^2$$

where I_C = current through capacitor and I_R = current through resistor.

Using the AC version of Ohm's Law:

$$I_C = V_S / X_C \quad \text{and} \quad I_R = V_S / R$$

Worksheet 9
L-C-R parallel AC circuit

The question of resonance again! Earlier, you looked at a series circuit. It favoured one particular frequency, called the resonant frequency, more than any other. Now for a parallel circuit.

Remember:
Inductors have a reactance that ***increases*** with frequency.
Capacitors have a reactance that ***decreases*** with frequency.
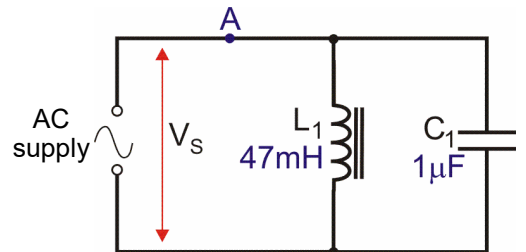**Resistors don't care** about frequency.

The parallel circuit has an inductor connected in parallel with a capacitor. In reality, the resistance of the wire used to make the inductor appears in series with the inductor. To begin with, we assume that this is so small that we can ignore it. The procedure is the same as that used for the series circuit - measure current and voltage over a range of frequencies, and use these to calculate the impedance of the circuit at that frequency.

Over to you:

- Connect a 47mH inductor and a 1µF capacitor in parallel, as shown in the circuit diagram.

- Set the AC supply to output a frequency of **100Hz**.

- Measure the current at A and record it in the table.

- Measure the AC supply voltage, V_s, applied across the two components, and record it in the table.

- Change the frequency to 200Hz, and repeat the measurements. Again record them in the table.

- Do the same for the other frequencies listed, and complete the table.

| Frequency in Hz	AC supply voltage V_S in V	Current I at A in mA	Impedance Z in kΩ
100			
200			
300			
400			
500			
600			
700			
800			
900			
1000			

Worksheet 9

L-C-R parallel AC circuit

So what?

- As before, the results will look clearer when we calculate the impedance of the circuit at the different frequencies.

- Complete the fourth column of the table by calculating the impedance, Z, at each frequency, using the formula: $Z = V_S / I$

- At low frequencies, the capacitor has a high reactance, and the inductor a low reactance, and so more current flows through the inductor than through the capacitor.

- As the frequency rises, the capacitor's reactance falls, but the inductor's reactance increases. Gradually, the capacitor offers an easier path for the current than does the inductor. The resonant frequency is where the combined effect of the two, the circuit impedance, is a ***maximum***.

- Plot a graph of impedance against frequency, and use it to estimate the resonant frequency. A typical frequency response curve is shown opposite.

w9c

w9d
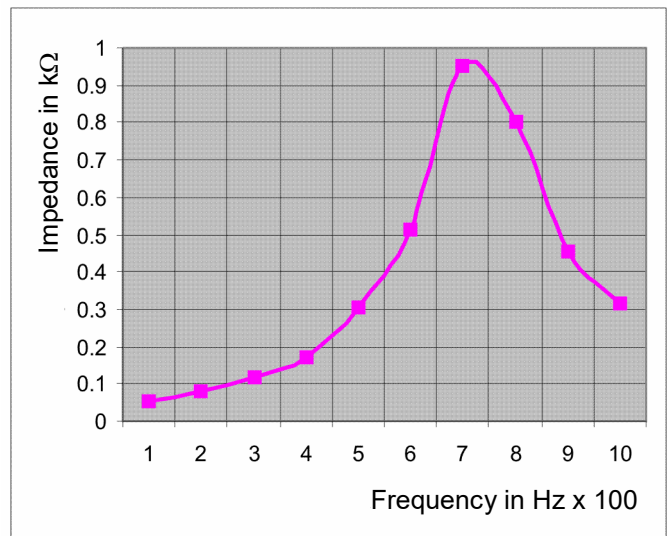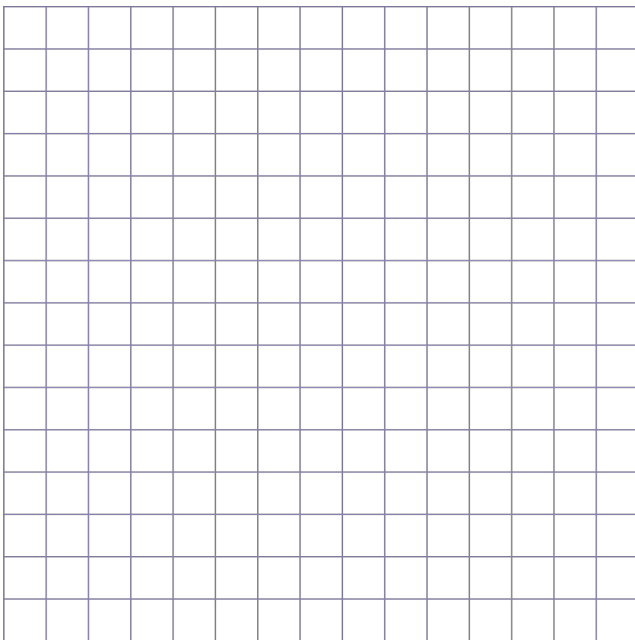
For your records:

For a parallel LCR circuit, the impedance is a maximum at the resonant frequency, f_R.

At frequencies below f_R, the inductor offers an easier route for the current.

At frequencies above f_R, the capacitor offers an easier route.

Worksheet 10
Q-factor and bandwidth

What connects trombones, bridges and wine glasses with LCR circuits? They all have a resonant frequency. In trombones, air vibrates at the resonant frequency, producing a musical note - usually desirable!

Resonance can have undesirable effects too. Everyone has heard of the opera singer singing so loud that she shatters a wine glass. Bridges can also resonate. In 1940, the bridge over Tacoma Narrows, near Seattle, USA, collapsed when the wind blowing over it made it vibrate at its resonant frequency. The replacement was made more rigid - more resistant to vibration!

Well - LCR circuits behave in the same way when you add some resistance! It suppresses the vibration, making it less likely to build up.

Over to you:

- Connect a 47mH inductor and a 1μF capacitor in series with the AC supply - the same circuit you used in worksheet 6.

- Set the AC supply to output a frequency of **100Hz**.

- Measure, and record V_S the supply voltage, and V_C the voltage across the capacitor.

- Change the frequency to **200Hz**, repeat the measurements and record them.

- Do the same for the other frequencies listed, and complete columns 2 and 3 of the table.

- Next, connect a 10Ω resistor in series with the inductor and capacitor, and repeat the measurements. Complete columns 4 and 5 with your results.
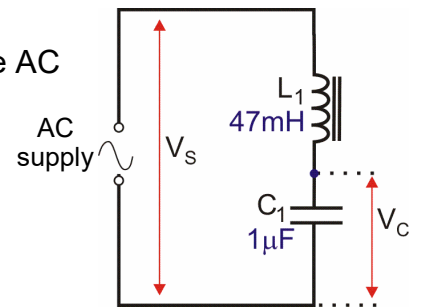
Frequency in Hz	No series resistor		10Ω series resistor		47Ω series resistor	
	V_S in V	V_C in V	V_S in V	V_C in V	V_S in V	V_C in V
100						
200						
300						
400						
500						
600						
700						
800						
900						
1000						

So what?

- The 'Q' in Q factor stands for 'Quality'. There are several ways to view this for a resonant circuit:
    - The higher the quality, the longer it takes for the oscillations to die down.
    - The Q factor is a measure of the sharpness of the peak of the frequency response curve.
    - It is the ratio of energy stored, to the energy lost per cycle of the AC.
    - The higher the quality, the greater the voltage amplification of a resonant circuit.

- **At resonance, the voltage across the inductor, V_L, is equal to the voltage across the capacitor, V_C.**

- **Voltage amplification:**

    The voltage amplification for a network is the ratio V_{OUT} / V_{IN}.

    In this case, it is the ratio of the voltage across the capacitor (or inductor, as it is equal,) to the supply voltage, V_S *at resonance*.

    Complete the table by calculating the ratio (V_C / V_S) for each frequency and for each value of series resistor used. The second, third and fourth columns show the value of the series resistor added to the internal resistance of the inductor.

| Frequency in Hz	0Ω	10Ω	47Ω
	V_C / V_S	V_C / V_S	V_C / V_S
100			
200			
300			
400			
500			
600			
700			
800			
900			
1000			

w10b

Worksheet 10

Q-factor and bandwidth

So what?

- Plot three graphs of voltage amplification against frequency to show the frequency responses of your three circuits:

    - with no added resistor,

    - with 10Ω added in series,

    - and with 47Ω added in series.

- Use the same axes for all three graphs.

- The results should resemble the graphs shown below.

- Use your 0Ω graph to estimate the Q factor of the L-C-R circuit.

- Notice the effect on the shape of the resonance curve, and on its Q factor of adding series resistance to the circuit.

is ....
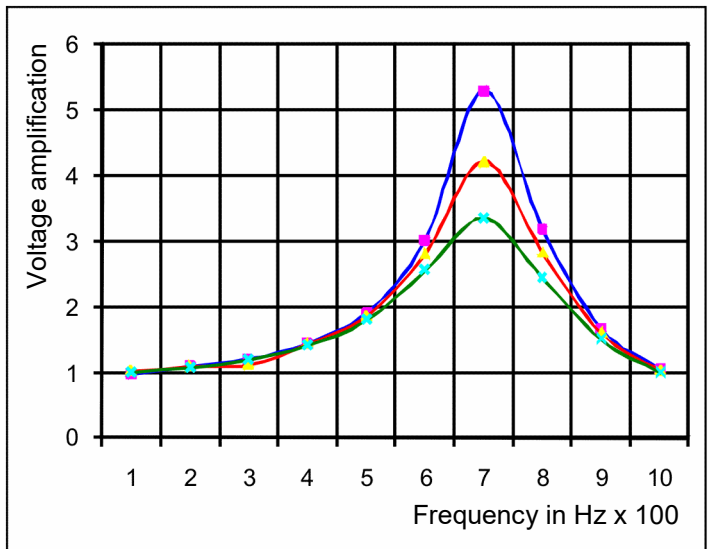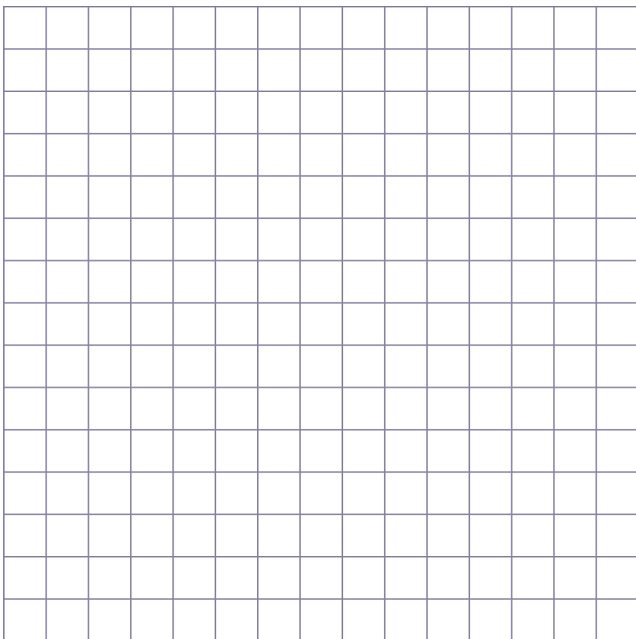
Q factor of L-C-R circuit

Worksheet 10

**Q-factor and bandwidth**

So what?

- Another way to represent the sharpness of the frequency response peak is to calculate its bandwidth.

- The bandwidth of a signal is a measure of the range of frequencies present in it.
  Obviously, there must be a cut-off where we say that any weaker frequency components don't really count. This cut-off is usually taken to be the half-power points.
  On the diagram opposite these occur at the frequencies f_H and f_L.
  The bandwidth is calculated as $f_H - f_L$.
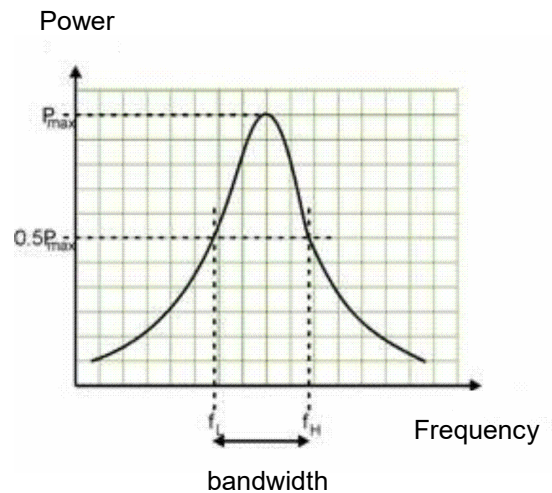
- The formula for electrical power, P, is:
  $$P = I \times V$$
  but, since $I = V / R$, this can be written as:
  $$P = V^2 / R$$
  In other words, the power dissipated depends on (voltage squared).
  This means that the half-power points on a voltage / frequency graph occur where the voltage has dropped to 0.7 of its peak value (because 0.7^2 is roughly equal to 0.5, i.e. half-power)

- Estimate the bandwidth of the resonant frequency curve for each of your three graphs.

For your records:

At resonance:

the voltage across the inductor, V_L, and the voltage across the capacitor, V_C are equal.

The higher the Q factor, the greater the voltage amplification of a resonant circuit.
Voltage amplification is the ratio of the voltage across the capacitor (or inductor, as it is equal,) to the supply voltage, V_S *at resonance*. In other words: Q factor = V_C / V_S

The bandwidth of a signal is a measure of the range of frequencies present in it.
It is defined as the range of frequencies between the half-power points, f_H and f_L or in other words, bandwidth = $f_H - f_L$. On a voltage / frequency graph, it is the frequency range between the points where the signal voltage has dropped to 0.7 (70%) of its peak value.

The effect of increasing the resistance in the resonant circuit is to reduce the Q factor, and increase the bandwidth of the resonance peak.

Worksheet 11
Low-pass filter

w11x

Filters used for signal applications are designed to work with specific input (source) and output (load) impedances, often 600Ω, 300Ω, 75Ω or 50Ω.

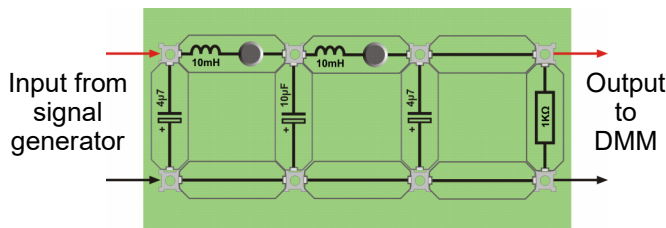Filters are also used in power line applications to remove noise and unwanted signals.

Low-pass filters pass signals at frequencies lower than the cut-off frequency and reject signals above that.

Over to you:

- Build the low-pass filter circuit shown below:
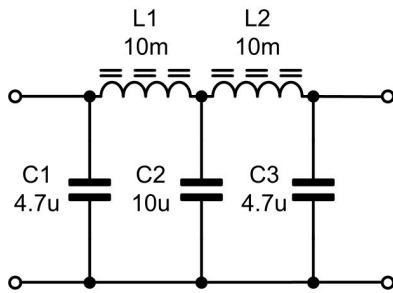
w11a

- A suitable Locktronics layout is shown in the picture.

w11b

Input from signal generator

Output to DMM

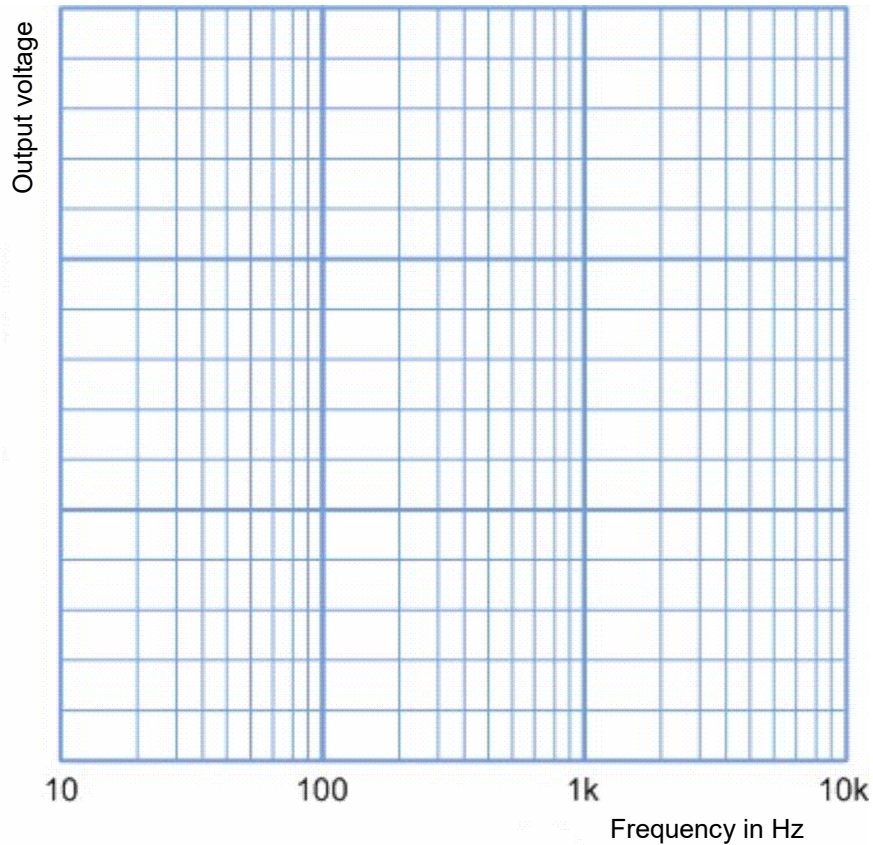| Frequency in hertz	Filter output voltage
10	
20	
30	
40	
60	
80	
100	
200	
300	
400	
600	
1000	
2000	

- Test it using a signal generator to provide an input signal and an AC voltmeter to measure the resulting output voltage. The signal generator should have an output impedance of 50Ω.

- Set the signal generator to output a sine wave with an amplitude of 1V.

- Vary the output frequency over the range 10Hz to 2kHz and, at each frequency, measure and record the output voltage.

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So what?

- Plot a graph showing how the output voltage varies with frequency.

Output voltage

10   100   1k   10k

Frequency in Hz

- Does the   shape of
  this graph match your expectations for a low-pass filter?

- Determine the cut-off frequency for the filter (where the output voltage has fallen to 70% of its maximum value).

For your records:

Low-pass filters:

The circuit of a simple low-pass filter is shown opposite.

To understand how this works, recall that the reactance of an inductor increases with frequency whilst the reactance of a capacitor decreases with frequency.

The result is a circuit that passes low-frequency signals and rejects high-frequency signals.

The cut-off frequency of the filter is determined by the values used for L1, L2, C1, C2 and C3.

L1 10m   L2 10m

C1 4.7u   C2 10u   C3 4.7u
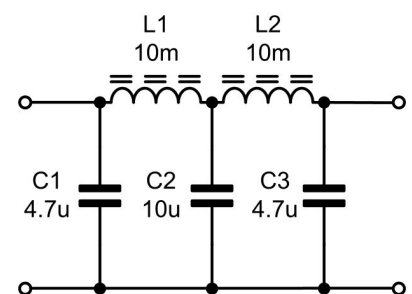
Worksheet 12
High-pass filter

As pointed out on the last worksheet, filters used for signal applications are designed to work with specific input (source) and output (load) impedances, often 600Ω, 300Ω, 75Ω or 50Ω.

High-pass filters pass signals at frequencies above their cut-off frequency and reject signals below it. The cut-off frequency occurs when the output voltage has fallen to 70% of its maximum value (corresponding to what are known as the half-power points, as before).

These filters can also be made from arrangements of inductors and capacitors.
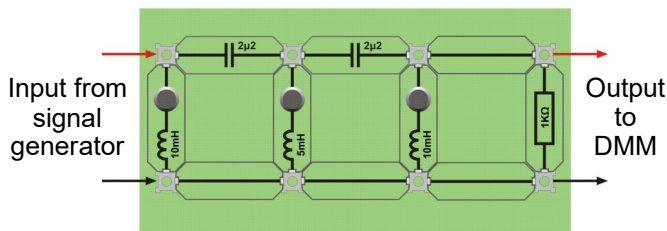In this worksheet you will investigate the performance of a high-pass filter.

Over to you:

- Build the high-pass filter circuit shown below:
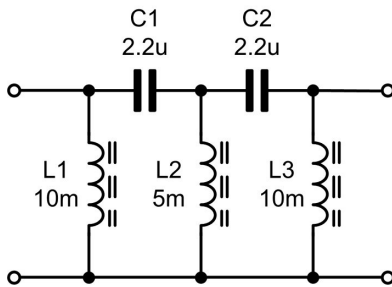
- A suitable Locktronics layout is shown in the picture.

Frequency in hertz	Filter output voltage
100	
200	
500	
600	
800	
1000	
1500	
2000	
3000	
4000	
6000	
8000	
10000	

- Test it using a signal generator to provide an input signal and an AC voltmeter to measure the resulting output voltage. Again, the signal generator should have an output impedance of 50Ω.

- Set the signal generator to output a sine wave with an amplitude of 1V.

- Vary the output frequency over the range 100Hz to 10kHz and, at each frequency, measure and record the output voltage.
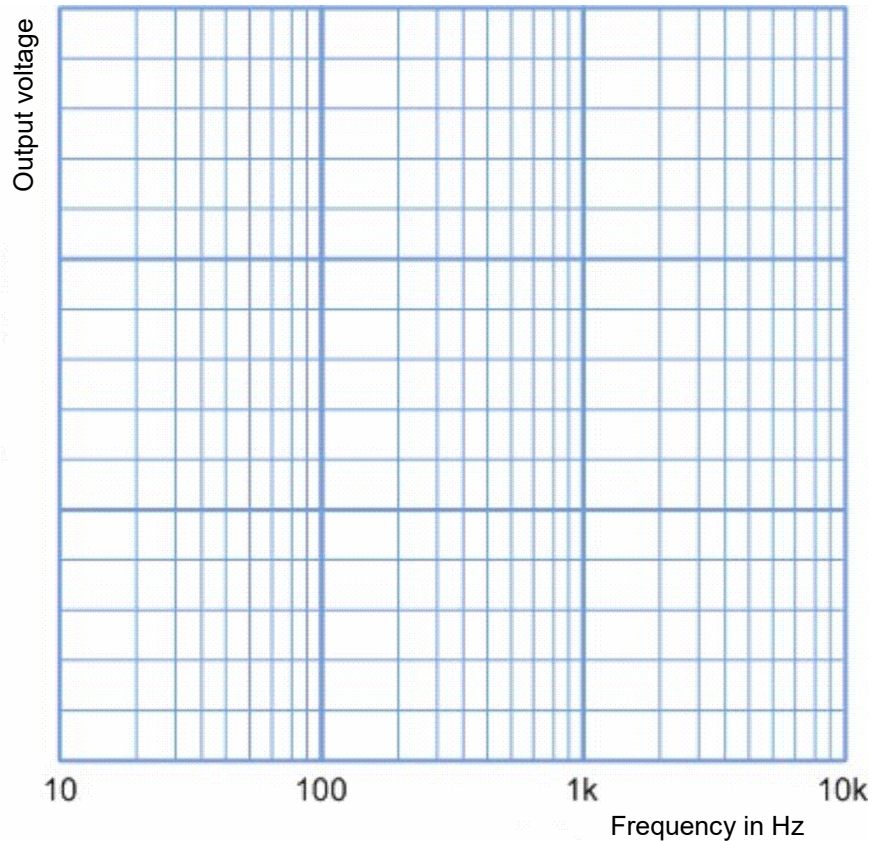
Worksheet 12
High-pass filter

So what?

- Plot a graph showing how the output voltage varies with frequency.

w12c

- Does the shape of this graph match your expectations for a high-pass filter?

- Determine the cut-off frequency for the filter (where the output voltage has fallen to 70% of its maximum value).

For your records:

High-pass filters:

The circuit of a simple high-pass filter is shown opposite.

To understand how this works, recall that the reactance of an inductor increases with frequency whilst the reactance of a capacitor decreases with frequency.

The result is a circuit that passes high-frequency signals and rejects low-frequency signals.

The cut-off frequency of the filter is determined by the values used for L1, L2, C1, C2 and C3.

w12d
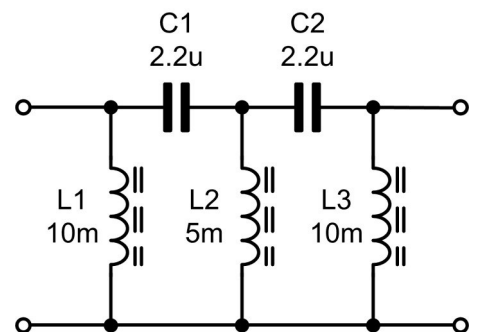
Worksheet 13
Band-pass filter

Band-pass filters pass signals within a pre-determined frequency range and reject signals outside this range. They have two cut-off frequencies, lower and upper. These occur at frequencies where the output voltage has fallen to 70% of its maximum value - the 'half-power points'..

In this worksheet you investigate the performance of a simple band-pass filter, again made from an inductor - capacitor network.

Over to you:

- Build the band-pass filter circuit shown below:
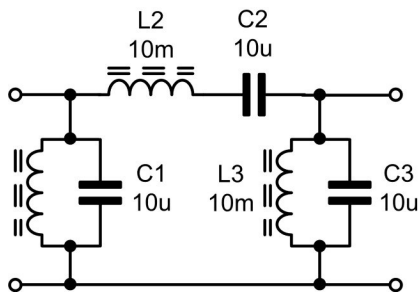
- A suitable Locktronics layout is shown in the picture.

Frequency in hertz	Filter output voltage
30	
60	
80	
100	
200	
300	
400	
500	
600	
800	
1000	
1500	
2000	

- Test it using a signal generator to provide an input signal and an AC voltmeter to measure the output voltage.

  Again, the signal generator should have an output impedance of 50Ω.

- Set the signal generator to output a sine wave with an amplitude of 1V.

- Vary the output frequency over the range 30Hz to 2kHz and, at each frequency, measure and record the output voltage.

So what?

- Plot a graph showing how the output voltage varies with frequency.

- Does the   shape of this graph match your expectations for a high-pass filter?

- Determine the two cut-off frequencies for the filter (where the output voltage has fallen to 70% of its maximum value).

For your records:

Band-pass filters:

The circuit of a band-pass filter is shown opposite.

In this circuit, a series-tuned network, of L2 and C2, is connected in series with the signal path. Two parallel-tuned networks, made from L1 and C1, and L3 and C3, are connected in parallel with the signal path.

The result is a circuit that rejects signals at low and high frequencies but accepts signals over a middle range of frequencies..

Worksheet 14
Band-stop filter

Band-stop filters reject signals within a pre-determined frequency range and pass signals outside this range. Band-stop filters have two cut-off frequencies, lower and upper. These occur at the frequencies where the output voltage has fallen to 70% of its maximum value .

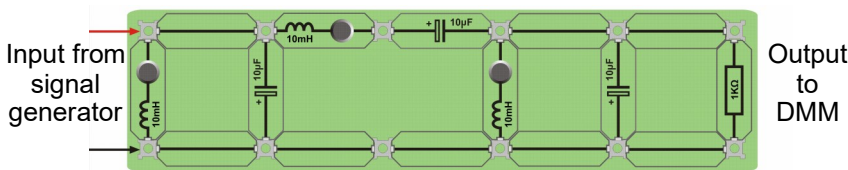In this worksheet you will investigate the performance of a band-stop filter made from inductors and capacitors.

Over to you:

- Build the band-pass filter circuit shown below:

w14a

L2
10m

L1
10m

C2
10u

L3
10m

C1
10u

C3
10u

- A suitable Locktronics layout is shown in the picture.

w14b

Input from signal generator

Output to DMM
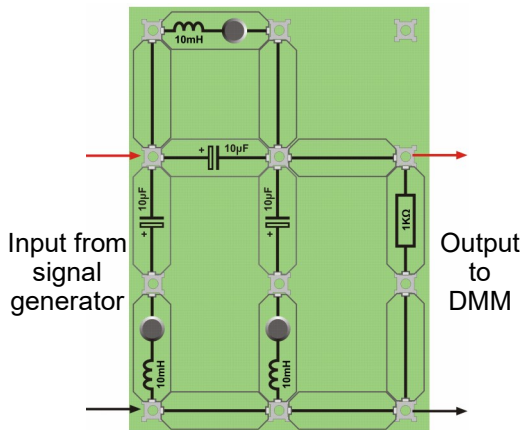
Frequency in hertz	Filter output voltage
20	
60	
80	
100	
200	
300	
400	
500	
600	
800	
1000	
2000	
3000	
4000	

- Test it using a signal generator to provide an input signal and an AC voltmeter to measure the output voltage. Again, the signal generator should have an output impedance of 50Ω.

- Set the signal generator to output a sine wave with an amplitude of 1V.

- Vary the output frequency over the range 20Hz to 4kHz and, at each frequency, measure and record the output voltage.
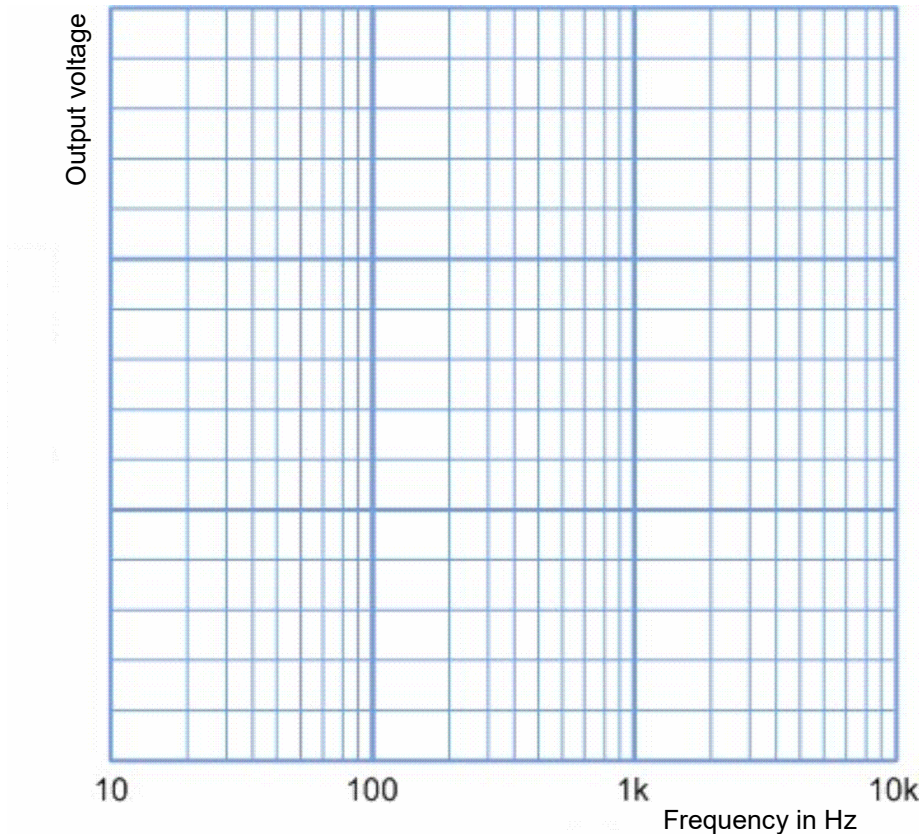
So what?

- Plot a graph showing how the output voltage varies with frequency.

Frequency in Hz

- Does the shape of this graph match your expectations for a high-pass filter?

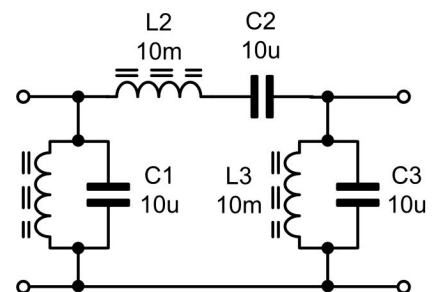- Determine the cut-off frequencies for the filter (where the output voltage has fallen to 70% of its maximum value).

For your records:

Band-stop filters:

The circuit of a simple band-stop filter is shown opposite.

In this circuit a parallel-tuned network, of L2 and C2, is connected in series with the signal path. Two series-tuned circuits, made from L1 and C1, and L3 and C3, are connected in parallel with the signal path.

The result is a circuit that passes signals at low and high frequencies but rejects signals over a middle range of frequencies..
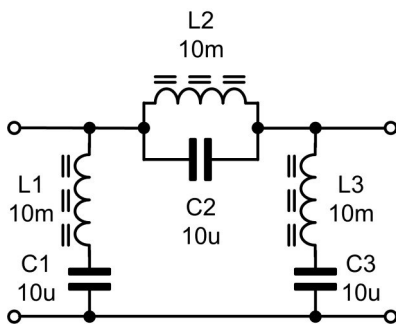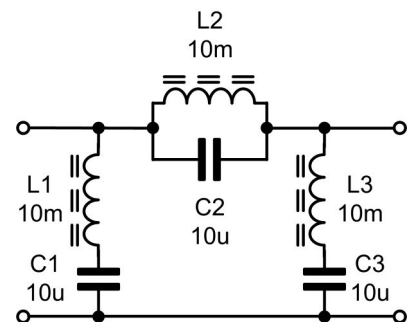
Revision Questions

About these questions

These questions are typical of those that you will be required to answer in the EASA Part-66 examination.

You should allow 15 minutes to answer these questions and then check your answers with those given on page 50.

Please remember that **ALL** these questions must be attempted **without** the use of a calculator and that the pass mark for all Part-66 multiple-choice examinations is 75%!

1. What is the periodic time of a 400Hz aircraft AC supply?
(a)   2.5ms
(b)   25ms
(c)   400ms

2. A sine wave has a periodic time of 0.5ms. What is its frequency?
(a)   200Hz
(b)   2kHz
(c)   20kHz

3. Which one of the following AC quantities is the same as the equivalent DC heating effect?
(a)   Root mean square
(b)   Average
(c)   Peak.

4. A sine wave has a peak value of 10V. What is its RMS value?
(a)   5V
(b)   7.07V
(c)   14.14V

5. A sine wave has an RMS value of 5A. What is its peak value?
(a)   6.37A
(b)   7.07A
(c)   10A.

6. A sine wave has a peak-peak value of 282.8V. What is its RMS value?
(a)   100V
(b)   141.4V
(c)   200V.

7. Inductive reactance:
(a)   increases with frequency
(b)   decreases with frequency
(c)   does not change with frequency.

8. If the frequency of the current flowing in a capacitor is doubled the current will:

(a)   be doubled

(b)   be halved

(c)   stay the same.

9. One advantage of using AC electrical power in aircraft is:

(a)   the greater ease in stepping the voltage up or down

(b)   AC electrical motors can be reversed while DC motors cannot

(c)   the effective voltage is 1.41 times the maximum instantaneous voltage; therefore, less power input is required.

10. A transformer has an input of 120V and a turns ratio of 4:1. What will the output voltage be:

(a)   30V

(b)   60V

(c)   480V.

11. A transformer with 115 V primary voltage and a ratio of 5:1 is used to supply a landing light rated at 24 V 45 A. What current will be supplied to the transformer?

(a)   205A

(b)   9A

(c)   4.5A.

12. In a parallel tuned circuit at resonance, the impedance will be:

(a)   minimum

(b)   maximum

(c)   zero.

14. A high pass filter consists of:

(a)   an inductor in parallel and a capacitor in series

(b)   a capacitor in parallel and an inductor in series

(c)   an inductor in series and a resistor in parallel.

15. A filter that rejects signals at all frequencies outside a given range is called:

(a)   a band-pass filter

(b)   a band-stop filter

(c)   a low-pass filter.

w2c

Answers are provided on page 46

Tutor's notes

About this course

Introduction
This workbook is intended to reinforce the learning that takes place in the classroom or lecture room. It provides a series of practical activities and investigations that complement syllabus sections 3.13 to 3.16 of EASA Part-66 Module 3, Electrical Fundamentals.

Locktronics kit makes it simple and quick to construct and investigate electrical circuits. The end result can look exactly like the circuit diagram, thanks to the symbols printed on each component carrier.

Aim
The workbook aims to introduce students to the basic underpinning principles and concepts of aircraft electrical and electronic equipment. It also provides a useful introduction to AC measurements in resistive, capacitive and inductive (LCR) circuits, transformers and filters.

Prior Knowledge
Students should have previously studied (or should be concurrently studying) Module 1 (Mathematics) and Module 2 (Physics) or should have equivalent knowledge at Level 2.

Learning Objectives
On successful completion of this course the student will have learned:

- the meaning of the terms amplitude, frequency and period applied to sinusoidal AC signals;
- how to carry out measurements in AC circuits using a signal generator and oscilloscope;
- the meaning of inductive reactance, and its dependence on frequency;
- the meaning of capacitive reactance, and its dependence on frequency;
- the meaning of impedance, and its dependence on inductive and capacitive reactance;
- the significance of rms quantities and the relationship with peak values for sinusoidal signals;
- the relationship between current and voltage in an AC circuit containing a series or parallel combination of resistance and reactance
- the behaviour of series and parallel resonant circuits with changing frequency;
- how to measure resonant frequency for series and parallel resonant circuits;
- the relationship between total current and currents through reactive components in parallel circuits;
- the significance of 'Q factor' in resonant circuits;
- how to measure 'Q factor' in resonant circuits;
- the relationship between Q-factor and bandwidth;
- the relationship between turns ratio, voltage ratio and current ratio for an ideal transformer;
- the relationship between primary and secondary power, power loss, efficiency and regulation for ideal and real transformers;
- the operation and characteristics of simple passive low-pass, high-pass, band-pass and band-stop filters.

Tutor's notes

What the student will need:

To complete the Electrical Fundamentals 4 course, students will have access to the Locktronic parts and equipment listed opposite:

Code	Description	Qty
LK2340	AC voltage source carrier	1
LK2347	MES bulb, 6V, 0.04A	3
LK2350	MES bulb, 6.5V, 0.3A	3
LK4025	Resistor, 10 ohm, 1W 5% (DIN)	1
LK4065	Resistor, 47 ohm, 1/2W, 5% (DIN)	1
LK4100	Resistor, 12 ohm, 1W, 5% (DIN)	1
LK4102	Motor, 6V, open frame	1
LK4123	Transformer, 2:1 turns ratio	1
LK5202	Resistor, 1k, 1/4W, 5% (DIN)	1
LK5203	Resistor, 10k, 1/4W, 5% (DIN)	2
LK5205	Resistor, 270 ohm, 1/2W, 5% (DIN)	1
LK5208	Potentiometer, 250 ohm (DIN)	1
LK5209	Resistor, 5.6k, 1/4W, 5% (DIN)	1
LK5221	Capacitor, 10 uF, Electrolytic, 25V	3
LK5250	Connecting Link	14
LK5291	Lampholder, MES	3
LK5607	Lead - yellow - 500mm, 4mm to 4mm stackable	2
LK5609	Lead - blue - 500mm, 4mm to 4mm stackable	2
LK6205	Capacitor, 1 uF, Polyester	1
LK6206	Capacitor. 4.7uF, electrolytic, 25V	2
LK6207	Switch, push to make, metal strip	1
LK6209	Switch, on/off, metal strip	1
LK6211	Resistor, 22k, 1/4W, 5% (DIN)	1
LK6213	Resistor, 15k, 1/4W, 5% (DIN)	1
LK6214R1	Choke, 10mH	3
LK6214R2	Choke, 47mH	1
LK6214R3	Choke, 5mH	1
LK6217	Capacitor, 2.2 uF, Polyester	2
LK6218	Resistor, 2.2k, 1/4W, 5% (DIN)	1
LK6482	Left hand motor rule apparatus	1
LK7409	AA battery holder carrier	3
LK7483	1:1 transformer with retractable ferrite core	1
LK7485	Alnico Rod Magnet	1
LK7487	Lenz's law kit	1
LK7489	Faraday's law kit	1
LK7746	Solar cell	1
LK7936	Fuse/universal component carrier	1
LK8275	Power supply carrier with battery symbol	2
LK8900	7 x 5 metric baseboard with 4mm pillars	1
LK8988	Thermocouple and carrier	1
LK9381	Ammeter, 0mA to 100mA	1

Tutor's notes

Using this course:

It is expected that the worksheets are printed / photocopied, preferably in colour, for the students' use. Students should retain their own copy of the entire workbook.

Worksheets usually contain:
- an introduction to the topic under investigation and its aircraft application;
- step-by-step instructions for the practical investigation that follows;
- a section headed 'So What?' which aims both to challenge learners by questioning their understanding of a topic and also provides a useful summary of what has been learned.
  It can be used to develop ideas and as a trigger for class discussion.
- a section headed 'For Your Records' which provides important summary information that students should retain for future reference.

This format encourages self-study, with students working at a rate that suits their ability. It is for the tutor to monitor that students' understanding is keeping pace with their progress through the worksheets and to provide additional work that will challenge brighter learners. One way to do this is to 'sign off' each worksheet, as a student completes it, and in the process have a brief chat with the learner to assess their grasp of the ideas involved in the exercises that it contains.

Finally, a set of examination 'Revision Questions' has been provided to conclude the work on each topic. These questions are of mixed difficulty and are typical of those that students will face when they sit their Module 3 CAA examinations. It is recommended that students should attempt these questions under examination conditions and without the use of notes or calculators.

Time:

It will take most students between eight and twelve hours to complete the full set of worksheets. It is expected that a similar length of time will be needed to support the learning in a class, tutorial or self-study environment.

Tutor's notes

Worksheet	Notes for the Tutor	Timing
1	In the first worksheet, students are introduced to alternating current (AC) measurements. They are provided with a brief introduction to the quantities and terminology used in conjunction with AC measurements. Students should be understand the relationship between root-mean-square (RMS), peak and peak-peak values and they should be able to relate these to sinusoidal waveforms displayed on the screen of an oscilloscope. They should also understand the relationship between frequency and periodic time and be able to manipulate the relationship in order to calculate frequency given the periodic time, and vice versa. Waveforms can be displayed using a conventional oscilloscope or using the Picoscope 'virtual instrument'. Students may need a brief introduction to the use, setting up and calibration of these instruments.	20 - 30 minutes
2	The aim of the investigation is introduce the student to the effects of inductive reactance. As students may be unfamiliar with using the AC supply, the instructor should check that it is set to the correct frequency of 50Hz. For those returning to electrical studies after a break, it is an opportunity to revisit the skills involved in using multimeters to measure current and voltage. In particular, students should be reminded that voltage measurements can be made without interrupting the circuit, as the multimeter is then connected in parallel with the resistor under investigation. On the other hand, to measure current at a point in the circuit, the circuit must be broken at that point and the multimeter inserted there to complete the circuit. Instructors need to be aware that the low current ranges on most multimeters are protected by internal fuses. If a student is having difficulty in getting readings from a circuit, it may be that this internal fuse has blown. It is worth having some spare multimeters available, and the means to change those fuses, to streamline the lesson. A comparison is made between resistors, which oppose current, and inductors, which oppose changing current. The instructor might wish to elaborate on this, and expand on what is meant by 'rate of change of current'. Students often find it confusing that reactance is measured in ohms. The point should be made that this comes from the definition of inductive reactance and a formula that looks like, but has nothing to do with, Ohm's law. The opposition caused by resistors is the resistance. However, the opposition caused by inductors is not the inductance, but the inductive reactance. They will need plenty of practice in calculating inductive reactance from the formula: $X_L = 2 \pi f L$ as they confuse the terms X_L, f and L, and find it difficult to convert multipliers such as 'milli' .	20 - 30 minutes

Tutor's notes

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Worksheet	Notes for the Tutor	Timing
3	This is the introductory worksheet for capacitive reactance, equivalent to Worksheet 2 for inductive reactance. It is important that students appreciate that inductors and capacitors are really mirror-images of each other. The former sets up a magnetic field, the latter an electric field. The former has a slowly increasing current, once a voltage is applied to it. The latter has a slowly increasing voltage across it, as a current flows in the circuit. Inductors oppose a changing current, capacitors a changing voltage. This opposition increases with frequency in inductors, but decreases with frequency in capacitors. The treatment given in the worksheet makes no mention of phasor diagrams, but the instructor may wish to introduce these to support the student's understanding. As for inductors, there is widespread confusion among students over the difference between reactance and, in this case, capacitance. The opposition caused by resistors is the resistance. However, the opposition caused by capacitors is not their capacitance, but their capacitive reactance. They will need plenty of practice in calculating this from the formula: $X_C = 1 / 2\pi f C$ as they find it difficult to convert multipliers such as 'micro' and 'nano'.	20 - 30 minutes
4	Whereas series combinations of inductors, resistors and capacitors make frequency-dependent voltage dividers, parallel combinations form frequency-dependent current dividers. This worksheet introduces the first of these, the series L-R circuit. The treatment deliberately avoids the issue of impedance in parallel circuits, because the relevant formula is quite complicated. Instead, it looks at the currents in various parts of the circuit, and how they are related. There are phase shift issues again, and the formula used to calculate total current comes directly from the phasor diagram for this circuit, though this is not explained. In this case, the voltage across the components is the same. The current through the resistor is in phase with it, but the current in the inductor lags behind by 90^0. The instructor must judge how much of this needs to be explained to the class. As before, students use their measured value of the supply voltage to calculate the currents flowing through the inductor and resistor, and then combine these to calculate a value for the total current flowing. The investigation is repeated for a second, higher, frequency to show that the distribution of current is frequency dependent.	20 - 30 minutes

Tutor's notes

Worksheet	Notes for the Tutor	Timing
5	This investigation parallels the one in the previous worksheet but this time for capacitor - resistor networks. The same ideas apply. The reactance of the capacitor and the resistance of the resistor cannot be combined in a simple additive manner because of the phase shifts involved. Again, the instructor might decide to go into this in more detail with a more able class. The approach is identical to that in Worksheet 3, except that the second frequency chosen is ten times smaller, i.e. 100Hz. The students should be encouraged to notice the similarities and differences between the two situations. Here, once again, the reactance is ten times bigger at the second frequency, and so this time the capacitor dominates the voltage divider at this second frequency. In other words, low frequencies set up large voltages across the capacitor, whereas high frequencies do so across the resistor.	20 - 30 minutes
6	Having studied inductors and capacitors separately , this worksheet now combines them, and introduces the concept of resonance in the process. Instructors should mention that resonance is a widespread effect seen in any oscillating system. In some, such as musical instruments, it is advantageous, whereas in others, particularly in civil and mechanical engineering, resonance can cause real problems, from annoying rattles that occur in cars at particular speeds, to vibrations in aircraft wings and bridges that threaten complete mechanical failure. Electrical resonance has a number of applications. The obvious one is the tuned circuit in a radio, where the very weak electrical signals picked up by the aerial stimulate the tuned circuit to oscillate at its resonant frequency. Other uses include implants which are heated to kill nearby cancerous cells by stimulating them at the resonant frequency with high frequency radio waves, and the increasingly important techniques of RFID (radio frequency identification,) where passive (unpowered) devices can pick up enough energy to transmit information to a nearby device, because of stimulation at their resonant radio frequency, . The approach here looks at what happens to the impedance of the circuit as the applied frequency is changed. Although there is no added series resistor, students should be made aware that the windings of the inductor coil have resistance. This effect will be explored later. At resonance, the voltage across the capacitor is equal and opposite to that across the inductor, and so the two cancel each other out. The only hindrance to the flow of current is then the resistance of the various elements in the circuit, particularly the inductor. Equally, because the voltages across the capacitor and inductor cancel each other out, there is no reason why these cannot be very large voltages. Again, this voltage amplification effect is explored later. These large-scale effects occur in other examples of resonance, such as the much-publicised shattering of a wine glass by the singing voice of an opera singer.	20 - 30 minutes

Tutor's notes

Worksheet	Notes for the Tutor	Timing
7	Whereas series combinations of inductors, resistors and capacitors make frequency-dependent voltage dividers, parallel combinations form frequency-dependent current dividers. This worksheet introduces the first of these, the parallel L-R circuit. The treatment deliberately avoids the issue of impedance in parallel circuits, because the relevant formula is quite complicated. Instead, it looks at the currents in various parts of the circuit, and how they are related. There are phase shift issues again, and the formula that is used to calculate total current comes directly from the phasor diagram for this circuit, though this is not explained. In this case, the voltage across the components is the same. The current through the resistor is in phase with it, but the current in the inductor lags behind by 90^0. The instructor must judge how much of this needs to be explained to the class. As before, students use their measured value of the supply voltage to calculate the currents flowing through the inductor and resistor, and then combine these to calculate a value for the total current flowing. The investigation is repeated for a second, higher, frequency to show that the distribution of current is frequency dependent.	20 - 30 minutes
8	This is the equivalent investigation for parallel C-R circuits. The approach is identical, and again the formula for impedance is studiously avoided, because of its complexity. Students should know that the formula used for impedance in earlier worksheets applied only to series combinations, but the investigations in this and the previous worksheet avoid the need to calculate impedance itself. The measurements are repeated for a frequency of 10kHz, to show that this changes the pattern of currents. Now the capacitor has a much lower reactance, and so passes a higher current. Students should be helped to visualise that here we are using a relatively pure single frequency, whereas in many systems, the signal is a combination of many frequencies, and then the way the currents divide differs depending on frequency.	20 - 30 minutes
9	Students should compare the behaviour of this circuit, a parallel LCR circuit, with that of the series LCR circuit studied in Worksheet 5. Students measure the AC supply voltage and the total current leaving the power supply, and from that calculate the circuit impedance. The emergence of a resonant frequency becomes apparent when the impedance calculations are carried out. This time, though, the circuit impedance is a maximum at the resonant frequency, not a minimum. The behaviour of inductive and capacitive reactances above and below the resonant frequency are described, but this may need reinforcing in class discussion.	30 - 45 minutes

Tutor's notes

Worksheet	Notes for the Tutor	Timing
10	Students have now investigated two forms of electrical resonance, one in series LCR circuits, and one in parallel LCR circuits.	30 - 45 minutes
	The next concept introduced is that of Q factor, essentially how sharp the resonance curve is. The controlling influence here is the total resistance of the circuit. The greater it is, the less the circuit notices the resonant frequency. For mechanical systems such as bridges, this is the ideal behaviour - despite stimulation at the resonant frequency, the vibrations of the structure are very small.	
	There are several ways to calculate the Q factor for a vibrating system. The one used here essentially looks at the ratio of energy stored to energy lost per cycle, though this boils down to the ratio of peak voltage across the capacitor (or inductor, as these are equal at resonance,) to the supply voltage.	
	The investigation then looks at the effect on the resonance curve of adding extra series resistors.	
	The concept of bandwidth is introduced, defined in terms of the half-power points on the frequency spectrum for the signal. In reality, this is not often a useful way to measure bandwidth, as usually voltage, not power is measured. Therefore, bandwidth is then defined in terms of voltages. To find the point at which the power has dropped to 0.5, we look for the points at which the voltage has dropped to 0.7 of its peak, since power depends on $(voltage)^2$, and $(0.7)^2 = 0.5$, roughly!	
11	Students need to be familiar with the operation and characteristics of different types of passive filter. In this first investigation students will build a simple low-pass filter and measure its performance over the frequency range 10 Hz to 2kHz. A signal generator with a 50 ohm output impedance is required for this investigation and the input voltage to the filter should be kept at 1V RMS. The output voltage of the filter can be measured using a multimeter on the 2V AC voltage range or, if preferred, it could be measured using an oscilloscope (or Picoscope) and the peak-peak value recorded. Students should plot a response curve for the filter (using the log-lin. template provided) and then use this to determine the cut-off frequency for the filter. Students should obtain a value of around 150 Hz.	30 - 45 minutes
12	In this second of the four filter investigations students will build a simple high-pass filter and measure its performance over the frequency range 100 Hz to 10kHz. A signal generator with a 50 ohm output impedance is required for this investigation and the input voltage to the filter should be kept at 1V RMS. The output voltage of the filter can be measured using a multimeter on the 2V AC voltage range or, if preferred, it could be measured using an oscilloscope (or Picoscope) and the peak-peak value recorded. Students should plot a response curve for the filter (using the log-lin. template provided) and then use this to determine the cut-off frequency for the filter. Students should obtain a value of around 2kHz.	30 - 45 minutes

Tutor's notes

Worksheet	Notes for the Tutor	Timing
13	In this third of the four filter investigations students will build a simple band-pass filter and measure its performance over the frequency range 30 Hz to 2kHz. Once again, a signal generator with a 50 ohm output impedance is required for this investigation and the input voltage to the filter should be kept at 1V RMS. The output voltage of the filter can be measured using a multimeter on the 2V AC voltage range or, if preferred, it could be measured using an oscilloscope (or Picoscope) and the peak-peak value recorded. Students should plot a response curve for the filter (using the log-lin. template provided) and then use this to determine the cut-off frequencies for the filter. They should obtain values of approximately 180 Hz and 1 kHz respectively (the filter should have a centre frequency of around 500 Hz).	30 - 45 minutes
14	In this final filter investigation students build a simple band-stop filter and measure its performance over the frequency range 20 Hz to 3kHz. Once again, a signal generator with a 50 ohm output impedance is required for this investigation and the input voltage to the filter should be kept at 1V RMS. The output voltage of the filter can be measured using a multimeter on the 2V AC voltage range or, if preferred, it could be measured using an oscilloscope (or Picoscope) and the peak-peak value recorded. Students should plot a response curve for the filter (using the log-lin. template provided) and then use this to determine the cut-off frequencies for the filter. They should obtain values of approximately 150 Hz and 2 kHz respectively (the filter should have a centre frequency of around 500 Hz).	30 - 45 minutes

Answers

Revision question paper

1.   (a)

2.   (c)

3   (a)

4   (c)

5.   (b)

6.   (b)

7.   (c)

8.   (c)

9.   (b)

10.   (a)

11.   (a)

12.   (a)

13.   (c)

14.   (b)

15.   (c)

Using the Picoscope

The Picoscope uses the same controls as an oscilloscope:

Timebase:
- controls the scale on the time (horizontal) axis;
- spreads out the trace horizontally if a lower number is used.

Voltage sensitivity:
- controls the scale on the voltage (vertical) axis;
- spreads out the trace vertically if a lower number is used.

AC or DC:
- shows only varying voltages if AC is chosen (so centres the trace on 0V vertically;)
- shows the true voltage levels if DC is chosen.

Trigger:
- looks at the selected signal to decide when to set off on the next trace;
- waits for that signal to reach the voltage level selected before starting;
- can be either when a rising or a falling signal reaches that voltage level.

Stop / Go:
- '**Stop**' indicates that the trace is 'frozen' (i.e. showing a stored event;)
- 'Go' shows that the trace is showing events in real-time;
- Click on the box to change from one to the other.

The settings are selected on-screen using the drop-down boxes provided.

p51a
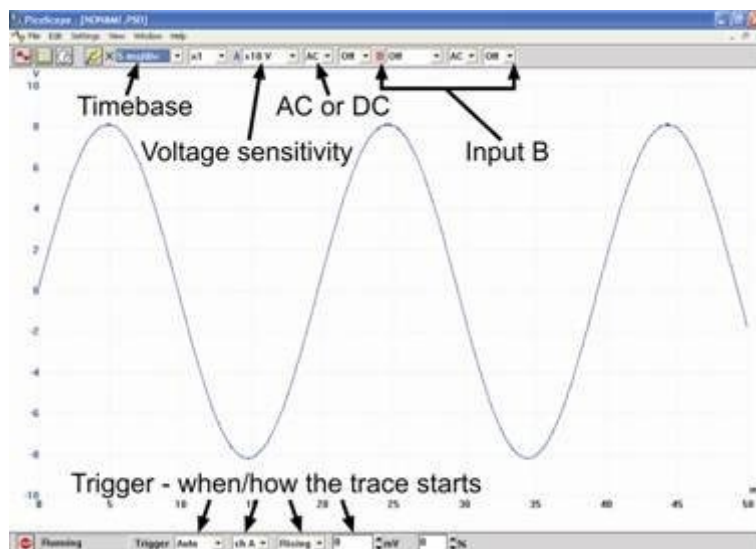
In this trace:

Timebase = 5 ms/div, so the time scale (horizontal axis) is marked off in 5 ms divisions.

Voltage sensitivity = ±10 V, so the maximum possible voltage range (vertical axis) is +10V to -10V.

Trigger - Auto - so will show any changes in the signal as they happen;
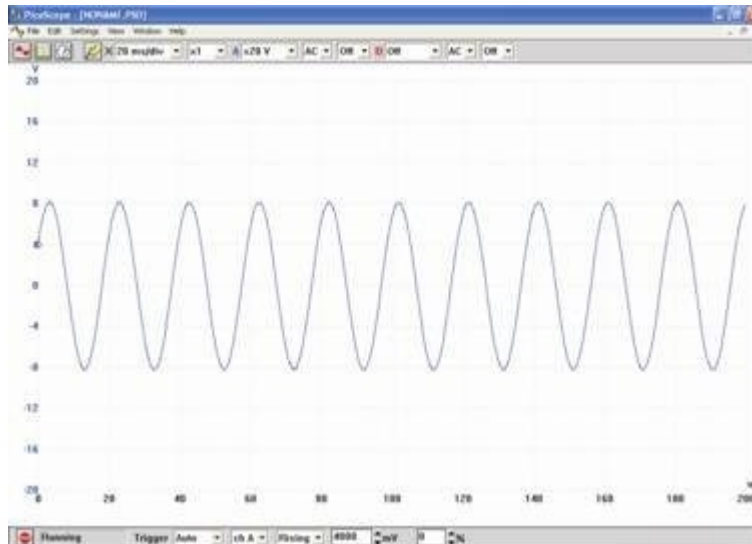
       Ch A - so looks at the signal on channel to decide when to start the trace;

       Rising - so waits for a rising voltage to reach the threshold;

       Threshold - 0 mV - so starts the trace when the signal on channel A rises through 0V.

Using the Picoscope

More Picoscope traces *for the same signal*:


p52a

In this trace:

Timebase = 20ms/div,

- the time scale (horizontal axis) is marked off in 20 ms divisions;
- the trace is 'squashed' horizontally, but shows a greater time duration.

Voltage sensitivity = ±20 V,

- the maximum possible voltage range (vertical axis) is +20V to -20V;
- the trace is 'squashed' vertically, but shows a greater possible voltage range.

Trigger - now 4000 mV, and so the trace does not start until the signal on channel A reaches 4000mV (4V)
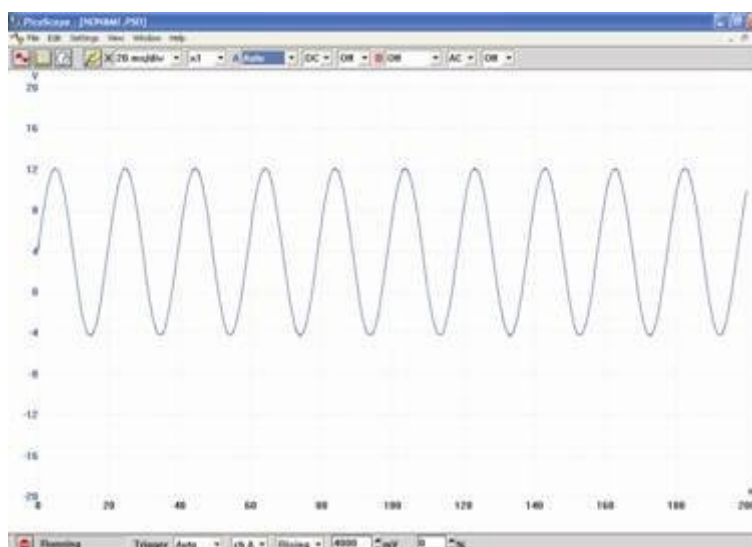
p52b

In this trace:

the settings are identical except that the DC option is chosen. The trace now reveals that, in addition to the AC signal, there is a steady DC component of +4V. The trace is centred vertically on 4V, not 0V. The AC component makes it swing by ±8V, i.e. between -4V and +12V.