Teach-In 2018

Get testing! – electronic test equipment and measurement techniques

Part 5: Inductors, resonant circuits and quartz crystals

by Mike Tooley

Welcome to *Teach-In 2018: Get testing! – electronic test equipment and measurement techniques*. This *Teach-In* series will provide you with a broad-based introduction to choosing and using a wide range of test gear, how to get the best out of each item and the pitfalls to avoid. We'll provide hints and tips on using, and – just as importantly – interpreting the results that you get. We will be dealing with familiar test gear as well as equipment designed for more specialised applications.

Our previous *Teach-In* series have dealt with specific aspects of electronics, such as PICs (*Teach-In 5*), Analogue Circuit Design (*Teach-In 6*) or popular low-cost microcontrollers (*Teach-In 7* and *8*). The current series is rather different because it has been designed to have the broadest possible appeal and is applicable to all branches of electronics. It crosses the boundaries of analogue and digital electronics with applications that span the full range of electronics – from a single-stage transistor amplifier to the most sophisticated microcontroller system. There really is something for everyone in this series!

Each part includes a simple but useful practical *Test gear project* that will build into a handy gadget that will either extend the features, ranges and usability of an existing item of test equipment or that will serve as a stand-alone instrument. We've kept the cost of these projects as low as possible and most of them can be built for less than £10 (including components, enclosure and circuit board).

This month

In this fifth part, *In theory* introduces inductors and the parameters that need to be measured when dealing with them. *Gearing up* introduces measuring instruments and techniques used for testing inductors, resonant circuits (where resistance, capacitance and inductance are all present at the same time), and quartz crystals. *Get it right!* helps you to avoid some of the pitfalls, providing some useful tips that will help you to improve the accuracy and relevance of your measurements. Finally, our fifth *Test gear project* is a quartz crystal checker that can also act as a handy calibration marker.

In theory: Measuring inductance and impedance

An inductor is an energy-storing device made up of a coil of wire (often comprising many turns) wound over a laminated steel, ferrite or air core. When current flows in the coil, a magnetic field is created in the core and in the space that immediately surrounds it. Inductors are specified in number of ways, including the value of inductance, tolerance and working current; they tend to fall within one of the following main types:.

- Inductors with laminated-steel cores
- Ferrite-cored inductors (often toroidal in shape)
- Air-cored inductors (with or without non-magnetic coil formers).

Depending on several factors (including the required value of inductance and operating frequency), different types of inductor are chosen for use in different applications. The type of inductor also has an impact on the tests and measurements carried out to determine whether it is functional and fit for purpose. For example, a large laminated-steel-core inductor will often have appreciable resistance due to the length of wire used in its construction. This results in a measurement that must take into account resistance as well as inductance, constituting an *impedance* rather than a pure inductance. We've summarised the properties of the main types of inductor in Table 5.1.

Equivalent circuit of an inductor

The equivalent circuit of an inductor is shows in Fig. 5.2. The components shown are:

- Effective inductance, L
- Parallel (or 'shunt') capacitance, C_P
- Equivalent series resistance (ESR), R_S
- Effective shunt resistance, R_P.

It is important to be aware that the additional components shown in Fig. 5.2 can affect the performance of an inductor. For example, at low frequencies, C_P is insignificant, but does become increasingly important at high and very high frequencies. R_P, on the other hand is of little consequence in low-impedance equipment (such as power supplies). Conversely, while R_S is unimportant in high-impedance circuits it becomes

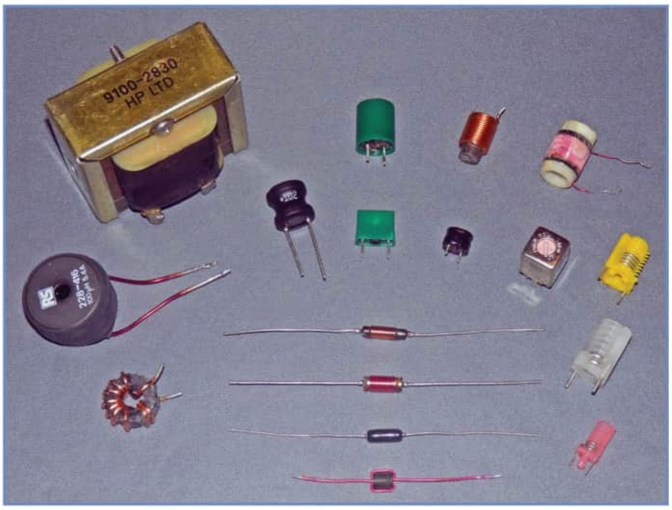

Fig.5.1 Different types of inductor with values ranging from 10µH to 10H

Table 5.1 Properties of various types of inductor

Type of inductor	Typical range of inductance	Typical tolerance	Typical resistance	Typical current rating	Typical applications
Laminated steel core	10mH to 10H	±10%	2Ω to 200Ω	500mA to 10A	Power and low-frequency applications
Ferrite core	10μH to 10mH	±5%	0.2Ω to 20Ω	1mA to 1A	Power supplies and filters
Air core	10nH to 10μH	±2%	0.01Ω to 1Ω	0.1mA to 100mA	RF tuned circuits and filters

critical in low-impedance situations (such as power supplies, amplifiers and switching circuits).

Effective series resistance (R_S)

The inductor's effective series resistance (R_S) is the internal resistance of the inductor expressed as a single resistance value considered to be connected in series with a perfect inductor. R_S is mainly attributable to the resistance of the (copper) wire used in an inductor's windings, but also takes into account the resistance of the connecting leads, contacts and tags (where appropriate). ESR is inversely proportional to frequency. In other words, as frequency increases, the 'copper loss' decreases.

While only a very small amount of power is dissipated in R_P, a very significant power can be dissipated in R_S when an appreciable current (either AC or DC) is flowing through the component. The power loss in R_S results in internal heating which can, in some cases, be responsible for impairing the properties of the magnetic core (this is particularly important with ferrite components used as filters and transformers in high-current power supplies).

Dissipation factor (D or DF)

The dissipation factor of an inductor is the ratio of the inductor's ESR to its reactance (X_L) at a specified frequency. As with a capacitor, dissipation factor is also referred to as 'tan δ' – ie, the tangent of the 'loss angle' of the inductor in which ESR (R_S) and reactance (X_L) are the adjacent perpendicular sides.

Since reactance (X_L) varies with frequency, an inductor's dissipation factor will also vary with frequency. Dissipation factor is usually quoted for sinusoidal AC power applications and is less meaningful when conditions are non-sinusoidal (as in switched-mode power supplies and class-C and D power amplifiers). Dissipation factor is given by:

$$D = \tan\delta = \frac{R_S}{X_L} = \frac{R_S}{2\pi fL}$$

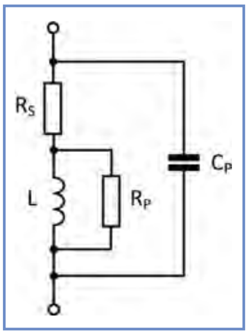

Fig.5.2 Equivalent circuit of a real inductor

To help put this into context, consider the following example. An inductor of 10H with an effective series resistance of 150Ω is used at a frequency of 50Hz. The dissipation factor is given by:

$$D = \frac{R_S}{2\pi fL} = \frac{150}{6.28 \times 50 \times 10}$$

$$= \frac{150}{6.28 \times 50 \times 10} = 0.048 \quad \text{(or 4.8\%)}$$

Quality factor (Q or Q_F)

Q is the ratio of inductive reactance (X_L) to effective series resistance at a specified frequency. Quality factor is the inverse of the dissipation factor. Hence:

$$Q = \frac{1}{D} \text{ and } D = \frac{1}{Q}$$

Thus, in the previous example, at 50Hz the inductor will have a Q-factor calculated from:

$$Q = \frac{1}{D} = \frac{1}{0.034} = 29.4$$

As with capacitors, most universal bridges (see last month's *Teach-In*) will allow you to measure Q and D to reasonable accuracy.

Shunt capacitance (C_P)

Shunt (parallel) capacitance is the effective capacitance of the inductor, including its connecting leads, tags or pins. It is important to be aware that this capacitance is made up of the sum of the component's internal capacitance (ie, the capacitance between winding turns) and the stray capacitance of its external connections.

Effective shunt capacitance reduces the effectiveness of an inductor at high frequencies. It is also responsible for a sharp rise in impedance that occurs at the component's *self-resonant frequency* (SRF). Depending on the inductor type, construction and value, the SRF occurs at frequencies of between about 1.3MHz for a 1mH ferrite cored choke to around 150MHz for a 1μH PCB-mounting component. Typical values of shunt capacitance range from between 10pF and 20pF for a 1mH ferrite choke, to less than 2pF for a 1μH PCB-mounted component. A large steel-cored inductor will have significantly higher values of C_P, but this is usually of little importance in low-frequency and power applications.

Measuring impedance

Impedance is an important parameter in a wide variety of electronic circuits and can be defined as the total opposition offered by a component or circuit to the flow of alternating current (AC) at a stated frequency. Unlike pure resistance in a DC circuit, impedance is a vector quantity that consists of a real part (resistance) and an imaginary part (reactance). The reactance can either be capacitive, $-jX_C$, or inductive, $+jX_L$. Note that the j-operator is used to indicate the quadrature phase angle with current leading or lagging voltage by 90° according to the sign placed immediately before the j-operator. Fig.5.3 illustrate this important relationship between resistance (R) reactance (X_C) and inductance (X_L). Note that the phase angle (ø) is defined as the angle between applied current (I) and voltage (V).

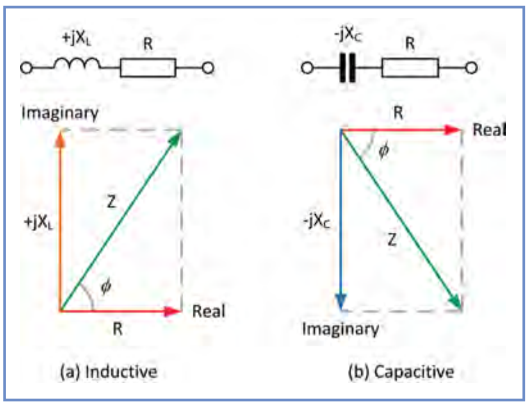

Fig.5.3 Impedance triangles for (a) inductive and (b) capacitive reactance

Resonant circuits

A resonant circuit is one in which there is resistance and a combination of both inductive and capacitive reactance present. In such circuits there will be one particular frequency at which the current and voltage are exactly in-phase and since the reactive components effectively cancel one another out the circuit behaves like one that contains only pure resistance. This can be extremely useful in a number of applications that require circuits to be selective, eg, accepting or rejecting current at a particular frequency.

Circuits that contain only a combination of resistance and pure capacitance or only a combination of resistance and pure inductance are 'non-resonant' because the voltage and current will not be in-phase at any frequency. More complex circuits, containing both types of reactance together with resistance are described as 'resonant' since there will be one frequency at which the two reactive components will be equal but opposite. At this particular frequency, (known as the *resonant* or *tuned frequency*) the effective reactance in the circuit will be zero and the voltage and current will be in-phase.

The reactive components in a series LCR circuit will effectively cancel each other out when a circuit is resonant. We can thus determine the frequency of resonance (f_0) by simply equating the two reactive components, as follows:

$X_L = X_C$, and thus:

$$\frac{1}{2\pi f_0 C} = 2\pi f_0 L$$

Making f_0 the subject of this equation gives:

$$f_0 = \sqrt{\frac{1}{4\pi^2 LC}} = \frac{1}{2\pi\sqrt{LC}}$$

At resonance, the impedance of this circuit will simply be equal to the resistance, R.

In the case of a parallel resonant circuit (L connected in parallel with C) and where the inductor has resistance R, the frequency of resonance will be:

$$f_0 = \frac{1}{2\pi}\sqrt{\left(\frac{1}{LC} - \frac{R^2}{L^2}\right)}$$

At resonance the impedance of the circuit will be given by:

$$Z_d = X_C \times \frac{X_L}{R} = \frac{2\pi fL}{2\pi fC} \times \frac{1}{R} = \frac{L}{CR}$$

This is often referred to as the *dynamic impedance* of the resonant circuit.

Q-factor

The *Q*-factor (or *quality factor*) is a measure of the 'goodness' of a tuned circuit and is sometimes also referred to as its *magnification factor*. In the case of a series tuned circuit, the *Q*-factor simply tells you how many times greater the inductor or capacitor voltage will be than the supply voltage. The better the circuit the higher the voltage magnification and the greater the *Q*-factor. Conversely, for a parallel circuit, the *Q*-factor tells you how many times greater the inductor or capacitor current will be than the supplied current. When dealing with resonant circuits it is thus important to have a means of measuring *Q*-factor as well as impedance. Practical values of *Q* for a resonant circuit range from about 20 to 200.

Gearing up: Testing inductors and resonant circuits

Measuring inductance

The value of inductance (L) can be measured in various ways. The traditional method is that of using an AC bridge arrangement, like that shown in Fig.4.3 last month. The bridge is adjusted for a null on the indicator and in this condition is said to be 'balanced'. In the balanced condition the value of inductance is read and interpolated from a calibrated scale. Note that some bridges incorporate provision for injecting a DC bias or for making use of external AC excitation. Automatic bridges are also available, and these eliminate the need for the manual balancing operation.

LCR meters

Unfortunately, while modern multimeters often incorporate capacitance ranges they very rarely incorporate inductance measuring facilities. Fig.5.4 shows an exception to this rule in the form of

Fig.5.4 A low-cost multi-range LCR meter

Fig.5.5 The Peak Electronics LCR40 being used to check the value of a small steel-cored inductor

a low-cost portable multi-range LCR meter available for purchase on-line for around £10. This instrument doesn't have the usual current and voltage ranges but instead has no less than nine resistance ranges, six capacitance and four inductance ranges. For good measure, this particular instrument also measures transistor current gain!

Instruments like the Peak Electronics LCR40 and LCR45 (described last month) can be a useful investment if you need to measure inductors on a regular basis and with a reasonable degree of accuracy. Note that, in addition, the Peak Electronics LCR45 measures complex impedance, complex admittance (both displayed in rectangular form) as well as the magnitude and phase of impedance displayed in polar form. Fig.5.5 shows the Peak LCR40 being used to measure the inductance of a steel-cored choke. Additional information can be obtained by simply scrolling the display.

Measuring impedance

Impedance measurement tends to be a little more complicated than simple inductance and capacitance measurement. However, several different methods are available, including:

- Manual or automatic impedance bridges
- Measurements based on resonance
- V-I techniques
- Network analysers.

Table 5.2 shows a comparison of the

Instrument or method	Advantages	Disadvantages	Typical frequency range	Typical application
Manual or automatic AC bridge	Accuracies of better than 0.5% can be achieved	May need manual adjustment and balancing	DC to well over 50MHz	Laboratory testing
Resonance	Only suitable for high-*Q* components	Requires manual adjustment	100kHz to 10MHz	Tuned circuits and other high-*Q* measurements
V-I method	Can be easily performed using readily available test instruments	Requires calculation using separate voltage and current measurements	50Hz to 1MHz (RF V-I instruments are available but can be expensive)	Low-*Q* inductors used in AC power and audio frequency applications
Network analyser	Very wide frequency range coupled with high accuracy	Expensive, may need recalibration at different frequencies	1MHz to 1GHz	Laboratory analysis and circuit design

Table 5.2 Comparison of impedance measuring techniques

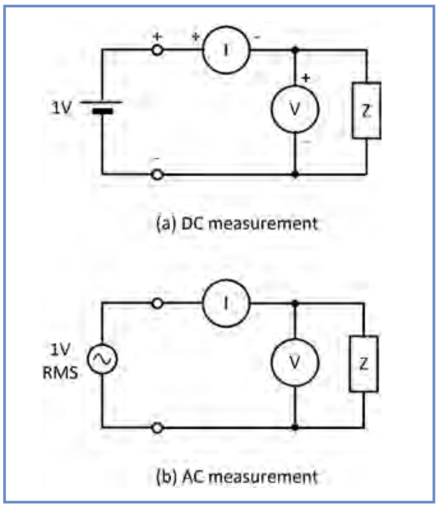

Fig.5.6 The V-I method of impedance measurement

above methods. Note that several of these methods require expensive test equipment.

Using the V-I method

The V-I method of inductance/impedance measurement can be quite effective and will yield useful results with reasonable accuracy. It is thus ideal for 'one-off' measurements. Fig.5.6 shows the simple arrangement used by the author. Two sets of measurements are required, one at DC and the other using an AC source. The unknown impedance is first connected to a DC power supply, as shown in Fig.5.6(a). The power supply (virtually any variable bench power supply will be suitable) is then adjusted until the DC voltmeter reads exactly 1V. At this point the DC current is measured and recorded.

Next, the unknown impedance is connected to an AC source, as shown in Fig.5.6(b). The AC source can be a signal generator with a low output impedance or a 50Hz transformer with a low voltage secondary winding and a suitably rated variable resistor connected in series with the secondary. The frequency of the AC source is set to the required test frequency (usually 50Hz, 100Hz or 400Hz) and the AC voltage is adjusted until the AC voltmeter reads exactly 1V.

At this point, the AC current is measured and recorded. Tests are often carried out at 50Hz or 100Hz for large inductors and at 400Hz, 1kHz or 10kHz for smaller ferrite-cored inductors. The recorded values can then be entered into a spreadsheet (available for download from the *EPE* website) and the impedance can then be automatically calculated (see Figs.5.7 and 5.8). The spreadsheet will save you having to perform several error-prone calculations by hand. The accuracy of this method is often comparable with other methods and will usually yield a result that is better than ±5%.

Q-measurement

Q-factor can be measured using various methods, but the most simple and convenient method is with the aid of a dedicated *Q*-meter. This instrument comprises a very low-impedance variable-frequency source together with a sensitive RF voltmeter. Typical examples of instruments that become available on the second-hand market from time to time are the Advance T2 (see Fig.5.9) and the Marconi TF1245 *Q*-meter. More complex network analysers have largely superseded such instruments, but they can still be invaluable if you design and/or manufacture resonant *LC* circuits on a regular basis. They also tend to be (much) more affordable than network analysers. Fig.5.10 shows typical results obtained from the author's *Q*-meter when designing a high-*Q* inductor for use in a high-power antenna tuner. To reduce losses, the 44µH inductor was manufactured using silver-plated copper wire wound on a large ceramic former and, as can be seen, it manages to achieve a *Q*-factor of 150 with a shunt capacitance of 40pF at a measurement frequency of 3.4MHz.

Fig.5.9 An Advance Electronics T2 Q-meter

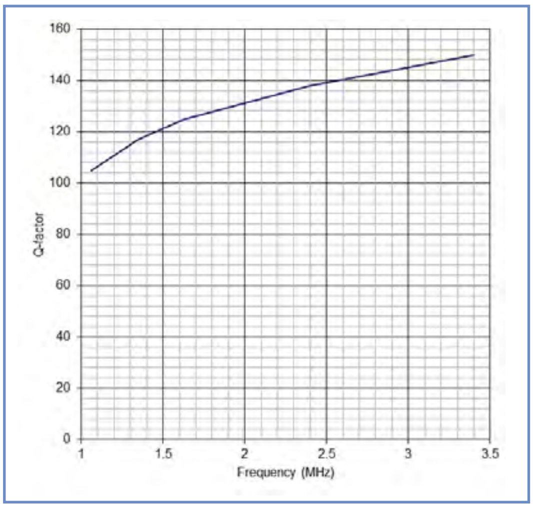

Fig.5.10 Variation of Q-factor with frequency for the inductor shown in Fig.5.11

Dip meters

A hand-held dip meter (see Fig.5.12) provides a very simple method of measuring the resonant frequency of a tuned circuit. The instrument comprises a variable frequency RF oscillator and a meter that either responds to the amount of current supplied to the oscillating device (eg, the collector current of the oscillator stage) or is arranged to indicate the RF voltage appearing across the oscillator *LC* 'tank' circuit. In use, a coil is selected from those supplied with the instrument

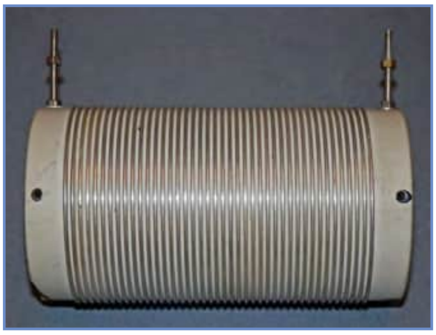

Fig.5.11 A large air-cored 44µH inductor wound on a low-loss ceramic former

V-I Method		
1. Apply 1V DC to the component or circuit.		
2. Select an appropriate DC current range.		
3. Measure the DC current flowing and enter it here:	230	mA
4. Apply 1V AC to the component or circuit		
5. Enter the AC signal frequency here:	100	Hz
6. Select an appropriate AC current range.		
7. Measure the AC current flowing and enter it here:	125	mA

Calculated results:		
	Impedance, Z =	8.00 ohm
	Resistance, R =	4.35 ohm
	Reactance, X =	6.72 ohm
	Inductance, L =	10.69 mH
	Power factor, PF =	0.543

Fig.5.7 Spreadsheet analysis of V-I results for a 10mH ferrite-cored inductor

V-I Method		
1. Apply 1V DC to the component or circuit.		
2. Select an appropriate DC current range.		
3. Measure the DC current flowing and enter it here:	900	mA
4. Apply 1V AC to the component or circuit		
5. Enter the AC signal frequency here:	100	Hz
6. Select an appropriate AC current range.		
7. Measure the AC current flowing and enter it here:	45	mA

Calculated results:		
	Impedance, Z =	22.22 ohm
	Resistance, R =	1.11 ohm
	Reactance, X =	22.19 ohm
	Inductance, L =	35.34 mH
	Power factor, PF =	0.050

Fig.5.8 Spreadsheet analysis of V-I results for the steel-cored inductor shown in Fig.5.4

Fig.5.12 A wide-range dip meter covering 1.5MHz to 250MHz in six ranges

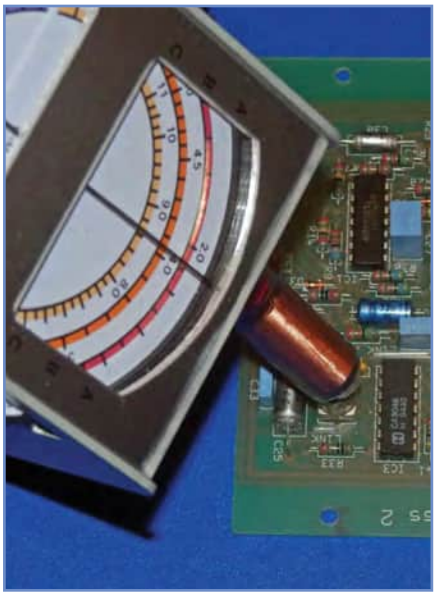

Fig.5.13 Using the dip meter to check a resonant circuit

Get it right when carrying out impedance, resonance and Q-measurement

- Always ensure that your measurements are made at an appropriate frequency. For example, when using the V-I impedance method ensure that the AC measurement is made at a frequency that's within the expected operating range for the component being tested
- When measuring small values of inductance, ensure that measurements are carried out with the shortest possible test leads. If using a hand-held instrument (like the Peak LCR40 and LCR45) ensure that the test probes are calibrated by opening and shorting them immediately before making a measurement. If using a bench instrument for testing inductors it is best to connect the component directly to the instrument (ie, without using test leads or prods)
- When using a *Q*-meter, ensure that the inductor is mounted well away from any ferromagnetic or ferrite components. It should also be supported clear of any grounded parts (such as the case of the instrument itself)
- When using a hand-held dip-meter ensure that there is adequate coupling between the instrument and the resonant circuit on test. Furthermore, some instruments will display false dips, so it can be useful to carry out an initial frequency sweep before attempting to make a measurement (the initial frequency sweep will reveal any problems before you attempt to locate a dip)
- When using an impedance bridge, select a higher range and work downwards, progressively increasing the sensitivity of the instrument in order to obtain a sharp null indication
- Self-resonant frequency (SRF) measurements can be misleading unless you are able to minimise the effects of stray capacitance and inductance resulting from instrument connections
- Don't rely on measurements where component values may be towards the end of the instrument's measuring range (accuracy will be impaired as the instrument's limits are approached).

covering the expected frequency range and then inserted into a socket on the hand-held unit. The sensitivity control is adjusted for a mid-range indication and the coil is held in close proximity to the *LC* circuit on test. This is accomplished with the coil held end-on to the inductor or resonant transformer to maximise inductive coupling, as shown in Fig.5.13. The oscillator frequency control is then carefully swept across the expected range while observing the meter indication. When the oscillator frequency matches that of the resonant circuit, energy is coupled into the circuit on test and, as a consequence, there is a sudden dip in the meter indication. The MFJ-201 dip meter shown in Fig.5.12 covers 1.5MHz to 250MHz in six ranges and this handy device can also operate as an absorption wavemeter and quartz crystal checker (see later).

Test Gear Project: Handy Crystal Checker

Quartz crystals are widely used in electronic circuits when an accurate reference frequency is required. A quartz crystal undergoes mechanical deformation when a voltage is applied across its faces. Conversely, a voltage is developed across the same faces when it is mechanically deformed. This phenomenon is known as the *piezoelectric effect* and it has several useful applications in electronics, including accurate frequency control of oscillators.

Quartz crystals used in electronic circuits usually consist of a thin slice of quartz. Opposite slice faces have electrodes made from a thin film of deposited gold or silver. Fine wires are soldered at nodal points on each electrode and the complete assembly is enclosed in an evacuated glass or metal envelope. Lead-out pins or wires are connected to external circuitry. The type of encapsulation, size, dimension and pin-spacing varies from one type of crystal to another. Some of the most common crystals are the HC18/U types that are miniature, metal encapsulated wire-ended types which may be soldered directly to a PCB without sockets. A similar type, fitted with pins for connection to a socket is the HC25/U (see Fig.5.14).

Fig.5.14 A selection of crystals with fundamental resonant frequencies of 32kHz to 18MHz

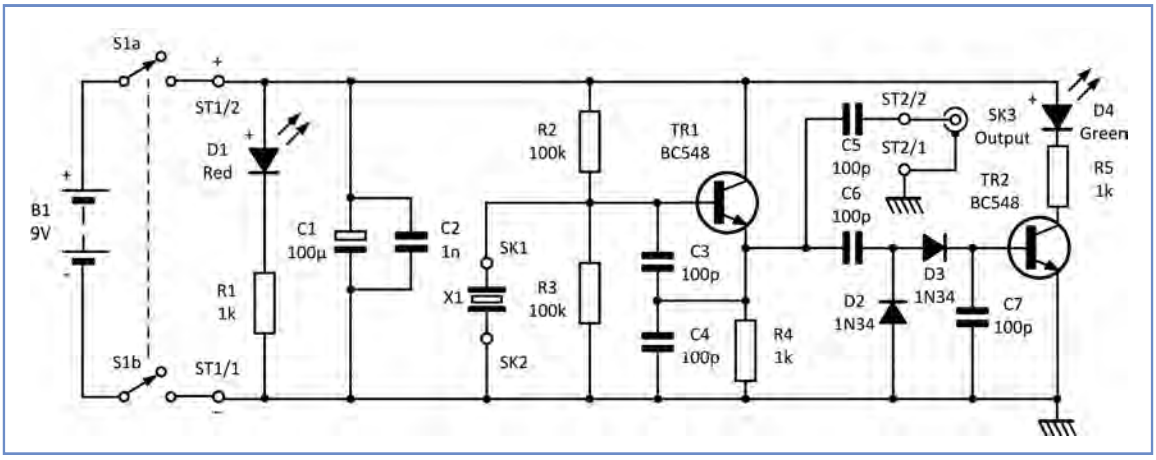

Fig.5.15 Complete circuit of the Handy Crystal Checker

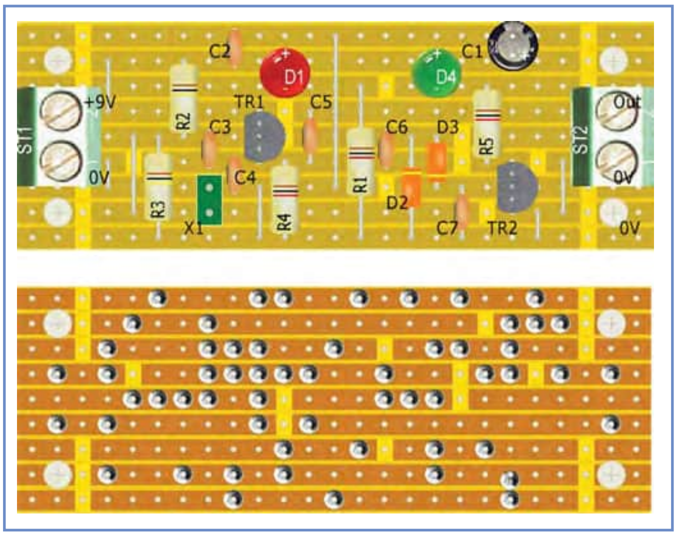

Fig.5.16 Stripboard layout of the Handy Crystal Checker

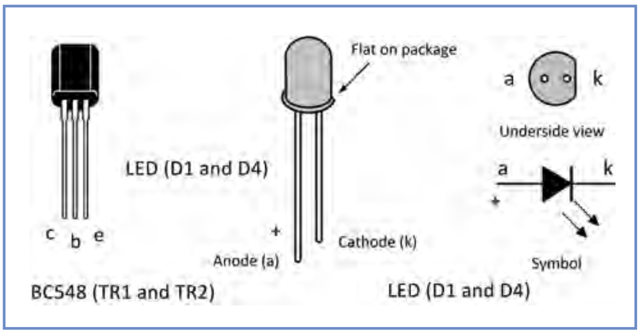

Fig.5.17 LED and transistor pin connections

Quartz crystals exhibit Q-factors that are many times larger than those that can be obtained with even the very best LC tuned circuits. The reason for this is that the ratio of equivalent inductance (L) to series loss resistance (R_S) is exceptionally high. It's also worth noting that the stability that can be attained by a crystal is directly related to its Q-factor. In other words, the higher the Q-factor the greater will be the stability of the output derived from a crystal-controlled oscillator.

Fundamental versus overtone operation

Crystals, and their associated oscillator circuits tend to fall into one of two main classes – fundamental and overtone. Crystals manufactured for fundamental operation are designed to oscillate at their basic resonant frequency, whereas those intended for overtone operation oscillate at, or very near, a whole number multiple of their fundamental resonant frequency. Generally, the third overtone is preferred, although fifth, seventh, and even ninth overtone devices are available. At high frequencies, crystals become extremely thin and are consequently more difficult and more expensive to manufacture. As a result, fundamental crystals are normally used at frequencies up to about 20MHz; beyond this, overtone units are usually employed. Note that, since the properties for a given crystal unit may be different at an overtone frequency when compared with its fundamental resonance, no reliance should be placed on the behaviour of a crystal at any frequency other than that for which it is designed.

Our handy crystal checker will allow you to test fundamental crystals between 2MHz and 20MHz and third/fifth overtone components from 20MHz up to 120MHz. Note that overtone crystals will be tested at their fundamental frequency so that, for example, a 48MHz third-overtone crystal will be operated at its fundamental resonant frequency of 16MHz.

The complete circuit of our *Test Gear Project* is shown in Fig.5.15. The circuit comprises a fundamental Colpitts oscillator stage (TR1) followed by a detector (D2 and D3) and a DC amplifier (TR2). Two LED indicators are fitted; D1 (red) indicates that the circuit is switched on while D4 (green) indicates oscillation and that the quartz crystal is functional. In addition, the output waveform is made available at a BNC connector (SK3). This makes it possible to connect an oscilloscope, digital frequency meter or small antenna.

Fig.5.18 Internal wiring of the Handy Crystal Checker

Fig.5.19 External appearance of the finished Handy Crystal Checker

You will need

Perforated copper stripboard (9 strips, each with 25 holes)

- 2 2-way miniature terminal blocks (ST1 and ST2)
- 1 ABS case with integral battery compartment
- 1 9V PP3 battery clip
- 1 9V PP3 battery
- 1 Miniature DPDT toggle switch (S1)
- 1 Red 2mm panel-mounting socket (SK1)
- 1 Black 2mm panel-mounting socket (SK2)
- 1 Chassis-mounting BNC connector (SK3)
- 1 2-way PCB header (X1)
- 2 BC548 transistors (TR1 and TR2)
- 2 1N34 diodes (D2 and D3)
- 1 5mm red LED (D1)
- 1 5mm green LED (D4)
- 3 1kΩ resistors (R1, R4 and R5)
- 2 100kΩ resistors (R2 and R3)
- 1 100µF 16V radial electrolytic (C1)
- 1 1nF 63V ceramic capacitor (C2)
- 5 100pF 63V capacitors (C3 to C7)
- 1 Optional crystal holders (see text)

Assembly

Assembly is straightforward and should follow the component layout shown in Fig.5.16. Note that the stripe on D2 and D3 marks the cathode connection, while the '+' symbol shown on D1 and D4 indicates the more positive (anode) terminal of the two LEDs. The pin connections for the LEDs and transistors are shown in Fig.5.17. The reverse side of the board (*not* an X-ray view) is also shown in Fig.5.16. Note that there's a total of 21 track breaks to be made.

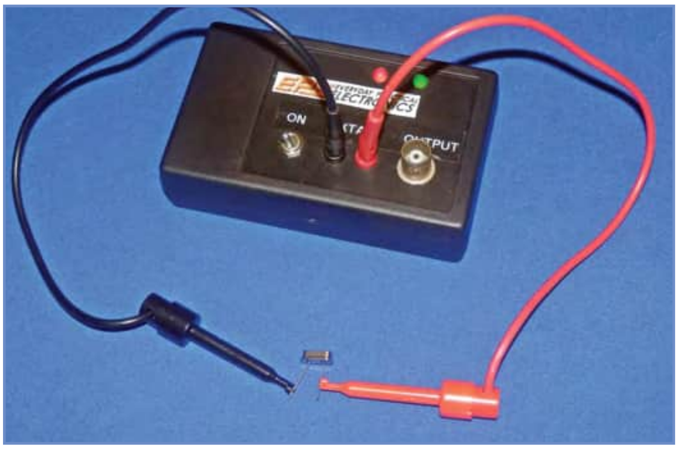

Fig.5.20 Using the Handy Crystal Checker to check a wire-ended crystal

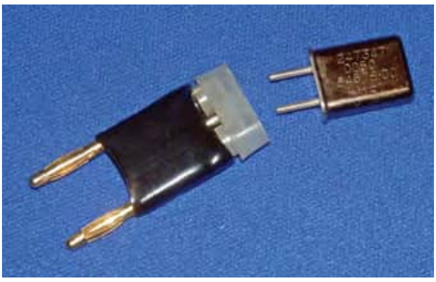

Fig.5.21 An adapter for testing HC25/U crystals

These can be made either with a purpose designed spot-face cutter or using a small drill bit of appropriate size. There are also seven links that can be made with tinned copper wire of a suitable diameter or gauge (eg, 0.6mm/24SWG). When soldering has been completed it is very important to carry out a careful visual check of the board as well as an examination of the track side of the board looking for solder splashes and unwanted links between tracks. The internal and rear panel wiring of the semiconductor junction tester is shown in Fig.5.18. Note that the PCB header connector (X1) is wired to ST2.

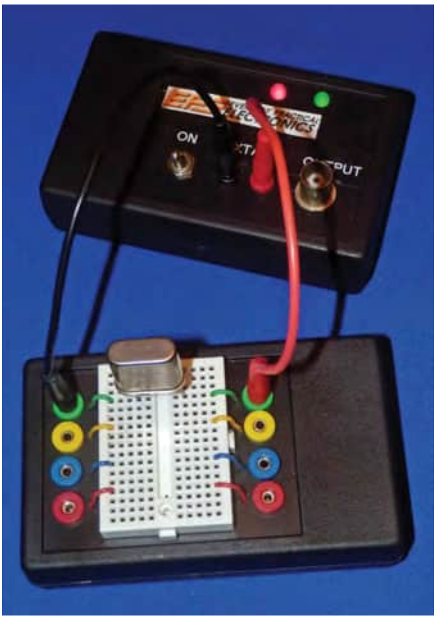

Fig.5.22 Using the breadboard text fixture to test a wire-ended HC6 crystal

Setting up

No setting up is required after assembly – all you need to do is to connect a PP3 battery and switch on! D1 should become illuminated – if not, check the battery and circuit connections carefully. Next, connect a quartz crystal (ideally, a fundamental mode unit in the range 4MHz to 14MHz) to SK1 and SK2, as shown in Fig.5.20. The green LED (D4) should then become illuminated to confirm oscillation. Figs.5.21 and 5.22 show how the *Handy Crystal Checker* can be used to test HC25/U and wire-ended HC6 crystals respectively. In the former, to simplify connection, we have constructed a simple adapter using two 2mm connectors and an HC25/U crystal socket covered with a short length of heat-shrink sleeving.

If required, you can easily check the frequency of oscillation by connecting a digital frequency meter or an oscilloscope to SK3, as shown in Fig.5.23. Alternatively, you can check the frequency of operation by connecting a short wire to the centre of the BNC connector and tuning a nearby radio receiver to locate the signal produced. In *Part 7* of our *Teach-In 2018* series we will show how a low-cost 'dongle' can be used with appropriate software to construct a basic software defined radio (SDR) which will provide you with a useful and inexpensive method of measuring a wide variety of RF (radio frequency) signals at frequencies from 150kHz to 1.5GHz.

Next month

Next month's *Teach-In 2018* will look at audio frequency tests and measurements. Our project will feature a low-distortion audio frequency test signal source.

Part 3 – ooops!

My thanks to Dr JCC Nelson from Horsforth, Leeds. He spotted an error in Fig.3.9 (*Teach-In 2018*, *Part 3*). The inputs to the 741 op amp (IC1) are incorrectly labelled and need to be swapped: '+' to '–' and vice versa. Fortunately, the stripboard layout is correct and the circuit will operate as designed and described.

Fig.5.23 Using a digital frequency meter to check the fundamental frequency of an HC25/U crystal