A set of accessory probes and adaptors for a multimeter will save you a lot of time and effort.

- Spring hook probes that use miniature hooks that will lock around terminals, eg the terminals inside an injector socket, allowing the measurement of injector resistance.

Buy leads that are silicone insulated as they'll be more durable than leads with conventional insulation.

Current clamp

A current clamp is a multimeter accessory that allows you to measure much higher current flows than a normal multimeter can handle. A current clamp outputs a precise voltage per measured amp. For example, it might have an output of 1 millivolt per amp (mV/A). This makes measuring the clamp's output easy – if the multimeter shows a measurement of 5mV on its voltage scale when connected to the operating clamp, the current flowing in the wire is 5A. If the voltage displayed on the multimeter is 100mV, the current flowing in the wire is 100A.

When using a current clamp, its jaws are opened, the clamp passed over the wire, and the jaws closed. The wire is then centred in the opening and the measurement made. Note that it's the *individual conductor* that is measured – not a cable containing both earth and power leads, for example.

Current clamps are not particularly good at accurately measuring very small currents. This is so for two reasons. Firstly, if the output scale of the clamp is 1mV/A, a current flow of 0.5A is only 0.5mV – a figure that is very low for many multimeters to accurately measure. In addition, because of the influence of stray magnetic fields, current clamps need to be zeroed before they can be used. That is, a knob on the clamp first needs to be turned until the current reading is zero – obviously, when there isn't any current flowing through a wire inside the jaws! Getting the meter to read precisely zero can be fiddly. For these reasons, current clamps are usually used for current measurements of about 5A and upwards. (Most multimeters have a maximum current rating of 10A, so in practice the overlap between a current clamp and a multimeter works fine.)

If you want to be able to directly measure the current draw of high-current devices like starter motors, air suspension compressors, car sound amplifiers, electric seat motors and the like, you need a current clamp. The same also applies when measuring alternator output.

Pressure sensor

Pressure sensors are available that will plug into a multimeter. The sensor can be used to measure fuel pressure, intake manifold pressure (both positive and negative), oil pressure and so on. The benefit of using an electronic sensor over a mechanical pressure gauge is that, depending on the meter being used, you may be able to measure not only the 'live' value but also the maximum, minimum and average values. A fast-response pressure sensor can also be used with an oscilloscope – more on scopes in Chapter 7. Like current clamps, pressure sensors output a certain voltage per unit of pressure. The Fluke PV350 sensor I have can be switched to either metric or Imperial units, and outputs a voltage of 1mV DC per unit.

A pressure measuring attachment for a multimeter. Used with a good multimeter, with peak-hold and similar functions, this accessory is very useful.

to power it. For example, most MAP sensors have three connections:

- 5V feed
- Ground
- Signal output

Most temperature sensors are exceptions to this ‘three wires’ approach. These comprise variable resistors, where resistance changes with temperature. In these cases, the ECU feeds a regulated voltage to the sensor and uses an internal voltage monitoring circuit to measure the voltage change caused by the varying resistance of the sensor (more on this in the next chapter). Such sensors have only two wires – ground and signal. Figure 5-3 shows part of the circuit diagram of an engine management system. The ECU is on the left, and you can see intake air temperature (IAT) and engine coolant temperature (ECT) sensors on the right. These are analog variable resistance sensors.

Most people have no problem in understanding analog signals, so I’ve kept the description brief. But digital signals often cause consternation!

DIGITAL SIGNALS

Digital signals are ones that change in steps. Usually (though not always) they’re either on or off. Figure 5-4 shows a graph of a digital signal varying over time. You can see that at any instant, the signal is either on (5V) or off (0V).

I said earlier that signals don’t usually flow much current, but most will still light an LED – and let’s use an LED as an example. If the on/off digital signal in Figure 5-4 were powering the LED, the LED would be flashing – on, off, on, off. On the other hand, with a varying analog signal voltage, the LED would instead be changing smoothly in brightness. To continue with the LED example – turning it on and off with a switch is to operate it digitally. Changing its brightness with a variable resistor is to operate it in an analog manner.

An electronic fuel injector is operated with a digital signal – the injector is either open or closed; there’s no attempt made to keep it open part-way. Let’s have a closer look at the way that electronic fuel injectors work, because their operation shows a lot of the characteristics of digital signals that we need to understand.

In the fuel-injection system, the fuel is supplied to injectors at high pressure. Injectors are simply solenoid valves with a built-in fine nozzle. When power is applied, the injector pintle rises, letting fuel flow through the nozzle in a spray. When power is removed, a spring shuts the nozzle, stopping the flow of fuel.

When the engine is spinning at 2000rpm, there are about 16 intake strokes every second. Since we add fuel every intake stroke, at 2000rpm we need to fire the injector (and so squirt in a bit of fuel) 16 times a second. Rather than write ‘times a second,’ we say the injector is being pulsed at 16 Hertz (abbreviated to Hz). This is the injector’s firing *frequency*.

So if someone says that a signal varies from 50Hz to 500Hz, we know that they’re referring to how many times per second the signal switches on and off – from 50 times a second to 500 times a second. As described earlier, you can directly measure the frequency of a signal using a good multimeter (the very cheapest don’t have this feature).

Another example of a variable frequency signal is that used by the car speed sensor. Many older sensors work just like a bicycle speedo that has a magnet on the wheel and a reed switch on the frame. Each time the wheel rotates, it closes a contact and so sends a pulse to the ECU. If there are lots of pulses per second, the ECU knows the vehicle is travelling faster than if there are only a few pulses per second. In this case, frequency is directly proportional to speed.

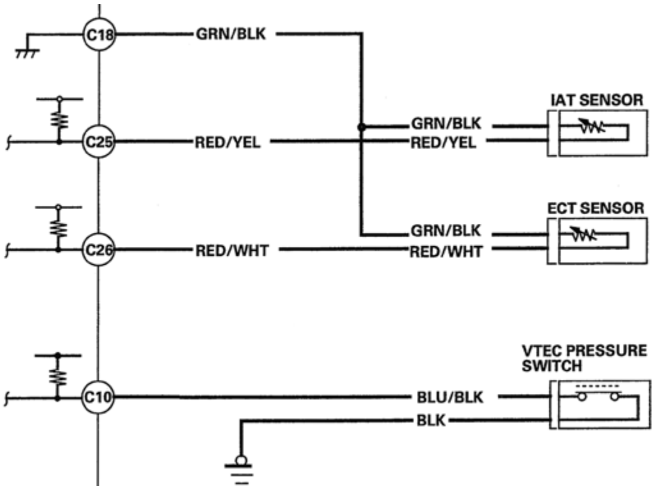

Figure 5-3: This extract from an engine management wiring diagram shows both analog and digital inputs. The Intake Air Temperature (IAT) and Engine Coolant Temperature (ECT) sensors are both two-wire, analog designs. The VTEC pressure switch, that shows when oil pressure has reached an appropriate pressure, is a digital sensor – it’s either on or off. Note how the VTEC switch uses a ground return. (Courtesy Honda)

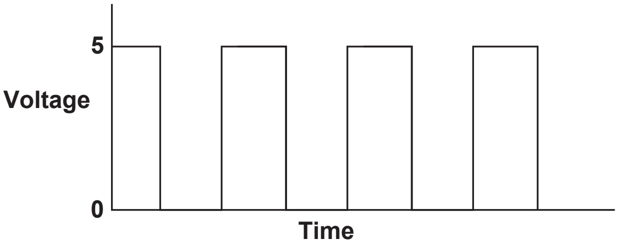

Figure 5-4: A graph of a digital signal that is either on (5V) or off (0V). Most (although not all) digital signals in cars are on/off signals

WAVEFORMS

The generic term for a pattern that repeats over time is a ‘wave’ – sound waves, brain waves, ocean waves, and voltage waves are all repetitive patterns. An oscilloscope measures voltage waves. One cycle of a wave is the portion of the wave that repeats. A waveform is a graphic representation of a wave. Remember, a voltage waveform on a scope shows time on the horizontal axis and voltage on the vertical axis.

Waveform shapes reveal a great deal about a signal. Any time you see a change in the height of the waveform, you know the voltage has changed. Any time there is a flat horizontal line, you know that there is no change for that length of time. Straight, diagonal lines mean a linear change – a rise or fall of voltage at a steady rate. Sharp angles on a waveform indicate sudden change.

You can classify most waves into these types:

- Sine waves
- Square and rectangular waves
- Triangle and saw-tooth waves
- Complex waves

In automotive applications, sine and square waves dominate.

Sine waves

The sine wave is the fundamental wave shape. It has harmonious mathematical properties – it is the same sine shape you may have studied in high school trigonometry class. Mains AC voltage varies as a sine wave (‘AC’ signifies alternating current, although the voltage alternates too. ‘DC’ stands for direct current, which means a steady current and voltage, such as a car battery produces). Figure 7-1 shows a sine wave.

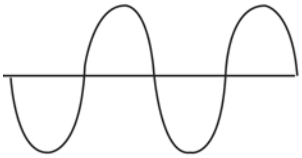

Figure 7-1: A voltage sine wave. The middle horizontal line represents 0V, so the signal is going plus and minus with respect to this. Inductive sensors output sine waves (although often not as nicely shaped as this one!)

Square and rectangular waves

The square wave is another common wave shape. A square wave is a voltage that turns on and off (ie goes high and low) at regular intervals. An injector waveform is fundamentally a square wave – the injector is either on or off. Figure 7-2 shows a square wave.

Figure 7-2: A square wave. Note that all of this wave is above the 0V line – this is not an AC waveform.

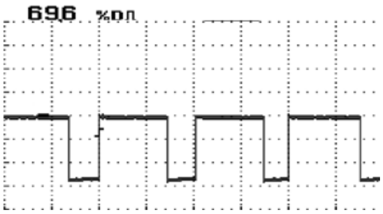

Figure 7-3: A rectangular wave, with the image taken from the scope screen. This waveform has a duty cycle of just under 70 per cent – that is, the voltage is high for 70 per cent of each repeating wave.

A rectangular wave is like the square wave, except that the high and low time intervals are not of equal length. That is, the ‘on’ and ‘off’ times are not equal. Again, this is often the case with an injector, where at low loads the ‘off’ time will be much longer than the ‘on’ time (ie variable duty cycle). Figure 7-3 shows an oscilloscope close-up of a rectangular wave.

WAVEFORM MEASUREMENTS

Many terms are used to describe the types of measurements made with an oscilloscope.

Frequency and period

If a signal repeats, it has a frequency. To remind you, frequency is measured in Hertz (Hz) and equals the number of times the signal repeats itself in one second. Hertz can also be referred to as ‘cycles per second.’ A repetitive signal also has a ‘period’ – this is the amount of time it takes the signal to complete one cycle. Period and frequency are reciprocals of each other, such that one divided by the period equals the frequency, and one divided by the frequency equals the period.

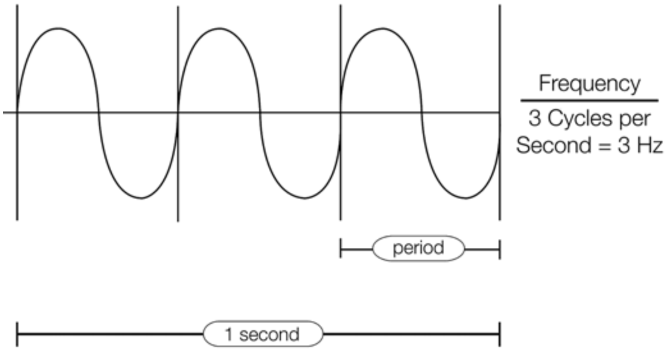

Figure 7-4: This shows a sine wave with a frequency of 3Hz – it repeats itself three times in the 1 second period. The period of the wave is therefore ⅓ of a second.

For example, a sine wave may have a frequency of 3Hz, which would give it a period of ⅓ of a second. This is shown in Figure 7-4. Some scopes can calculate frequency and display it as a standalone number, while in other cases, the period needs to be read off the scope screen and the frequency then calculated from this.

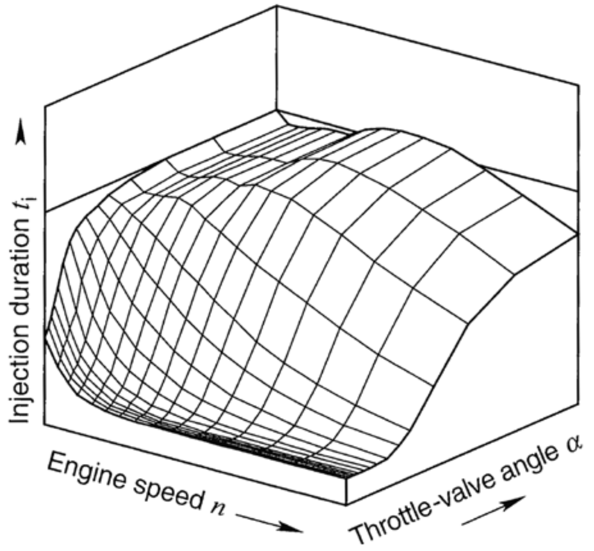

Figure 8-9: Mono-Jetronic 3D map of injection duration versus throttle position and engine speed. (Courtesy Bosch)

to deliver a stoichiometric air/fuel ratio under all operating conditions. The map consists of 225 control co-ordinates, made up of 15 reference co-ordinates for throttle position, and 15 for engine rpm. Because of the extremely non-linear shape of the air-charge curves, the data points are situated very closely together at the low-load end of the map. The ECU interpolates between the discrete points within the map.

If the ECU registers deviations away from stoichiometric air/fuel ratios, and as a result is forced to correct the basic injection duration for an extended time, it generates mixture correction values and stores them as part of the adaptation process. In this way engine-to-engine variations and engine wear are compensated for.

Compensations

Because the Mono-Jetronic system uses just a single injector location, manifold wall wetting through condensation is a much more major problem than in multipoint systems. As in all digital EFI systems, injector pulse width is increased when the engine is cold. However, because condensation of the fuel also depends on the air velocity, the starting injector duration is reduced as engine speed increases. To counteract the possibility of flooding, the longer the engine cranks, the less fuel that is injected, with it reduced by 80 per cent after six seconds of cranking. Once the engine has started, the injector opening duration is based on the values stored within the Lambda map, suitably modified on both a time and temperature basis by the engine coolant temperature input.

While all EFI systems use the equivalent of a carburettor accelerator pump during rapid throttle movements, the single injector location of the Mono-Jetronic system makes this a critical area. During sudden changes in throttle position three factors need to be taken into consideration:

- Fuel vapour in the central injector unit and intake manifold is transported very quickly – at the same speed as the intake air.
- Fuel droplets are generally transported at the same speed as the intake air, but are occasionally flung against the intake manifold walls, where they form a film which then evaporates.
- Liquid fuel is transmitted as a fuel film on the intake manifold walls, reaching the combustion chambers after a time lag.

At idle and low loads, the air pressure within the manifold is low (ie there is a high vacuum), and the fuel is almost entirely vapour with no wall wetting. When the throttle valve is opened, the intake manifold pressure rises, and so does the proportion of fuel on the manifold walls. This means that when the throttle is opened, some form of compensation is necessary to prevent the mixture becoming lean due to the increase in the amount of fuel deposited on the walls. When the throttle is closed, the wall film reduces, and without some form of leaning-compensation the mixture would become rich!

Rather than basing the transitional compensation on throttle position alone, the system uses the *speed* with which the throttle is opened or closed as the determining factor. Maximum correction occurs when the throttle is opened at more than 260 degrees per second. Also incorporated in these dynamic mixture corrections are the input of the engine and intake air temperature sensors.

Mixture adaptation

The mixture adaptation system uses the EGO sensor input. The system must compensate for three variables:

- air-density changes when driving at high altitudes
- vacuum leaks after the throttle butterfly
- individual differences in injector response times

The frequency of the updates varies between 100 milliseconds and 1 second, depending on the engine load and speed.

BOSCH MOTRONIC – IGNITION AND FUEL CONTROL

When most people think of standard engine management systems, they are likely to be thinking of the Bosch Motronic system or one of its of close derivatives. Engine management – the control of *both* fuel and spark – really came about with this system. It is an approach that is still widely used today. Motronic uses digital ECUs that contains ‘maps’ – three-dimensional look-up tables that allow the controlled output (for example injector pulse width or ignition timing) to be set on the basis of load and rpm.

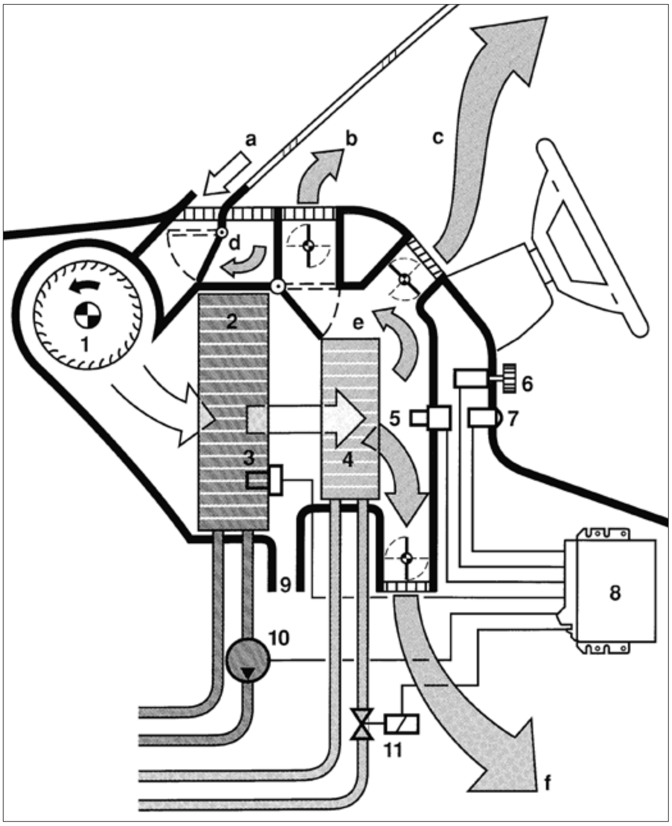

Figure 9-9: A simple climate control system. (1) blower, (2) evaporator, (3) evaporator temperature sensor, (4) heater, (5) air exit temperature sensor, (6) driver temperature adjust, (7) interior temperature sensor, (8) ECU, (9) drain, (10) compressor, (11) heater water valve, (a) fresh air, (b) defrost, (c) ventilation, (d) circulating air, (e) bypass, (f) footwell. (Courtesy Bosch)

Inputs:

- Interior temperature sensor
- Ambient temperature sensor
- Fresh air temperature sensor
- Footwell outlet temperature sensor
- Solar sensor
- Footwell/defrost flap position sensor
- Central flap position sensor
- Temperature mixing flap position sensor
- Fresh air/recirculation flap position sensor
- Refrigerant pressure switch

Outputs:

- Footwell/defrost flap actuator
- Central flap actuator
- Fresh air/recirculation flap actuator
- Blower speed regulator
- Heater flow valve actuator
- Air conditioner compressor clutch relay
- Diagnostic connector

In older cars, flaps in the climate control system were often moved by vacuum actuators, but in more modern cars, direct DC motor control is used. The ECU logic may include inhibiting cabin airflow until the coolant is warm enough to provide heat, or the air-conditioning system is cool enough to provide cooling airflow. Some systems also have a road speed input that reduces cabin fan speed as aerodynamic ram effect increases.

Figure 9-9 shows a schematic view of a fairly simple climate control system using vacuum-operated actuators, as might be found in a 1990s luxury car. This type of system does not feature self-diagnostics. Figure 9-10 (overleaf) shows part of the wiring diagram of a more sophisticated climate control system that uses electrically-driven actuators and has links to other car ECUs.

AUTOMATIC TRANSMISSIONS

On many cars, the control of the automatic transmission is integrated into the engine management system. This allows the same input sensors (eg throttle position, intake airflow, engine temperature, etc) to be used in transmission control without the need for duplicate sensors. It also allows the engine operating conditions to be varied as required – eg the ignition timing to be retarded during the gear changes to momentarily drop engine power and so give smoother shifts. On other cars, a dedicated ECU looks after the transmission.

Automatic transmission control is carried out by the actuation of a number of hydraulic valves within the transmission. These control the flow of hydraulic oil which apply and release the internal clutches and bands, causing the gearshifts to take place. The two main inputs used to determine both the internal clamping pressures and when gearshifts occur are throttle position and road speed. Throttle position can be signalled to the ECU by the output of the throttle position sensor, or the ECU may internally model the torque output of the engine (eg by looking at throttle position, airflow, etc) and then use this information. Some older cars had transmissions that, while otherwise electronic, still used a throttle cable that mechanically connected the throttle to the transmission.

Line pressure is also varied within auto transmissions. This pressure controls the clamping forces and has a major influence on when gear changes occur; as engine power output increases, line pressure is increased. Transmissions also have a lock-up clutch in the torque converter, which when engaged stops any slip. This clutch is controlled on the basis of road speed and load, and may also be automatically disengaged when braking.

Transmission fluid control solenoids use two approaches – they're either turned on or off, or they are a variable flow design where the ECU steplessly alters their opening. The solenoids that control the gear change