DIY RF Inductors

The ABCs of inductors

By B. Kainka

Electronics hobbyists often wish to copy a circuit for which suitable coils or fixed inductors are not readily available. However, you can wind just about any type of inductor if you only know how. Or you can take inductors from old equipment and modify or adjust them. All you have to do is determine is how many turns you need.

Low-value inductors are primarily used in RF circuits. A general distinction must be made between inductors with magnetisable cores (made from ferrite or iron) and 'air-core' inductors, which are wound on insulating forms or entirely without any sort of coil form.

Air-core inductors

Let's first turn our attention to air-core inductors. **Figure 1** shows an example of an inductor for a short-wave resonant circuit, which has 20 turns, a diameter of 16 mm and a length of 35 mm. It has an inductance of around 3 μH, and with a variable capacitor having a maximum value of 300 pF it has lower frequency limit of approximately 5.3 MHz. How can this be calculated? Read on to learn more… (and by the way, there's also a simple utility program to make things easier).

For a 'long' inductor with $l > D$ and n turns, a cross-sectional area A in m^2 and a length l in m, the following relationship generally holds true:

$$L = (\mu_0 \times n^2 \times A) \div l$$

where μ_0 is the *magnetic constant* or *permeability of free space* and has a value of

$4\pi \times 10^{-7}$ henry/metre
1.2466×10^{-6} henry/metre.

Although this formula is strictly true only for infinitely long inductors, it can be used as a satisfactory approximation for inductors with lengths down to $l = D$.

For an inductor with a given number of turns, the magnetic coupling between the individual turns increases as the length of the inductor decreases, which yields a greater inductance. By reverse token,

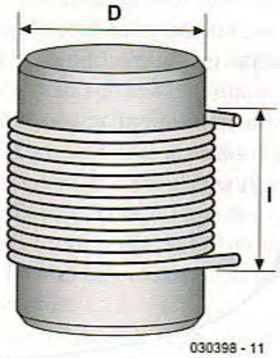

Figure 1. Structure of an air-core inductor.

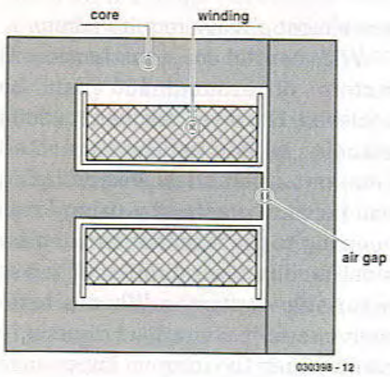

Figure 2. Structure of an inductor with an E-I core.

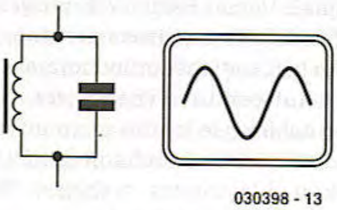

Figure 3. A inductor in a resonant circuit.

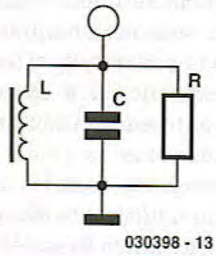

Figure 4. A resonant circuit with a loss resistor.

increasing the spacing between the turns of an inductor decreases its inductance, and this is sometimes used to tune inductors.

For inductors having a circular cross section, the above formula can be simplified to the following approximate formula, where the diameter D and length l of the coil are given in millimetres:

$$L = n^2 \times D^2 \div l \quad \text{[nH]}$$

This formula includes the approximation $\pi^2 \approx 10$, which introduces a small error (approximately 1.3 %). Extreme accuracy should anyhow not be expected, since the inductance depends in part on the shape of the coil, particularly the ratio of its length and diameter, as well as the thickness of the wire and even its surroundings. Consequently, for many purposes it is adequate to be able to calculate the inductance of an air-core inductor within a 10 percent tolerance margin.

Inductors with cores

RF inductor forms with threaded ferrite cores are often used in practice. The core increases the inductance, typically by a factor of four or even more. The inductor can be tuned by adjusting how far the threaded core is screwed into the inductor. Ferrite cores are made for specific frequency ranges, within which they exhibit small energy losses.

Significantly higher inductances can be obtained using closed cores with or without air gaps. Although an air gap reduces the inductance, it allows a higher magnetisation levels to be used, since it prevents the core from becoming magnetically saturated even at high currents. The types of cores commonly used are toroidal (ring) cores, E-I transformer cores (**Figure 2**) and closed pot cores.

With such cores, the inductance strongly depends on the material used and the geometry of the core, as well as the number of turns. This means that it is not possible to give a general formula for calculating the inductance, as with air-core inductors. Instead, manufacturers state an 'A_L value' in nH/n^2 for each core, such that

$$L = A_L \times n^2 \quad \text{[nH]}$$

For example, an Amidon T37-2 ring core has an A_L value of 40 nH/n^2. If you wind a coil of 10 turns on such a core, you will obtain an inductance of L = 4000 nH = 4 µH.

Ring-core inductors, like air-core inductors, are suitable for building RF resonant circuits. Besides the A_L value, the design frequency range of the core is also important. Amidon Type xxx-2 cores (with red marking) are suitable for frequencies up to 30 MHz. The calculation program, which is described in more detail below, can be used to quickly determine the inductance of air-core inductors and inductors with known A_L values.

Resonant circuits

Although resonant circuits are the most important application for inductors, resonant frequency and damping are also significant when inductors are used for other purposes. For one thing, it's important to recognise undesired resonances, and for another thing, it's very easy to determine the value of an unknown inductor by using frequency measurements.

If an inductor and a capacitor are connected together as shown in **Figure 3**, the result is a resonant circuit. Electrical energy can 'swing' back and forth between the inductor and the capacitor, similar to the motion of a pendulum, and such a circuit has a characteristic resonant frequency. After being excited by a short current pulse, a resonant circuit will oscillate freely at a frequency given by the formula

$$f_0 = 1 \div [2\pi \times \sqrt{(LC)}] \quad \text{[Hz]}$$

Resonant circuits are often used in circuits where several different frequencies are present and in frequency mixers. This allows currents and voltages to be distinguished according to their frequencies. A parallel resonant circuit has a complex impedance Z whose peak value occurs at the resonant frequency f_0. At this frequency, $R_C = R_L$, and the currents through the inductor and the capacitor exactly cancel each other since they have a 180-degree phase difference. An ideal parallel resonant circuit with no damping would have infinite impedance at its resonant frequency.

However, energy losses always occur in practice, due to the ohmic resistance of the coil, magnetic losses in the core of the inductor and electromagnetic radiation. The resonant impedance thus remains finite. This causes the oscillation to be damped. For simplicity, the losses can be grouped into an equivalent parallel 'loss resistance' R, as shown in **Figure 4**.

For every resonant circuit, it is possible to specify a quality factor, or 'Q factor', or simply 'Q', which is inversely proportional to the bandwidth of the circuit. Q is dimensionless and can easily be determined by taking the ratio of the parallel damping resistance R to the inductive impedance $R_L = 2\pi f L$ or capacitive impedance $R_C = 1/(2\pi f C)$ at the resonant frequency:

$$Q = R / R_L = R / R_C$$

If a resonant circuit is excited by an alternating current I with constant amplitude and variable frequency, for example using an AC generator with a high internal impedance, the voltage across the resonant circuit will be proportional to the magnitude of the complex impedance Z. The voltage will reach its maximum value at the resonant frequency.

The amount that the voltage increases at resonance is inversely proportional to the extent to which the oscillations are damped by any sort of energy loss, and thus directly proportional to the Q factor of the resonant circuit. At either side of the resonant frequency, points can be found at which the voltage is reduced from its maximum value by a factor of $1/\sqrt{2} = 0.707$ (–3 dB). The difference between the frequencies of these two points is defined to be the bandwidth BW of the circuit. The relationship between the bandwidth BW and the resonant frequency f_0 and Q factor of the circuit is:

$$BW_{(-3dB)} = f_0 / Q$$

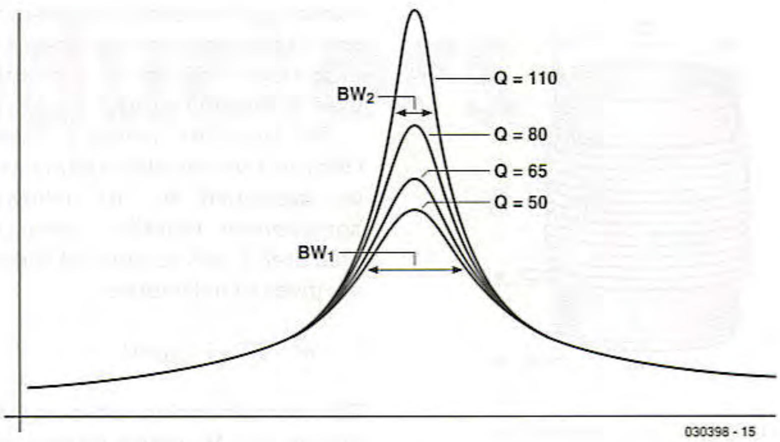

Figure 5. Resonance curves with various Q factors.

Figure 5 shows resonance curves for several different Q factors. A circuit with $Q = 50$ has a greater bandwidth (BW_1) than one with $Q = 110$ (BW_2). You can also see that the peak value at resonance increases as the Q factor increases. This means that the resonant circuit oscillates more strongly at its resonant frequency. By contrast, the various circuits show nearly the same behaviour in regions far away from the resonant frequency.

In practice, the circuit damping, and with it the Q factor, almost always arises from a combination of series and parallel resistances. The series resistance comes from the wire used to form the coil, and at a given frequency it is greater than the DC resistance of the inductor, due to the 'skin effect'. The parallel resistance is determined by the matching impedance in the circuit. However, iron cores and ferrite cores also have losses that can be expressed in the form of a parallel resistance. For a given inductance, an inductor with a core requires fewer turns and thus has smaller copper losses, but this comes at the price of core losses.

At high frequencies (above approximately 100 MHz), pure air-core inductors wound using thick, silver-plated wire give the best results, while at medium frequencies (around 10 MHz) the best Q factor can be obtained using closed cores, such as ring cores. However, air-core inductors can also be used down to frequencies of approximately 1 MHz. By contrast, inductors and transformers for use at low frequencies use almost always require cores.

With careful coil construction, Q factors of around 100 can be achieved. However, resonant circuits can also be damped by connected circuitry or an aerial. This damping can be counteracted by using loose coupling to the resonant circuit via a small auxiliary winding, a coil tap or a suitable capacitor. When a resonant circuit is connected directly to an amplifier, the internal impedance of the amplifier must be very high in order to minimise the damping.

Inductor calculations using software

A small Visual Basic (VB) program called **LCFR** has been written to make calculations for inductors and resonant circuits. The source and executable code for this program can be obtained free of charge from the *Elektor Electronics* website. The number is **030398-11**, see this month's Free Downloads. This program, whose user interface is shown in **Figure 6**, calculates the inductance of air-core inductors and inductors using cores with known A_L values. In addition, it can determine the resonant frequency and inductive impedance R_L of the inductor at resonance if a capacitance value is entered in addition to the inductance value.

The program consists of three parts that independently perform calculations, which for purely practical reasons are merged into a single user interface. Calculations for air-core inductors are made using the

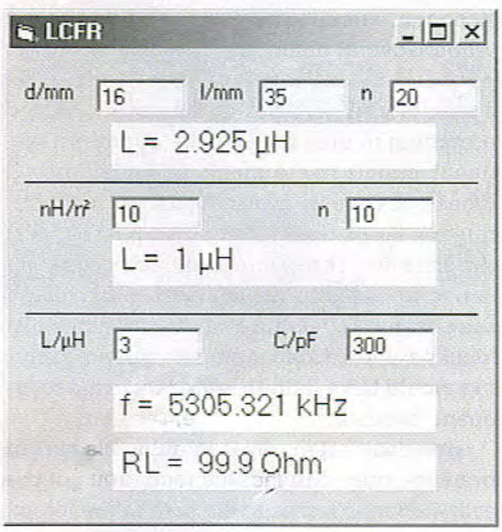

Figure 6. User interface for the inductor calculation program.

upper portion of the window, and magnetic-core calculations are made using the middle portion. At the bottom you can see the calculated resonant frequency and inductive impedance. If a new value is entered in any of the boxes, the results will change immediately. The most recently calculated inductance is automatically used for the calculations in the bottom section.

This program is ideal for quickly 'trying out' new parameters. The fact that the inductance is shown to three decimal places should not be taken as an indication of the accuracy of the result. Instead, it is intended to allow calculations to be made for inductors covering a wide span of inductances, ranging from a few nanohenries (1 nH = 0.001 µH) to many millihenries (1 mH = 1000 µH).

If you want to build a resonant circuit for a specific frequency, you can start by entering the capacitance, then calculating the inductance and finally determining the number of turns for a type given type of core or coil form. However, a less systematic approach often works better. You can simply select a type of inductor and then try several inductance and capacitance values until you find a satisfactory result. For instance, you may wish to determine which standard component values of fixed inductors and capacitors can be used to build a resonant circuit that will have a particular resonant frequency in a specific circuit. Here a trial-and-error approach often yields results faster than systematic calculation.

Some practical examples

Suppose you want to wind a 330-µH inductor for a medium-wave detector radio on a cardboard roll with a diameter of 42 mm. Further suppose that the wire diameter is 0.5 mm, so 100 turns will yield a coil length of 50 mm. Now you can simply try several different values, which ultimately yields a result of approximately 80 turns. For tuning the medium-wave (MW) band starting at 530 kHz, the variable capacitor must have a maximum capacitance of at least 45 pF.

For higher frequencies, you will need fewer turns. An inductor for a VHF FM receiver, for example, will have only five turns, with $D = 8$ mm and $l = 10$ mm. The calculated inductance is 0.16 µH. With a 20-pF capacitor, this inductor will resonate at 88.9 MHz, which is almost exactly the lower limit of the VHF FM broadcast band.

The above examples use air-core inductors. But how can you use a ferrite core? Usually, you won't have any exact data for the core. You will thus have to estimate how much it will increase the inductance or reduce the frequency. An inductor for the short-wave band, for example, might have $n = 18$ turns, $D = 8$ mm and $l = 12$ mm. For a pure air-core inductor, this gives a calculated inductance of 1.7 µH. But with a 275-pF variable capacitor, this inductor achieves a lower frequency limit of approximately 5 MHz with the core fully threaded in, which corresponds to an inductance of approximately 3.7 µH.

The frequency can thus be reduced by a factor of two using a threaded core, and the inductance can be up to four times as large. A relatively long medium-wave ferrite rod can in turn increase the inductance by a factor of approximately ten. Roughly speaking, we can say that an inductor on a ferrite rod only needs to have approximately one third as many turns as a similarly dimensioned air-core inductor having the same inductance.

The resonant frequency of a resonant circuit can change considerably when it is built into a circuit. Particularly at relatively high frequencies, wiring capacitances have a significant effect. This means that it is often necessary to make adjustments after assembly or build tuning capability into the circuit by means of a threaded core or trimmer capacitor.

For major modifications, it is often helpful to use a few rules of thumb that can be directly derived from the formulas give above and simulated using the LCFR program. For instance, doubling the number of turns quadruples the inductance and cuts the frequency in half if the capacitance remains the same. The frequency is thus inversely proportional to the number of turns and inversely proportional to square of the capacitance. This means that twice the frequency can be attained with one fourth of the capacitance. In order to tune over a frequency range of 1:3 using a variable capacitor, you need a capacitor with a capacity ratio of at least 1:9.

Inductors are not necessarily limited to RF circuits. They are also used in interference filters, low-frequency/audio filters and voltage converters. Schematic diagrams often show only the inductance value, without any other data for the inductor. Particularly in blocking-type voltage converters, the saturation current level and resistance of the inductor are also important factors.

It is also certainly possible to use a fixed inductor with the correct inductance but still not obtain the optimum result. Consequently, it is often worthwhile to wind your own inductors, even if only for initial testing. For instance, a 1.5-mH inductor for a voltage converter can be wound on a ferrite rod from an old medium-wave radio. If you have a relatively small ferrite rod that originally had 100 turns (which can be easily counted when you unwind the coil), it must have had an inductance of 300 µH, since the commonly used variable capacitors have a maximum capacitance of approximately 300 pF. You can thus calculate an A_L value of 30 nH/n^2. From here it's only a small step to the desired result: you will have to wind approximately 220 turns on the rod to obtain 1.5 mH.

Damping, Q and bandwidth

If you know the value of the damping resistance for a resonant circuit, it's easy to calculate the circuit's Q factor, and thus its bandwidth. This following example shows how a specific problem can be solved using the LCFR program.

Suppose you want to build an aerial filter for the medium-wave frequency of 1296 kHz (BBC, AM and DRM) using a fixed inductor. A possible solution can be found using the standard values of 100 µH and 150 pF. The program calculates a resonant frequency of 1299.5 kHz, and the small deviation of 3.5 kHz lies within the allowed tolerance. The program also indicates an inductive impedance of approximately 800 Ω.

If the DC resistance of the inductor (1.7 Ω) is taken as the series resistance and divided by the inductive impedance, the resulting Q factor is approximately 500, which is unrealistically large. In actual fact, you should assume a Q factor of around 50 for small fixed inductors. The extra damping arises from the skin effect and core losses.

In order to avoid excessive loss of energy

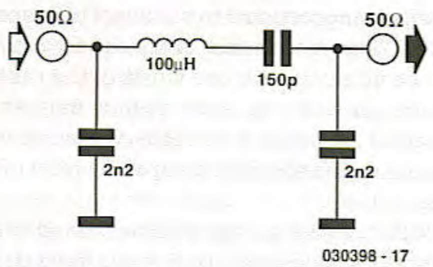

Figure 7. A filter circuit.

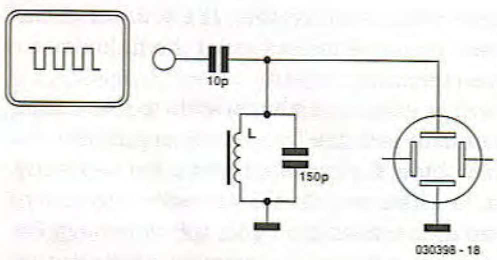

Figure 8. Exciting free oscillations.

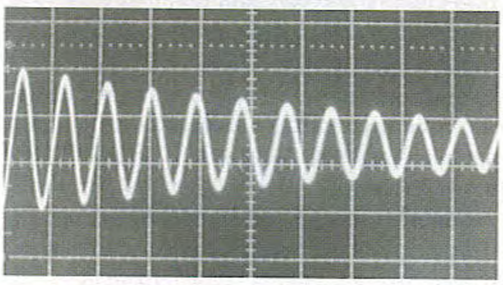

Figure 9. Damped self-resonant oscillations.

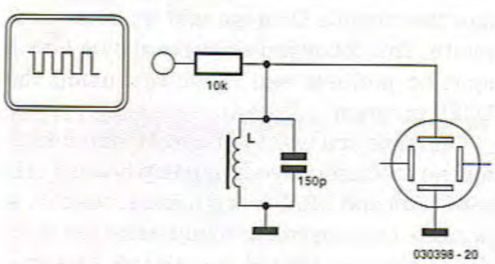

Figure 10. Resistive coupling

from the aerial, the filter should primarily be damped by the connected circuit. We thus chose a low working value of $Q = 10$. This also means that there's a reasonable chance that frequency deviations due to component tolerances will lie within the bandwidth of 130 kHz. A Q factor of 10 can be obtained with a parallel resistance of 8 kΩ.

If the aerial input of the receiver has an impedance of 50 Ω, an impedance conversion ratio of 160 is necessary. This corresponds to a voltage conversion ratio of $\sqrt{160} = 12.6$. If you used a inductor that you wound yourself, you could achieve this using a suitable tap or coupling coil. For a resonant circuit using a fixed inductor, a capacitive voltage divider can be used. The initial form of the resulting circuit is shown in **Figure 7**.

The actual resonant frequency has now been increased slightly, since the capacitance of the resonant circuit has been reduced by the two additional capacitors. You could thus suitably modify the values of the capacitors or provide a supplementary trimmer. However, it may be better to first try out the circuit. It may well be that the self-capacitance of the fixed inductor partially compensates for this error. In fact, this circuit proved to be satisfactory in practice in a DRM receiver without subsequent adjustment.

Would it be possible to use a T37-2 ring core with $A_L = 4$ nH/n^2 to make a DIY inductor? This idea can be quickly simulated and equally quickly rejected, since 158 turns is an unrealistic value for a small ring core. However, an air-core inductor with $D = 8$ mm, $l = 8$ mm and 110 turns is conceivable. If you have a suitable threaded core, you can manage with approximately half as many turns. This also allows the exact frequency of the filter to be adjusted using the core.

Measurements

If you do not have a suitable signal generator or dip meter, the only way to measure the resonant frequency of a resonant circuit is to use an oscilloscope. The frequency can be measured by exciting the circuit so it oscillates freely (**Figure 8**).

This requires a steep-edged square-wave signal with a frequency well below the resonant frequency. Many oscilloscopes have a square-wave output for calibration purposes (usually 1 kHz). This should be coupled to the resonant circuit as loosely as possible via a small capacitor. With suitable adjustment of the time base, you will be able to observe free oscillations. Besides the resonant frequency, damping can also be measured in this manner.

Figure 9 shows a measurement made using the previously calculated resonant circuit. What is important is to affect the circuit as little as possible. This means you should use a 10:1 probe with an internal impedance of 10 MΩ. The figure shows the result of a measurement made with a horizontal deflection factor of 1 µs/division. The measured frequency is slightly greater than 1100 kHz.

The Q factor can be determined from the number of oscillations required for the amplitude to drop to 0.37 (1/e) of the initial value. Here the Q factor is approximately 10.

The frequency and Q factor are affected by the measurement set-up. However, they will be affected even more strongly in an actual circuit.

A 10-kΩ coupling resistor can be used instead of a 10-pF coupling capacitor (**Figure 10**). In this case, the resulting oscillations will be somewhat weaker, so a more sensitive vertical scale must be selected. Using a resistor for coupling generates higher damping. However, the advantage of this approach is that it avoids any shift in the resonant frequency due to the coupling capacitor, so the frequency can be measured more accurately. In addition, measurements can also be made over a wide frequency range, from around 10 kHz to many megahertz.

This simple measurement technique can also be used to measure the values of unknown inductors. If you use a known capacitance value and measure the frequency, you can then determine the inductance. It is often necessary to try several different capacitors before you obtain readily measurable oscillations. With relatively large inductances, it is necessary to use correspondingly large capacitors. It is also possible to determine the value of an unknown capacitor using a known inductance.

The A_L values of unknown cores can also be determined using this technique. To do this, wind a small test coil on the core and determine the resonant frequency with this coil connected to a known capacitor. From the number of turns and the inductance, you can then determine the approximate A_L value.

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