

# locktronics

Simplifying Electricity

## Aircraft Maintenance - Electrical Fundamentals 3



CP7393

**MATRIX**

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# Worksheet 1

## Electrostatics and capacitors

Static electric charges can be produced by friction, (for example, by rubbing a balloon on a woollen sweater). Charges separated by this method have positive and negative polarity depending on whether an excess or surplus of electrons is present.

Once separated, the charges can remain for some time until they eventually leak away to the atmosphere or to ground.



Stray static charge can cause electrical noise and interference to avionic and communications equipment and special measures, such as static discharging wicks, shown in the picture, are used to avoid the build-up of charge on the airframe structure.

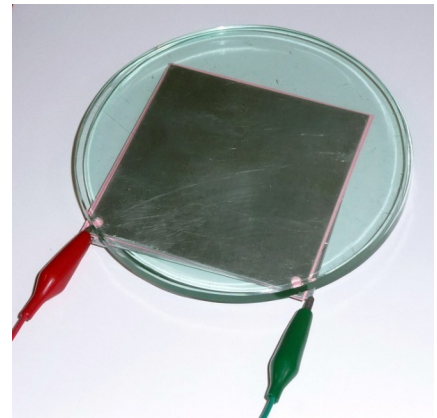
**Capacitors** are electrical components that provide us with a means of accumulating and storing electric charge. A simple capacitor consists of nothing more than two metal or aluminium foil plates separated by an insulating dielectric, such as polyester film.

The charge  $Q$ , (in coulombs,) stored in a capacitor, is equal to the product of the capacitance  $C$ , of the capacitor (in farads) and the applied voltage,  $V$ , (in volts). Thus:

$$Q = C \times V .$$

### Over to you (optional investigation):

- Make your own capacitor by placing a square of thin card or 'Clingfilm', between two square aluminium sheets, such as kitchen foil, with an area of around  $0.1\text{m}^2$ .
- It may help to keep the plates clamped together by placing the capacitor between two heavy glass plates, with a heavy object sitting on the top plate.
- Measure the capacitance of your capacitor using a digital multimeter switched to the  $2\text{nF}$  ( $= 2 \times 10^{-9}\text{F}$ ) range.
- Increase the separation of the plates by adding extra pieces of card, or 'Clingfilm' (up to six). Measure and record the capacitance each time. Plot a graph showing how the capacitance changes with plate separation.
- Next change the amount by which the plates overlap (whilst keeping the plates parallel). Mark lines on the capacitor at 75%, 50%, 37.5%, 25% and 12.5% of the surface and for each overlap, measure and record the capacitance in the table.
- Use the graph template to plot a graph showing how capacitance changes with the overlapping area of the plates.



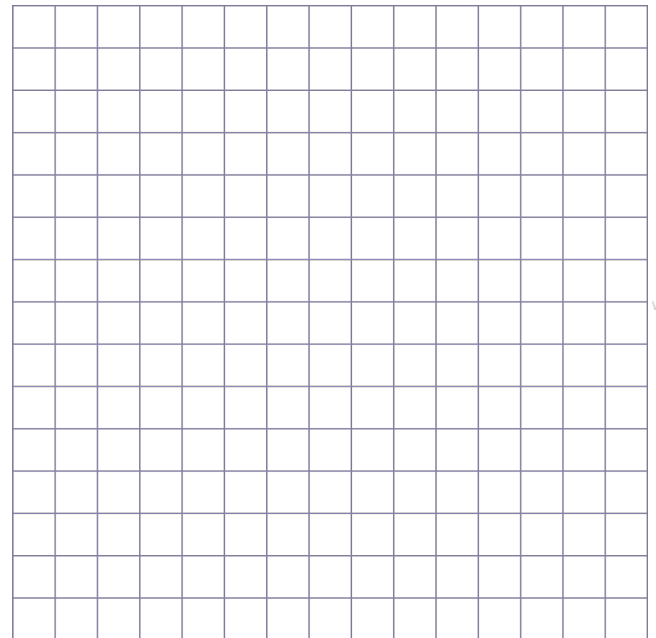
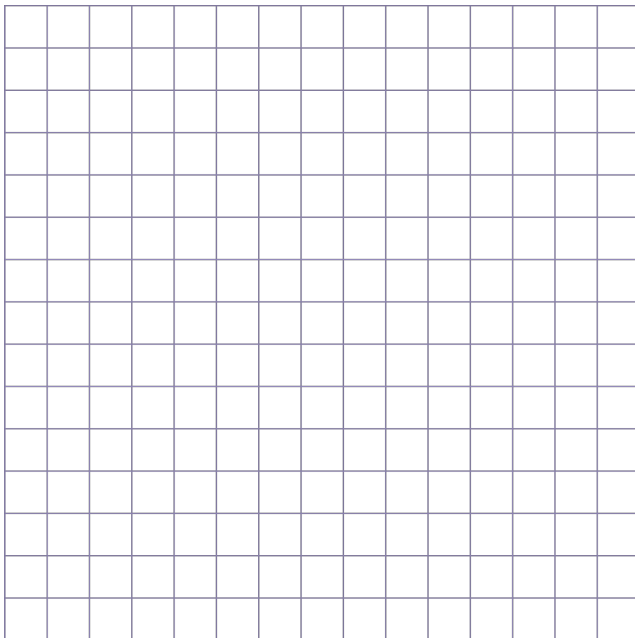
# Worksheet 1

## Electrostatics and capacitors



Separation of plates (layers)	Capacitance (nF)
1	
2	
3	
4	
5	
6	

Area of overlap (%)	Capacitance (nF)
100%	
75%	
50%	
25%	



### So what?

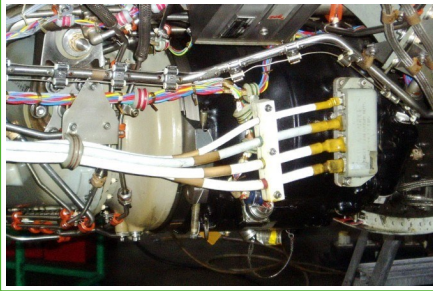
- What do the two graphs tell you?
- Increasing the separation of the plates reduces the capacitance.  
More precisely, capacitance,  $C$ , is inversely proportional to the plate separation,  $d$ .
- Increasing the overlap of the plates increases the capacitance.  
More precisely, capacitance,  $C$ , is directly proportional to plate area,  $A$ .
- Combining these results we can arrive at the important relationship:

$$C \propto \frac{A}{d} = k \frac{A}{d} = \frac{\epsilon_0 \epsilon_r A}{d}$$

where  $\epsilon_0$  is the permittivity of free space and  $\epsilon_r$  is the relative permittivity of the dielectric material (insulator).

# Worksheet 2

## Electromagnetism

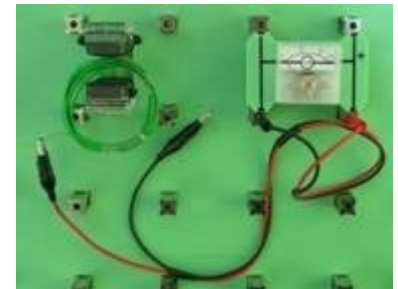
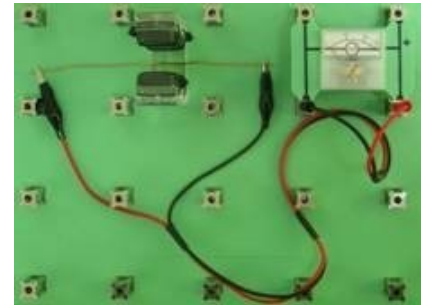


Many aircraft electrical components, like the generator shown here, are based on the laws of electromagnetism.

To be able to generate an emf, all you need is a magnetic field, a wire conductor and some relative movement as you will see from this investigation.

### Over to you:

- Set up the arrangement shown in the diagram. The amount of electricity generated will be tiny. We can observe it (just) using the Locktronics milliammeter module, shown in the diagram, but the effect is very small.
- Alternatively, use multimeter, set to its most sensitive DC current scale. One problem is that the multimeter samples the input signal periodically. If you move the wire at the wrong moment, in between samples, then the meter may miss the event so you may need several attempts to produce convincing results.
- Move the wire into the magnetic field between the magnets as fast as you can. The movement must be in the right direction - at right-angles to the field and at right-angles to the length of wire.
- Watch the meter reading, as you do so.
- Then reverse the direction of motion, again watching the meter to see the effect.
- Next replace the single strand of wire with a coil of about fifty turns of wire. You can use sticky tape, or a paper clip to hold the turns together. The diagram opposite shows you how to set this up.
- Move the coil up and down, into and out of the magnetic field. Watch the meter reading as you do so.
- What is the effect of speed of movement on the amount of electricity produced?
- To see these effects more clearly, set up an oscilloscope to monitor the emf. generated. Connect the piece of wire or the coil to the oscilloscope input. Suitable settings are given in the next section.



### Oscilloscope settings:

Timebase - 5s/div

Trigger mode—Auto

Trigger direction—Rising

Voltage range  $\pm 100\text{mV DC}$

Trigger channel Ch.A

Trigger threshold 10mV



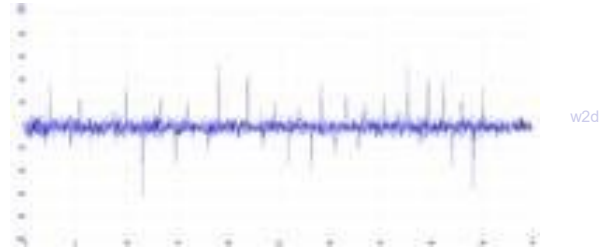
# Worksheet 2

## Electromagnetism

### So what?

From the results, the generated current and voltage have:

- a **magnitude** that depends on:
  - the speed of movement;
  - the number of wires present.
- a **direction** that depends on the direction of motion.

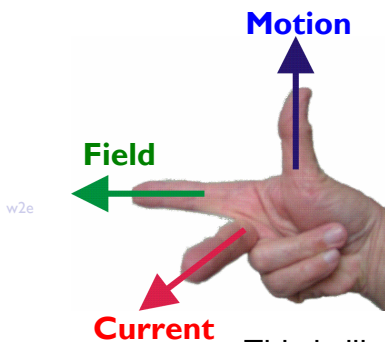


These results can be seen in oscilloscope traces like that shown above. The sharp peaks indicate pulses of current generated by moving the coil inside the magnetic field.

Again, sampling has an effect. The system can miss some peaks because they occur between samples. (Experiment with other timebase settings to try to get more reliable results.)

Here's the underlying physics:

- When you move the wire at right-angles to the magnetic field, its electrons move with it.
- When electrons move, they generate a magnetic field.
- This interacts with the field of the magnets, exerting a force on the electrons at right-angles to the direction of motion and to the magnetic field.
- This force pushes electrons from one end of the wire to the other, generating a voltage and a current if there is an electrical circuit.
- Using a coil of wire increases the size of voltage and current generated because each turn in the coil is moving inside the magnetic field, and so has electricity generated in it. The effects of all these turns adds together, increasing the amount of electricity generated.



### Fleming's Right-hand Rule:

Fleming devised a painful way of predicting the generated current direction, using your **right**-hand held in the position shown, with thumb, forefinger and centre finger all at right angles to each other.

When the **F**ore finger points in the direction of the magnetic **F**ield (from North pole to South pole,) and the thu**M**b points in the direction of the **M**otion, the **C**entre finger points in the direction of the resulting **C**urrent.

This is illustrated in the diagram. This is also known as the *dynamo rule*.

### For your records:

- What factors determine the emf generated?
- How can you predict the polarity of the emf generated?

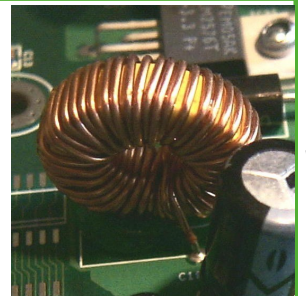
# Worksheet 3

## Inductance and inductors

When a current flows in a conductor, a magnetic field appears in the space that surrounds it. This can be concentrated by winding the conductor into a coil and further intensified by winding the coil on a core of high-permeability ferromagnetic material such as iron, steel or ferrite.

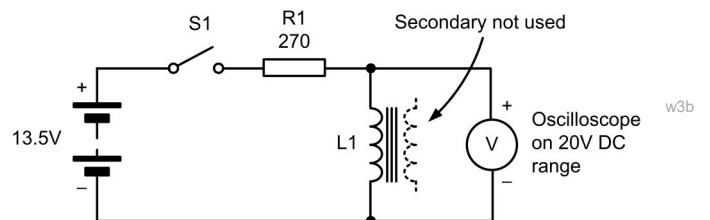
When a *changing* current is passed through an inductor, an induced emf appears across its terminals. This induced emf opposes the original change that created it. Because of this opposition to current change, large inductors are often referred to as **chokes**.

Inductors are used in many aircraft applications, including filters and high-energy ignition units



### Over to you:

- Connect the circuit shown opposite.
- The power supply should be set to 13.5V DC.
- The press-to-make switch (S1) is connected in series with the 270Ω current limiting resistor (R1).
- The inductor (L1) is to be made from one of the windings of a small transformer (the secondary winding, L2, is left disconnected).
- Connect an oscilloscope to display the voltage drop across the inductor (L1). Make sure that you connect the leads with the same polarity as that shown on the circuit diagram. The recommended initial settings for the oscilloscope are shown below.
- Switch on the DC power supply and press, and hold, S1 so that current is delivered to the inductor.
- Keep the switch closed for a few seconds then release the switch and observe the oscilloscope display. You should notice a very sudden and very large negative voltage spike that rapidly decays back to zero (see the waveform on page 3).
- You may have to repeat this step several times until you have a satisfactory display showing the large, brief back emf generated as the magnetic field in the inductor suddenly collapses when the current is interrupted.



### Oscilloscope settings:

**Timebase** 1 ms/div

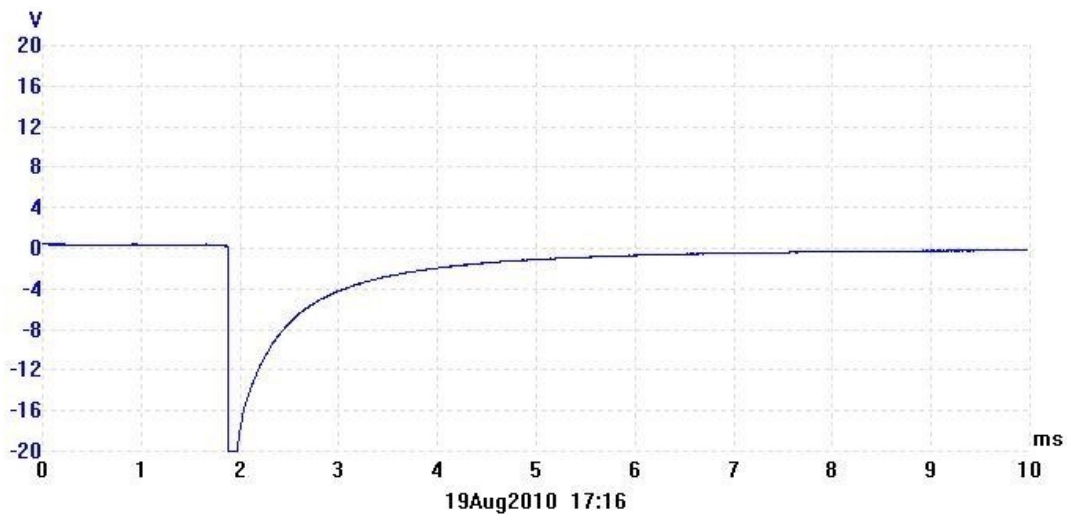
**Voltage range** Input A ±20 V DC

**Trigger mode** Repeat **Trigger channel** Ch.A

**Trigger direction** Falling **Trigger threshold** 1000 mV

# Worksheet 3

## Inductance and inductors



w3c

Typical oscilloscope output

### So what?

Let's break down this process into small steps:

- When the switch is closed, a steady current flows in the inductor which produces a magnetic field in its core.
- When this steady current is interrupted by opening the switch, the field collapses rapidly.
- When the field collapses through the coils of the inductor, a voltage appears across its terminals which can be many times greater than the initial supply voltage.
- This induced voltage is negative - it opposes the original direction of flow. Because of this we refer to it as a *back emf*.
- A large back emf can be dangerous and can cause considerable damage such as arcing at switch or relay contacts and destruction of low-voltage electronic components.

### For your records:

- Back emf appears whenever current is suddenly removed from an inductor.
- Back emf opposes the original flow.
- Back emf . can be very large and many times greater than the supply voltage.
- We should take precautions to limit the amount of back emf generated when an inductive component (such as a relay coil) is used. In Module 4 you will find that this can be achieved by a reverse biased diode connected in parallel with the inductive component.



# Worksheet 4

## DC motors

Electric motors are available for use in a wide variety of different applications. Depending on type and construction, electric motors can operate from alternating current (AC) or direct current (DC). There are brushed and brushless types, single phase and three phase, induction, synchronous, stepper, and servomotors.

In an aircraft they provide a number of useful functions, including motorised actuators, pumps and combined engine starter-generator units.

When a direct current is applied to a loop of wire, two equal and opposite forces are set up which act on the conductor in opposite directions. Together these forces produce a torque which causes the loop to rotate.

To increase the torque, the loop can comprise a number of turns wound on a high-permeability magnetic core. This rotating assembly is referred to as an **armature**. The radial magnetic field that surrounds the armature can be produced either by means of a permanent magnet or by an electromagnet where direct current is passed through a separate **field winding**.



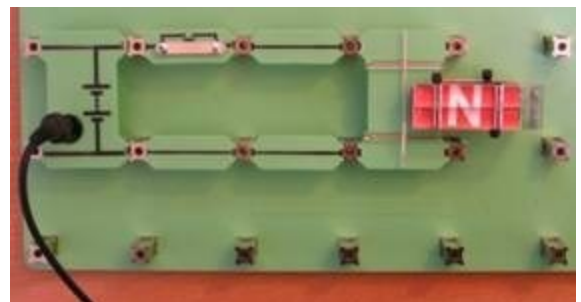
w4a

### Over to you:

- This investigation uses the Motor-effect carrier, shown opposite. It has two fixed conductors, with a moveable metal rod sitting on top, across them.
- Build the system shown in the second picture.
- For clarity, the magnet has not been pushed right over the metal rod in the picture, but you should do so, so that the moveable rod sits in the middle of the magnetic field.
- The power supply is set to 3V.
- Press the push switch, and notice what happens.
- Next, flip the magnet over so that the South pole is on top.
- Press the push switch again. What is the difference?
- Reverse the current direction by rotating the power supply carrier so that the negative end (short line on the symbol) is at the top.
- What happens now when you press the push switch?
- Increase the power supply voltage to 13.5V to increase the current flowing through the rod.
- What happens now when you press the push switch?



w4b



w4c

# Worksheet 4

## DC motors

### So what?

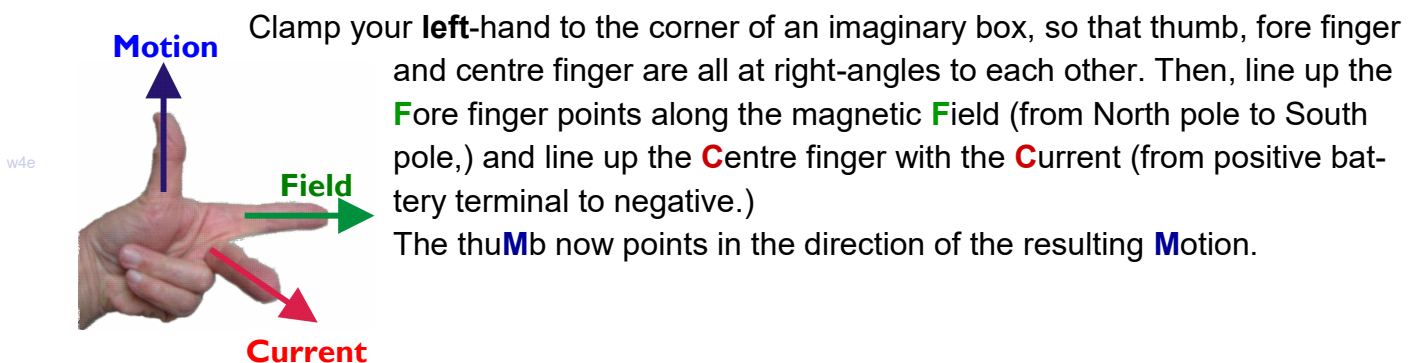
Here's the underlying physics:

- a current is a flow of electrons, tiny negatively-charged 'particles' found in all atoms;
- when electrons move, they generate a magnetic field;
- this interacts with the field of the magnets, causing attraction / repulsion, except that it acts at right-angles to the current direction and to the magnetic field.



### Fleming's Left-hand Rule:

John Ambrose Fleming devised a way to work out the direction a wire will move in (also known as the *motor rule*):



### For your records:

Copy and complete the following, using your observations from the investigation:

- The magnetic field exerts a force on a conductor which is at .....-angles to the direction of the .....and to the direction of the .....
- When the magnetic field is reversed, the .....is reversed.
- When the current is reversed, the .....is reversed.
- Increasing the current, increases the .....

Complete the following version of Fleming's motor rule:

- Using the .....hand, hold the thumb, fore finger and centre finger at .....to each other.
- Keeping this shape, move the hand until the fore finger points in the direction of the ....., (from .....to .....and the centre finger points in the direction of the ..... ( from .....to .....)
- The thumb now points in the direction of .....

# Worksheet 5

## A closer look at DC motors

Electric motors usually consist of a coil rotating inside the magnetic field of either a permanent magnet or an electromagnet. They rotate because some mechanism reverses the current at just the right time.

There are two problems to be solved then:

- making electrical connections to a rotating coil;
- reversing the current at the right time.

Two solutions are:

- use slip rings with an AC supply;
- use a commutator and carbon brushes with a DC supply.

The Locktronics kit uses the second of these approaches.



w5a

### So what?

#### The electric motor:

Most motors rotate, so how does that happen?

The diagram on the right shows a cutaway coil of wire, disappearing into the sheet of paper. There is a magnetic field from left to right.

Current flows into the paper on the left side of the coil, and out of the paper on the right. Using the Left-hand rule, the sides of the coil try to move in the directions shown by the blue arrows.

As a result, the coil starts to rotate.

(There is no force on the back section of the coil, because the current flows parallel, not at right-angles, to the magnetic field.)

When the coil reaches the position shown in the second diagram, the forces on the two sides are in line, but in opposite directions. There is no longer a twisting effect, but momentum carries the coil it past that position.

We now need to reverse the current, so that when the coil reaches the position shown in the third diagram, the forces on the coil keep it rotating.

Provided that the current reverses again at the right time, then the rotation will continue.

There are two ways to reverse the current:

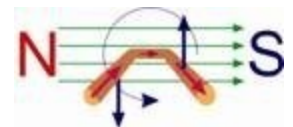
1. use **slip-rings** with brushes:

Each end of the coil is connected to its own full brass ring.

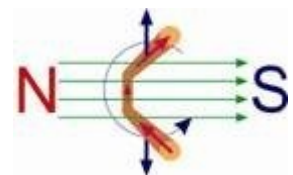
Electrical contact is made to each ring with a carbon brush, which moulds itself to the shape of the ring, reducing contact resistance.

The coil is supplied with AC, and so the current automatically changes direction in step with the mains supply.

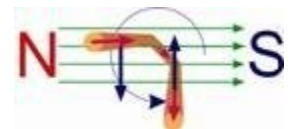
The picture shows one form of slip-ring.



w5b



w5c



w5d



w5e

# Worksheet 5

## A closer look at DC motors

### So what?

2. use a **commutator** with brushes:

The diagram shows the design of a simple commutator, a brass drum, split into two halves, separated by an insulator. Electrical contact is made by carbon brushes. The coil is connected to the two halves at X and Y. As the coil rotates, X is connected to the positive supply for roughly half of the time, and then to the negative supply. At all times, Y is connected to the opposite supply to X.



The pictures show a typical design of carbon brush, and an electric motor. Its rotor contains a large number of coils, and so requires a more complicated commutator.



### Over to you:

This investigation uses any of the three Locktronics DC motors.

- Build the system shown opposite.
- The power supply is set to 6V.
- Press the push switch, and watch the ammeter reading.
- Next, keeping the push-switch closed, press gently on the shaft of the motor, or against the plastic wheel attached to it, to slow down the motor.

Watch the ammeter reading as you do so.

- Press the push switch again. Press on the shaft or on the wheel to stop the motor rotating for a moment. Again watch the ammeter reading as you do so.
- Copy the table, and complete it with your measurements.



Motor speed	Current in A
Maximum	
Slow	
Zero	

### So what?

The current is a minimum when the motor is spinning fastest - why?

We will see that when a coil spins round inside a magnetic field, it generates a voltage. The faster it spins, the bigger the voltage. This voltage opposes the external voltage producing the motion. That makes sense because otherwise we could switch off the external voltage, and we'd have perpetual motion! The overall voltage, and so the current, is reduced.

Putting it another way, when we ask the motor to do more work, spinning against the extra friction of us pressing on the axis, it needs more current.

### For your records:

- When the work done by the motor increases, the current it draws from the supply increases.
- When running freely, at maximum speed, the current is at a minimum because the rotating coil generates a voltage that opposes the externally applied voltage.

# Worksheet 6

## Generator principles



Worksheet 2 focussed on the fundamentals of electricity generation.

This one looks at how to generate more electricity and at an important application.

In an automotive context, for example, the electrical system obtains energy from a combination of the battery and the alternator.

The alternator output is rectified and regulated, and then delivers electrical energy to peripheral units, like headlamps, and keeps the lead-acid battery charged.

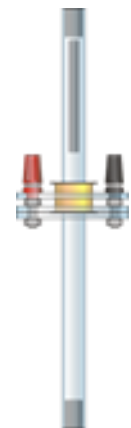
Elsewhere, eddy current braking is a useful application that uses the same principles to slow down vehicles without relying on friction braking.

### Over to you:

#### 1. Generating more electricity:

Here, we use a 400 turn coil mounted on a clear plastic tube, and drop a magnet through it to show electricity generation.

- Connect the apparatus shown opposite to an oscilloscope, which is used to monitor any electricity generation. The settings are given in the section at the bottom of the page.
- Plunge the magnet into the coils, and record the result on the oscilloscope.
- Do the same as you withdraw the magnet.
- Investigate the effect of speed of movement on the amount of electricity produced.



LK7489

#### 2. Eddy current magic:

Faraday's law kit consists of a copper tube and two identical-looking projectiles. One is a magnet; the other is not.

- Find out which is which - you might need an object like a paper clip to help you decide.
- Hold the copper tube in a vertical position.
- Drop first one projectile and then the second down the tube.
- What is the difference?
- Look at the two projectiles. Which fell faster? Why?



LK7487

### Oscilloscope settings:

Timebase - 1s/div

Trigger Mode - Auto

Trigger Direction - Rising

Voltage range - Input A -  $\pm 500\text{mV DC}$

Trigger Channel - Ch A

Trigger Threshold - 10mV



# Worksheet 6

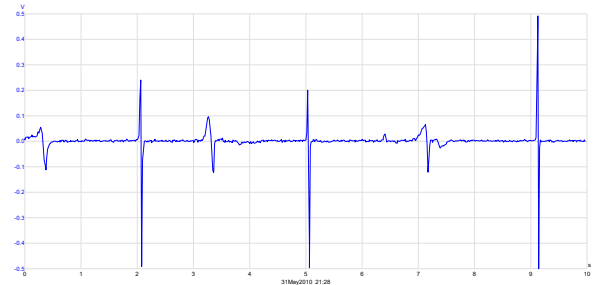
## Generator principles

### So what?

The trace is typical of the output for the first investigation.

The spikes show pulses of current generated when the magnet was plunged into the coil. These are around ten times higher than in the previous investigation.

The bipolar nature of the pulses (above and below the centre axis,) is because the magnet first approaches and then retreats from the turns in the coil, generating a current in one direction and then the other.



w6b

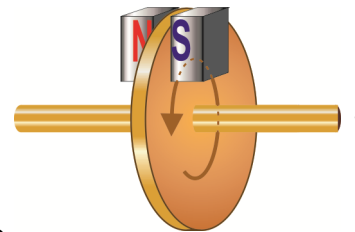
### Eddy current magic -

The unmagnetised projectile did exactly what was expected - it fell under gravity. The magnet fell much more slowly, because it generated random currents in the copper pipe as it fell. Its moving magnetic field interacted with the conductor, the copper pipe, and as a result currents were generated. The accompanying magnetic field opposed the motion, slowing it down.

This effect is used in braking systems, for some buses and trains. A disc attached to the rotating wheels of the vehicle sits in between the poles of an electromagnet.

Normally, there is no effect on the spinning disc. However, when the electromagnet is

energised, the resulting magnetic field induces eddy currents in the spinning disc. These produce a magnetic field that opposes the motion, slowing down the disc and converting the energy of rotation to heat. The braking effect is varied by adjusting the current to the electromagnet. As the spinning disc slows, the induced eddy currents decrease, reducing the braking effect. In this way, the vehicle is braked smoothly.



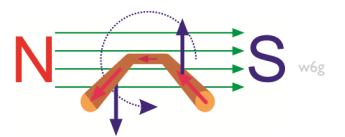
w6f

### The generator:

Most generators rotate, so our approach is rather like that used with the motor.

The diagram shows the cutaway coil of wire again, disappearing into the sheet of paper. There is a magnetic field from left to right.

This time, we are forcing the coil to rotate, driving it from the auto engine, for example. Since one side of the coil moves up, while the other side moves down, both in the same magnetic field, the induced currents in the two sides flow in opposite directions, one into the paper, the other out of it. In other words, the induced current flows around the coil. Reverse the direction of rotation and you reverse the direction of the current flow.



w6g

As with the motor, electrical connection to the rotating coil can be made in two ways - using commutators or slip-rings. Using commutators produces a DC output, whereas using slip-rings gives an AC output.

In practice, most of our electricity is generated the other way round, by rotating the magnetic field inside a coil of wire. The rotating magnetic field could be produced by rotating a magnet, but is often produced by a rotating electromagnet.



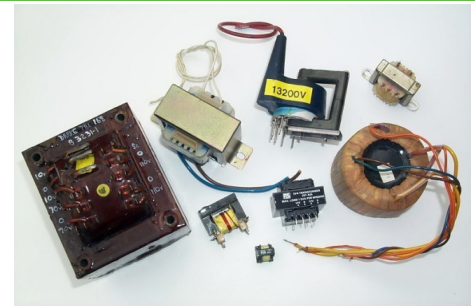
# Worksheet 7

## Transformers

A huge advantage of generating electricity as AC is that it allows us to use transformers. These allow us to step-up or step-down and AC voltage to any desired value.

Transformers can also isolate DC potentials from one part of a circuit to another - effectively coupling AC but not DC.

We develop the ideas behind the transformer in four steps, linking the transformer to the same principles that we met earlier for electricity generation.



### Over to you:

#### Step 1 - Moving the magnet:

- Set up the arrangement shown in the picture on worksheet 4 - 1.
- Plunge the magnet into the coil, and then pull it out, watching the oscilloscope as you do so.

#### Step 2 - Moving the coil:

- Next, move the coil over the magnet, while watching the oscilloscope.

#### Step 3 - Electromagnet, not magnet:

- Now, replace the magnet with an electromagnet, made from the second coil connected to a 3V DC power supply.
- Move the first coil over the electromagnet, as in step 2, observing the effect.
- Switch the electromagnet on and off, watching the oscilloscope as you do so.

#### Step 4 - AC not DC:

- This time, the moving magnetic field is produced not by physically moving the magnet, or the coil, but by using an alternating magnetic field.
- Disconnect the DC power supply from the electromagnet, and instead connect a signal generator, set to an amplitude of 3V and a frequency of 300Hz.
- Sit the electromagnet on top of the first coil.
- Switch on the signal generator, and watch the effect on the oscilloscope.
- Lower a ferrite core down the middle of the two coils, and notice the effect this has. We now have a simple but very inefficient transformer!
- Notice the effect of doubling the amplitude of the supply from the signal generator.
- Explore what happens if you separate the two coils or use a material like steel instead of ferrite for the core.

#### Oscilloscope settings:

Timebase - 1s/div

Trigger Mode - Auto

Trigger Direction - Rising

Voltage sensitivity -  $\pm 500\text{mV}$  DC

Trigger Channel - Ch.A

Trigger Threshold - 10mV

# Worksheet 7

## Transformers

### So what?

The traces show typical results for two steps of the investigation:

- The upper one shows the spikes of current generated when the DC supply to the electro-magnet is switched on and off in step 3.
- The lower one shows the current generated when the AC supply is connected to the electro-magnet.

It was pointed out earlier that to generate electricity all you need is a magnet, a piece of wire and movement. The only difference here is that we have replaced the magnet with an electromagnet, and produced the movement by using an alternating magnetic field.

As a result, one coil, called the **primary**, is supplied with AC current, and generates an alternating magnetic field. This links with the other coil, called the **secondary**. As a result, an alternating voltage is generated in the secondary. This is the principle of the transformer.

Let's refine that picture a little!

The *strength* of the magnetic field in the primary depends on factors like:

- the number of turns of wire in the primary coil
- the current flowing through it, which, in turn, depends on the voltage applied to it.

The *voltage generated* in the secondary coil depends on factors like:

- the strength of the magnetic field generated by the primary
- the number of turns of wire in the secondary coil
- how effectively the magnetic field of the primary links with it.

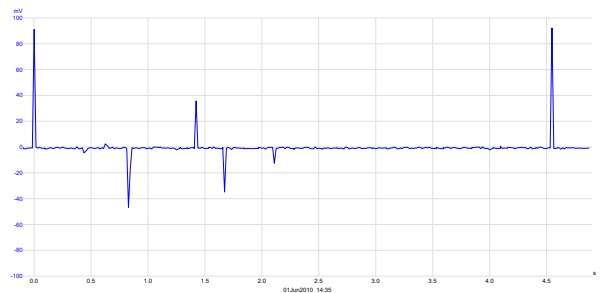
In other words, the voltage generated in the secondary coil depends on the number of turns in the primary coil, and the number of turns in the secondary. The next worksheet will explore this link in more detail.

### For your records:

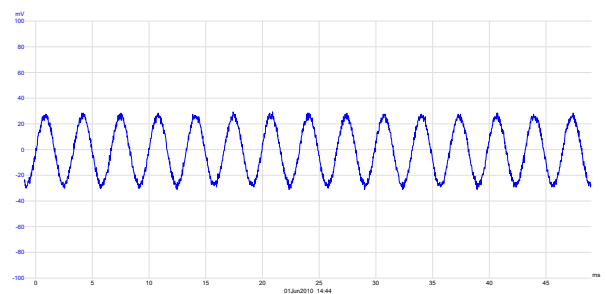
1. Here is the circuit symbol for the transformer:

2. Describe the role played by each of the following three components in the transformer:

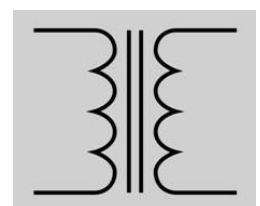
- (a) the primary coil,
- (b) the secondary coil,
- (c) the core.



w7b



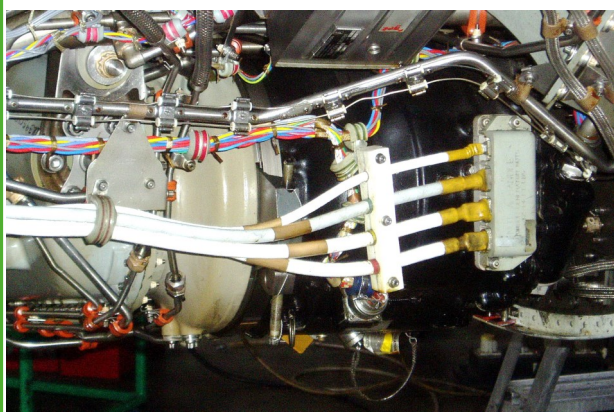
w7c



w7d

# Worksheet 8

## Practical transformers



The photograph shows part of the electricity generation system in a commercial aircraft. Transformers play a vitally important role by allowing voltages derived from the AC bus to be stepped up or down to any desired value.

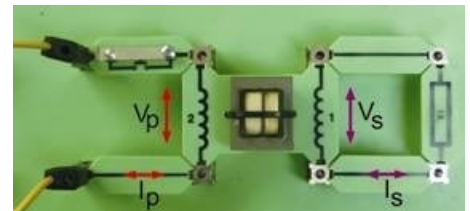
In this investigation, you use a commercial transformer with a turns ratio of 2:1, meaning that one coil has twice as many turns as the other, to explore step-down and step-up transformer action.

### Over to you:

#### Step-down transformer:

In a step-down transformer, the primary coil, the one supplied with AC power, has more turns of wire than the secondary, the one that generates the output voltage. Here, the primary has twice as many turns as the secondary.

- Set up the system shown opposite, which delivers power to a  $1\text{k}\Omega$  load.
- Connect the low impedance output (typically  $50\Omega$ ) of a signal generator to the '2' coil. Set it to output a sine wave with a frequency of 300Hz, and an amplitude of 6.0V.
- Use a multimeter, on the 20V AC voltage range, to measure  $V_P$  the voltage across the primary (the '2') coil, and then  $V_S$  across the secondary (the '1' coil.) and record both.
- With the multimeter on the 20mA AC current range, measure and record the primary current  $I_P$ , and the current  $I_S$  in the secondary coil.



#### Step-up transformer:

Now, the primary coil has fewer turns than the secondary - in this case, half as many.

- The system is the same, except that the transformer carrier is reversed, to swap over the coils.
- Connect the multimeter to measure the secondary voltage  $V_S$ . Adjust the amplitude of the signal until  $V_S$  is the same as in the investigation above.
- Now measure and record  $V_P$ ,  $I_P$  and  $I_S$ .

Measurement	Step-down	Step-up
$V_P$		
$V_S$		
$I_P$		
$I_S$		

# Worksheet 8

## Practical transformers



### So what?



The previous investigation explored the principles behind the transformer, but the final device was very inefficient. This investigation used an improved version - two coils sitting side by side, as in the prototype, but linked by a much more elaborate core. This threaded through the centre of the coils, and wrapped around the outside too. The result - a much more effective linkage between the secondary coil and the magnetic field generated in the primary.

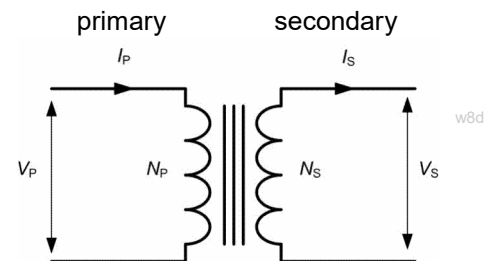
- Calculate the ratio  $V_P:V_S$  and the ratio  $I_P : I_S$  for both step-up and step-down transformers.
- The transformer equation says that for an ideal transformer:

$$V_P / V_S = N_P / N_S$$

where  $N_P$  and  $N_S$  are the number of turns on the primary and secondary coils respectively.

- In general terms:

- the step-up transformer 'steps up' the voltage but 'steps down' the current - the current in the primary is greater than that in the secondary.
- the step-down transformer 'steps down' the voltage, but delivers the same secondary current as in the previous case for a much smaller primary current.



- In both cases, the output voltage  $V_S$  was identical, and so  $I_S$ , the secondary current, should have been very similar.
- The acid test - how efficient is the process?  
In other words, how does the electrical power delivered to the primary compare with the power delivered from the output of the secondary?

- Use the formula  $\text{Power} = \text{Current} \times \text{Voltage}$  to calculate:

Power delivered to the primary coil,  $P_P = I_P \times V_P = \dots\dots\dots$ mW

Power delivered from the output of the secondary,  $P_S = I_S \times V_S = \dots\dots\dots$ mW

- For an ideal transformer (100% efficient):  $P_P = P_S$   
and  $I_S / I_P = N_P / N_S$

	$N_P$	$N_S$	$V_P$	$V_S$	$I_P$	$I_S$
1	5000	500	1V			0.1A
2		1000	12V	4V	0.3A	
3	2000		10V		100mA	500mA
4	4000	400		1V		10mA
5		5000		2.0V	250mA	50mA

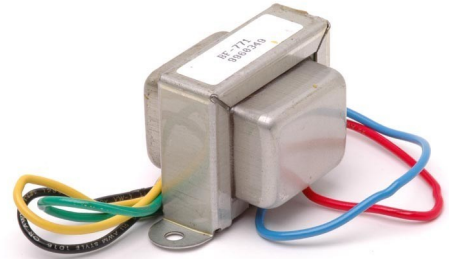
# Worksheet 9

## Transformer losses

For convenience, we often regard a transformer as being loss-free, and assume that all of the power applied to the primary is transferred to the load connected to the secondary.

In a real transformer this is not the case. Some power is wasted as 'iron loss' (power used to magnetize the core of the transformer) and some as 'copper loss' (power wasted due to the resistance of the transformer windings).

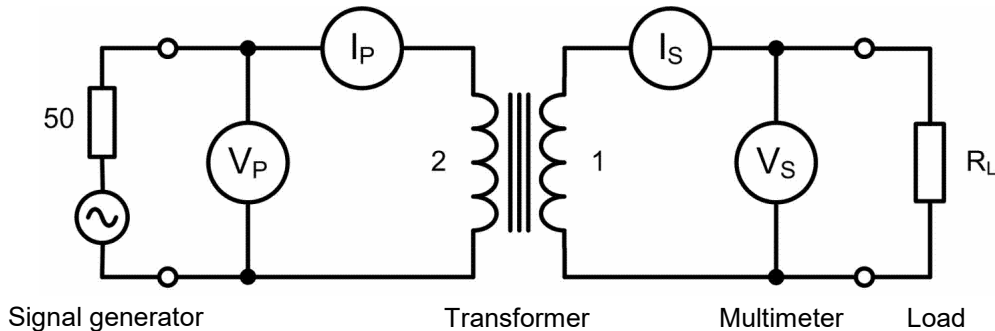
In an aircraft, where significant power is consumed, we need to be aware of the losses and efficiency of power transformers and also of their ability to maintain their performance (i.e. operate without significant loss) as the load increases (a property known as 'regulation'). This worksheet investigates the losses, efficiency and regulation of a small transformer.



w9a

### Over to you:

- Set up the arrangement shown.



w9b

- The primary input is obtained from a signal generator with an output impedance of  $50\Omega$  (or less). Set the signal generator frequency to 400 Hz (the normal aircraft AC supply frequency).
- Disconnect the load resistor,  $R_L$ , so that the secondary winding is open-circuit. (This is known as the 'no load' condition.)
- Set the digital multimeter to the 2V AC range and connect it to measure the primary voltage,  $V_P$ . Adjust the output voltage of the signal generator to give exactly 1V.
- Now connect the multimeter to measure the secondary voltage,  $V_S$ . Record this in the table.
- Set the multimeter to the 20mA AC range and connect it to measure first  $I_S$  and then  $I_P$ . Record these in the table.
- Repeat this process with load resistances of  $1k\Omega$ ,  $270\Omega$ ,  $100\Omega$  and  $27\Omega$  in turn.

# Worksheet 9

## Transformer losses

So what?

Load $R_L$	$V_P$	$V_S$	$I_P$	$I_S$	$P_P$	$P_S$	$P_L$	Efficiency
No load	1V			0		0		0%
1k $\Omega$	1V							
270 $\Omega$	1V							
100 $\Omega$	1V							
27 $\Omega$	1V							

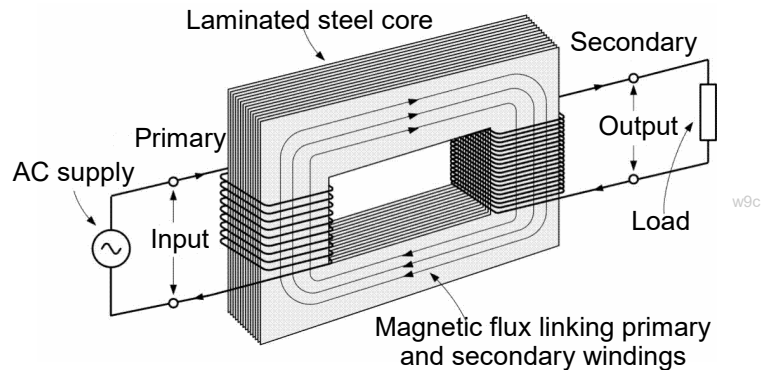
### Transformer efficiency

For each value of load resistance, calculate:

- the primary (input) power,  $P_P$ , and secondary (output) power,  $P_S$ , using the relationships,  $P_P = I_P V_P$  and  $P_S = I_S V_S$ .  
Record these values in the table.

- the power loss,  $P_L$ , using the relationship:  $P_L = P_P - P_S$ .  
Record these values in the table.

- the efficiency of the transformer using the relationship:  $\text{Efficiency} = \frac{P_S}{P_P} \times 100\%$



For your records:

### Transformer regulation:

- Using the formula: 
$$\text{Regulation} = \frac{V_{S(\text{no load})} - V_{S(\text{full load})}}{V_{S(\text{no load})}} \times 100\%$$

calculate the voltage regulation of the transformer when supplying:

- a 100 $\Omega$  load
- a 27 $\Omega$  load.
- What do you notice about the voltage regulation as the load on the transformer increases?



# 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 28.

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. Electric charge will become concentrated:

- (a) at a sharp point
- (b) on a smooth surface
- (c) at an earth or ground connection.

2. The capacitance of a parallel plate capacitor will increase with:

- (a) plate area
- (b) plate separation
- (c) both plate area and plate separation.

3. Capacitance is measured in:

- (a) joule (J)
- (b) farad (F)
- (c) coulomb (C).

4. The charge present on a capacitor will:

- (a) increase with applied voltage
- (b) decrease with applied voltage
- (c) be independent of the applied voltage.

5. Which one of the following gives the relationship between charge, voltage and capacitance?

- (a)  $Q = C \times V$
- (b)  $Q = C / V$
- (c)  $Q = V / C$

6. A  $20\mu\text{F}$  capacitor is charged to a voltage of 50V. The charge present will be:

- (a)  $0.5\mu\text{C}$
- (b)  $2.5\mu\text{F}$
- (c) 1mC

7. Which one of the following materials is suitable for use as a capacitor dielectric?

- (a) aluminium foil
- (b) polyester film
- (c) carbon granules.

8. The e.m.f. generated when a conductor moves in a magnetic field will:

# Revision Questions

- (a) increase with both magnetic field strength and relative velocity
  - (b) increase with magnetic field strength but decrease with relative velocity
  - (c) increase with relative velocity but decrease with magnetic field strength.
9. In order to maximise the e.m.f. generated when a conductor moves through a magnetic field the conductor should move:
- (a) along the same lines as the magnetic field
  - (b) at  $45^\circ$  to the magnetic field lines
  - (c) at right angles to the magnetic field lines.
10. When applying Fleming's Right Hand Rule:
- (a) the thumb points in the direction of motion
  - (b) the forefinger points in the direction of motion
  - (c) the middle finger points in the direction of motion.
11. Examples of ferromagnetic materials include:
- (a) copper and brass
  - (b) germanium and silicon
  - (c) iron and steel.
12. In a DC motor, if the strength of the magnetic field is doubled and at the same time the number of turns on the coil is halved, the speed of rotation will:
- (a) be halved
  - (b) remain the same
  - (c) increase by a factor of four.
13. Inductance is measured in:
- (a) ampere (A)
  - (b) farad (F)
  - (c) henry (H).
14. The e.m.f. that appears across the terminals of an inductor will be proportional to:
- (a) the inductance divided by the rate of change of current
  - (b) the rate of change of current divided by the inductance
  - (c) the product of the inductance and the rate of change of current.
15. Commutators are found on:
- (a) AC generators
  - (b) DC generators
  - (c) both AC and DC generators.

**Answers are provided at the end of the module**

## 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 3.4 and 3.9 to 3.12 of EASA Part-66 Module 3, Electrical Fundamentals.

Locktronics equipment 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 electrical measurements and the use of ammeters and voltmeters.

### 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 basic construction of a parallel plate capacitor;
- the relationship between capacitance, plate separation and area of a capacitor;
- the underpinning principles of generators and motors;
- the principle of induced e.m.f. when the current changes in an inductor;
- how back e.m.f. is produced when the flux in an inductor suddenly collapses;
- the construction and function of slip-rings, commutators and brushes.

## What students will need:

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

Note that the Aircraft Maintenance Kit contains many other parts that are used in the other workbooks that together cover aspects of Module 3 and 4.

Students will also need:

- either two multimeters, such as the LK1110, capable of measuring currents in the range 0 to 100mA, and voltages in the range 0 to 15V;
- or an ammeter with a range of 0 to 100mA, and a voltmeter with a range 0 to 15V.

For other modules in the series, they will need:

- a function generator, such as the LK8990, or equivalent;
- and an oscilloscope capable of monitoring the signals it produces, such as the LK6730 Pico 4000 virtual oscilloscope.

If you are missing any components, or need additional items, please contact Matrix or your local dealer.

## Power source:

The larger baseboard is appropriate for use with this power supply, which can be adjusted to output voltages of either 3 V, 4.5 V, 6 V, 7.5 V, 9 V or 13.5 V, with currents typically up to 1 A. The voltage is changed by turning the selector dial just above the earth pin until the arrow points to the required voltage.

The instructor may decide to make any adjustment necessary to the power supply voltage, or may allow students to make those changes.

Each exercise includes a recommended voltage for that particular circuit.

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



p25b

## 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 four and six 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.

Worksheet	Notes for the Tutor	Timing
1	<p>In the first worksheet, students investigate the construction and operation of a simple parallel plate capacitor. The materials for this are NOT included in the Locktronics Aircraft Maintenance Kit, as the essence of the investigation is that it uses everyday materials. (Commercially produced capacitors are mysterious packages that hide any details of inner structure.)</p> <p>The plates are separated by one or more squares of thin card, having a thickness of 0.2 mm, or kitchen food wrapping such as 'ClingFilm'. The arrangement must be kept flat and to help ensure that the plates are truly parallel they should be placed between two glass plates. If this arrangement is placed flat on the surface of a table, a non-metallic weight (such as a bag of sugar) may be applied to the upper glass plate.</p> <p>The capacitance of this arrangement (with one single sheet of card) will be around 1 nF and should be easily measurable using a digital multimeter with a 2 nF or 20 nF capacitance range. Care should be taken when assembling the apparatus to avoid short circuits and unwanted stray capacitance.</p>	30 - 45 minutes
2	<p>This practical exercise needs careful attention. The effects being studied are small and easily missed. If students are using digital multimeters, they need to be aware that these sample the input signal periodically, so that short-duration pulses may be missed.</p> <p>Traditionally, students are always nervous about using multimeters - selecting the right range, using the correct sockets, etc. Instructors may need to run a brief revision session beforehand, or be prepared to assist with the readings.</p> <p>A further complication is that many multimeters have an internal fuse to protect against overload on DC current ranges. These 'blow' very easily, but do so out of sight, leaving the student puzzled as to the lack of activity on the meter. Instructors will need to check the meters regularly, and have a ready supply of new fuses.</p> <p>Similarly with the oscilloscope, the input may be sampled. Repeating the action several times will help to convince the student what is going on, and may produce a good trace on the oscilloscope eventually.</p> <p>Fleming's right-hand (dynamo) rule will need careful explanation, and a great deal of practice if students are to feel confident about its use. Some will confuse the use of the left-hand and right-hand rules.</p> <p>An explanation is given in terms of the behaviour of electrons. The instructor should judge how far to take this with a given class of students.</p>	30 - 45 minutes



Worksheet	Notes for the Tutor	Timing
3	<p>This worksheet is designed to introduce students to the concept of inductance.</p> <p>First of all, a steady magnetic field is generated in the core of an inductor by applying a DC current. Then, the student observes the emf induced across the inductor's terminals when the current is interrupted and the magnetic flux collapses.</p> <p>Due to the transient nature of this back emf, it is necessary to use a triggered oscilloscope to display it. Some initial experimentation may be required in order to optimise the oscilloscope settings but those given in the worksheet should make a good starting point.</p> <p>Note that the inductance used for this investigation is obtained from the primary winding of the Locktronics transformer component. This has optimum characteristics for this investigation (smaller components may produce much shorter transients which may be accompanied by a significant amount of damped oscillation resulting from the presence of shunt capacitance in the oscilloscope leads).</p>	20 - 30 minutes
4	<p>Motors abound in aircraft systems, and they come in a variety of shapes and sizes. It is helpful to have a display of examples to introduce this topic.</p> <p>The experiment itself lasts only a few minutes, but the students should be allowed to 'play' with the kit until they are confident about what is happening.</p> <p>The instructions tell students how to reverse the magnetic field, and reverse the current direction, to see what effect these changes have.</p> <p>Ultimately, the effect is pretty mysterious, and relies on the properties of electrons themselves. It depends on the previous experience of the students, and of the instructor, as to how far the explanation on page 3 is taken.</p> <p>Electrons are 'magical' and their behaviour is beyond our everyday experience. For example, if an electron moves past us, we experience a magnetic field. Equally, if the electron is at rest and we move past it, the result is the same. If we move along at the same rate as an electron, we experience no magnetic field. Moving electrons are the source of all magnetic effects, even those in 'permanent' magnets, where there is no obvious flow of electrons.</p> <p>It is important that students learn to use the left-hand (motor) rule to relate the direction of the force on a conductor to the current and magnetic field directions. They will need plenty of practice in applying this rule.</p>	30 - 45 minutes

Worksheet	Notes for the Tutor	Timing
5	<p>In worksheet 4, the motion was linear. Students need time to appreciate the change to rotary motion. The diagrams on page 11 should be studied carefully, with liberal application of the left-hand rule.</p> <p>Students need to realise that a single coil will produce 'lumpy' motion . Maximum torque occurs when the plane of the coil is parallel to the field, as in the first and third diagrams. When the coil is vertical, there is still a force on the two sides, but it has no turning effect. Fortunately, the momentum built up will carry the coil through that position.</p> <p>Students need to realise that rotation can continue if there is some means of reversing the current direction. In a DC motor, this is achieved through the use of a commutator. For a single coil, this is a drum split into halves. For multi-coil rotors, the commutator is more complicated.</p> <p>For AC motors, the current reverses automatically in every cycle of the AC supply. It can be delivered to the coil by two slip rings, brass rings connected one to each end of the coil.</p> <p>A common cause of difficulty is the relationship between speed of rotation and current demanded from the power source. If the motor is running at maximum speed, the only work it has to do is against frictional forces in the bearings and air resistance. As a result, it draws only a small current. When required to do additional work, the motor draws extra current to provide it with extra energy.</p>	25 - 40 minutes
6	<p>There are two parts to this worksheet, both using pre-prepared kit.</p> <p>The first looks at the electricity generated when a magnet drops through a coil. The results are relatively small, and are short-lived and so are monitored on an oscilloscope. Students may need time and practice at this before they obtain convincing results.</p> <p>The resulting waveform is complex, as it is the result of first one pole of the magnet, and then the other, first approaching and then receding from the coil. This waveform needs careful analysis, and the tutor needs to ensure that the students recognise these elements of the waveform.</p> <p>The second looks at Lenz's law - "An induced current flows in such a direction as to oppose the effect producing it." The two projectiles look identical, but one is magnetised, and the other is not. The unmagnetised one falls 'normally' under gravity. The magnet, however, induces currents in the copper tube, which in turn generate magnetic fields that oppose the effect producing them - the falling magnet. As a result, the magnet falls only slowly. The experiment takes only seconds, but students should be allowed to repeat it to appreciate what is happening.</p>	20 - 30 minutes

Worksheet	Notes for the Tutor	Timing
7	<p>Transformers can appear mysterious. The aim here is to introduce them as an extension of what has gone before.</p> <p>If students can accept that electricity is generated when a magnet is plunged into a coil, then they should have no difficulty with the transformer. The magnet is replaced with an electromagnet, and the motion with a moving magnetic field generated by an alternating current.</p> <p>It may not be obvious to some that switching a DC electromagnet on and off causes a moving magnetic field, and hence induces current in the secondary coil. Instructors may wish to develop their understanding on this through questioning them.</p> <p>The difficulties here probably centre on the use of signal generators and oscilloscopes. The tutor may need to support students with these devices.</p>	30 - 45 minutes
8	<p>The main aim here is to distinguish between step-up and step-down transformers. Some find it easy to accept 'step-down' but see 'step-up' as defying the laws of nature - something for nothing. The investigation tackles this by looking at currents, and the overall power issues.</p> <p>The transformer used here is much more efficient than the primitive device used in worksheet 7 but is far from ideal. An ideal transformer wastes no energy and so obeys the transformer relation and the link between current ratio and turns ratio. The need for cooling fins and coolant circulation in substation transformers shows that ideal transformers are difficult to design. The treatment of the results introduces the transformer relation, which works pretty well, and the issue of stepping up and stepping down current, which is more problematic. Students should be asked to compare the use of a transformer to reduce AC voltage, with the use of a series resistor to drop some of the voltage. The transformer wins every time!</p> <p>The difficulties here probably centre on the use of signal generators and digital multimeters.</p>	30 - 45 minutes
9	<p>For convenience we often regard transformers as being loss-free and assume that all the power applied to the primary is transferred to the load connected to the secondary. In a real transformer this is rarely the case because power is wasted as 'iron loss' (power used to magnetize the core of the transformer) and as 'copper loss' (power wasted due to the <math>I^2R</math> losses in the transformer windings). In an aircraft, where significant power is consumed, we need to be aware of the losses that can occur in power transformers and the consequent impact on efficiency and regulation.</p> <p>This worksheet investigates these losses for a small transformer. In this task, they should make measurements at the usual aircraft supply frequency (400 Hz) to determine the primary (input) and secondary (output) voltages and currents as a transformer supplies different loads.</p> <p>Measured and calculated values of power loss and efficiency are recorded. Tutors should discuss the significance of these results and emphasise the impact of transformer loading on power loss and efficiency. Students should obtain values of efficiency around 70% for the loaded transformer and regulation of around 4% for a <math>270\Omega</math> load, falling to around 34% for the <math>27\Omega</math> load.</p>	30 - 45 minutes

## 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.

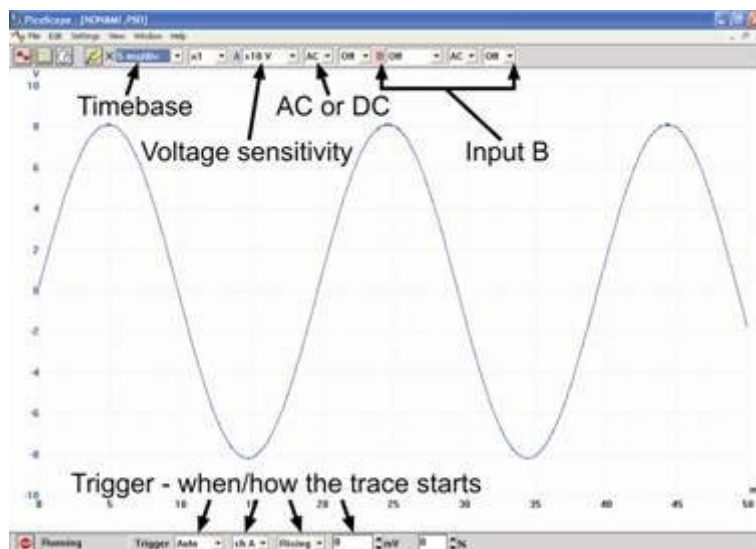
## Trigger:

- 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.



In this trace:

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

Voltage sensitivity =  $\pm 10$  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;

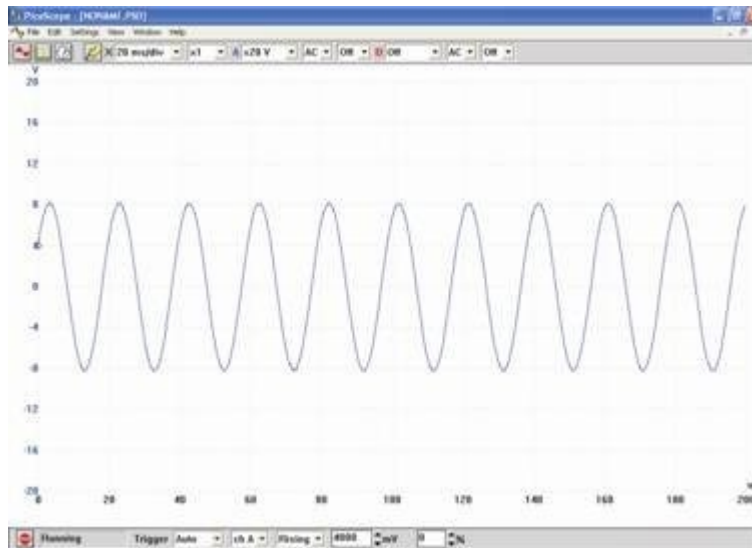
Ch A - so looks at the signal on channel to decide when to start the trace;

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*:



p23a

In this trace:

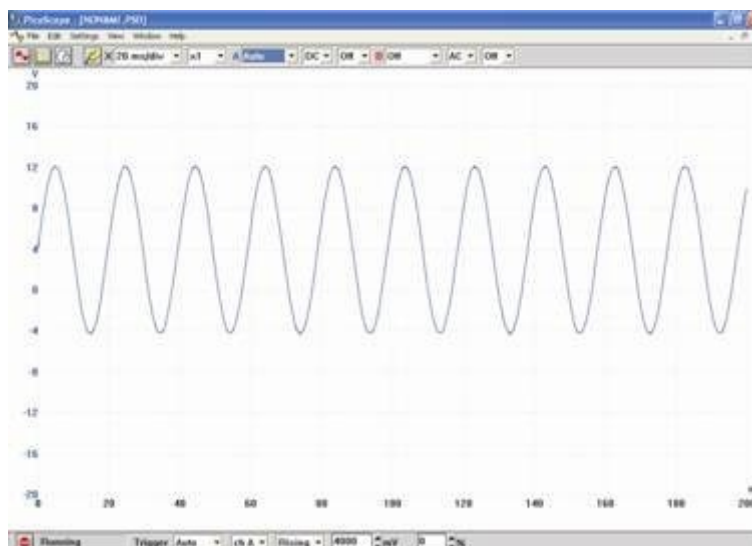
**Timebase** = 20ms/div,

- 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** =  $\pm 20$  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)



p23b

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  $\pm 8$ V, i.e. between -4V and +12V.