Crossover NETWORKS

How To and Why

by Robert Saunders

Remove the cover from a cheap 'n' nasty loudspeaker enclosure and you will invariably find little more than a pair of wires between the input terminals and the loudspeaker terminals. Remove the cover from a speaker cabinet of considerably better quality, and you may find a veritable spider's nest of wiring, with resistors, capacitors, coils and perhaps even whole circuit boards.

Why should this be so? Surely, the loudspeaker end of the audio chain ought to be the easiest part, all the necessary 'processing' having been done by the preceding amplifiers and whatnot.

In an ideal universe, a single loudspeaker driver system would adequately cover the whole audio frequency range, 20Hz to 20kHz, but in reality, a single driver able to cover that whole range has not yet been made. This is a matter of basic physics: to produce a sufficient sound pressure level at bass frequencies requires the movement of a lot of air volume, by either pushing a small cone a long way, or a large cone a short way.

At the other end of the range, the driver must, inevitably, be excessively directional unless it is fairly small compared with the wavelength of the sound. At a frequency of 20kHz, this works out at only 17mm, this being the maximum permissible radius of the diaphragm.

The established way of getting around these problems is to use several drivers, each constructed to best cater for a particular range of frequencies. This precludes that the electrical driving signal from the amplifier must be divided into these bands.

This is the function of a crossover, which, most commonly, is of the 'passive' variety, as it is invariably accommodated within the speaker cabinet and is the easiest to connect to, requiring only one pair of signal wires from the amplifier. What the crossover does is to divide the incoming broadband signal into two or more narrower bands, directing each to a particular design of driver that has been specifically developed to best operate in that range. Even so, such drivers are not perfect by any means and will still need some 'tweaking' for best results – more of that later.

Passive Networks

Passive networks typically consist of capacitors, inductors and resistors. There are three basic types of passive crossover network, based on three different orders of the filter circuit used. In essence, the order is the highest power of the variable representing frequency in the equation describing the attenuation characteristic of the filter.

First Order Filters

These have a rate of cut-off of only 6dB per octave (20dB per decade), which is too slow for anything except the simplest 'general purpose' designs, and shouldn't be used for 'serious' speaker systems. A first order network circuit is shown in Figure 1. The formulae for deriving the component values are as follows:

Rb = Bass driver impedance in Ω
Rt = Treble driver impedance in Ω
Fc = Crossover frequency in Hz

$$L = \frac{Rb}{2\pi Fc}$$

$$C1 = \frac{1}{2\pi FcRt}$$

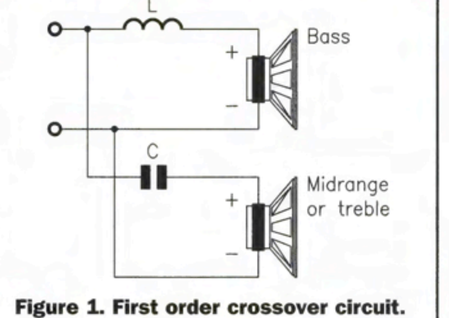


Figure 1. First order crossover circuit.

L is in Henries and C is in Farads. Here, the order of each filter requires that both drivers would have to work well for some two octaves beyond the crossover frequency, which is most unlikely. Tighter control from a first order crossover is just not possible, as the slope of the filter is too shallow.

It is very important to bear in mind that the value of Rb or Rt is not necessarily exactly the same as the DC resistance of the voice coil, as measured by an ohmmeter, but it can be quite close. Furthermore, voice coil impedances of exactly 8Ω or 4Ω, etc., are in fact extremely rare. The real value tends to be less; 7·6Ω, for example, or 6·5Ω. Sufficient manufacturer's data for the driver in question is essential, including Thiele/Small parameters. Failing this, the DC resistance should be a good guide.

Second-Order Filters

These have cut-off rates of 12dB per octave, which is better, and may be sufficient. A second order crossover circuit is shown in Figure 2. The formulae are as follows:

As before,
Rb = Bass driver impedance in Ω
Rt = Treble driver impedance in Ω
Fc = Crossover frequency in Hz

$$L1 = \frac{Rb}{2\pi Fc}$$

$$L2 = \frac{Rt}{\sqrt{2}\pi Fc}$$

$$C1 = \frac{1}{2\sqrt{2}\pi FcRb}$$

$$C2 = \frac{1}{2\sqrt{2}\pi FcRt}$$

Note that in Figure 2, the driver connections are marked '+' and '-', indicating that the tweeter connections are reversed.

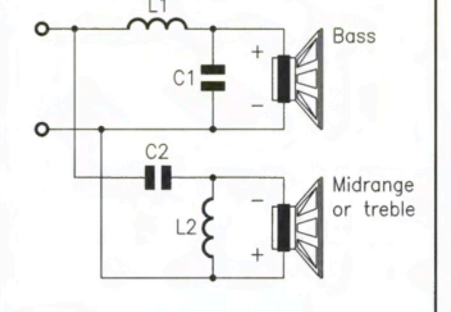


Figure 2. Second order crossover circuit.

This is because the low-pass and high-pass filters that make up the crossover network each shift the phase of the signal, and with a second order crossover, the phase difference between the bass and treble arms turns out to be 180Ω at all frequencies.

This means that at the crossover frequency, where, by definition, the outputs of the two drivers are equal, there is a null in the response exactly on the axis of the system. This can be overcome by reversing the connections to one of the drivers, so that they would be in phase at the crossover frequency. But this will produce a +3dB peak in the response, which is better than a

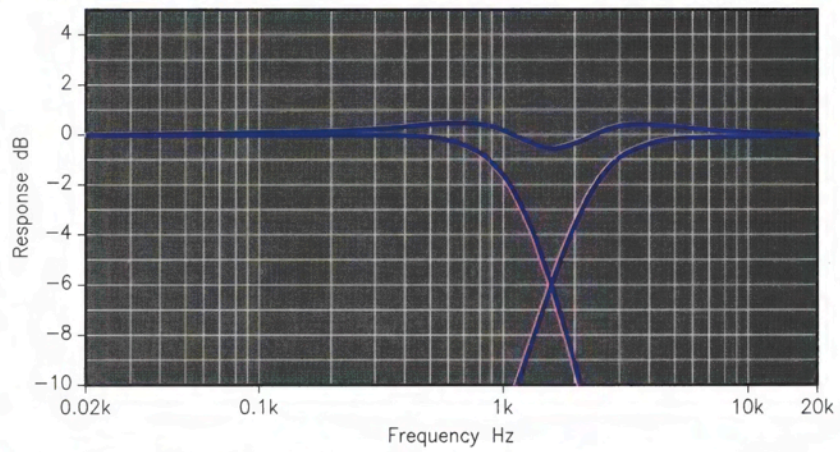


Figure 3. Individual and combined responses of a second order crossover with separated responses and one driver reversed.

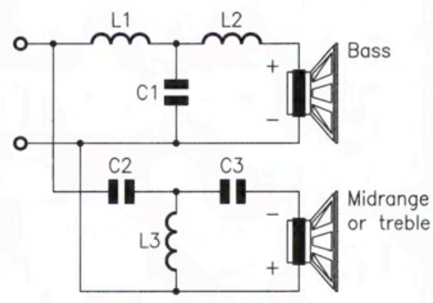


Figure 4. Third order crossover circuit.

null, but still not ideal. This comes about because each drive signal is 3dB down at the crossover frequency, but the two drivers are now in phase, so that their outputs add arithmetically, i.e., the sum is twice (+6dB) that of one driver alone.

One way of getting a truly flat response is to reverse the tweeter, which would result in a peak, but then shift the filter cut-off frequencies apart, by dividing the low-pass cut-off frequency by a factor of 43, and multiplying the high-pass cut-off frequency by the same factor:

$$Fc\ bass = \frac{FC}{4^3}$$

$$Fc\ treble = Fc \times 4^3$$

So that both drivers are 6dB down, instead of 3dB down, at the frequency at which they are equal. Figure 3 shows the effect of this, where the individual roll-off points are pulled apart, but the net overall response with one driver reverse-connected is nearly flat.

In use, pressure response discrepancies will be small and occur only in a narrow frequency range. The inter-driver phase difference is only 45° at the crossover frequency if one driver is connected in reverse polarity.

Third-Order Filters

Another practicable crossover network is based on third-order filters, having cut-off rates of 18dB per octave. This is, supposedly, the best type to choose for true Hi-Fi aspirations and clearer, better defined sound reproduction (although some people would argue that a second order filter will sound more 'natural'). A circuit diagram of a third-order crossover is shown in Figure 4.

In this case, both the power response and the pressure response are constant in the crossover range, without having to manipulate the filter cut-off frequencies as with the second-order crossover. Each driver is 3dB down at the crossover frequency, and the inter-driver phase difference is 90°.

This means that whichever way round the tweeter (for example) is connected, the pressure response remains flat, but it can be shown that the group delay is three times less if it is (again) connected in reverse polarity. The power response is also flat, which means that the directional response varies in the crossover frequency range.

This variation is less damaging if the drivers are mounted vertically one above the other, and for some listening conditions, it may be better to have the tweeter below the bass driver rather than above. The necessary formulae are given below:

Using Rb, Rt and Fc as before for first-order filters:

$$L1 = 3L2 = 2L3 = \frac{Rb}{4\pi Fc}$$

$$C1 = 2C2 = \frac{2C3}{3} = \frac{2}{3\pi FcRb}$$

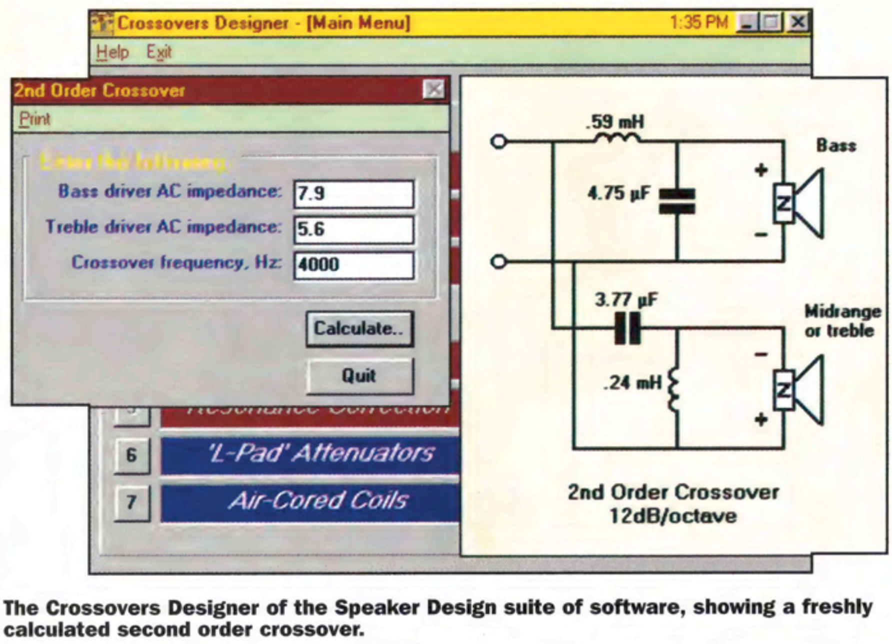
This will provide component values for the low-pass filter according to the value of Rb, ignoring C2, C3 & L3. To derive values for the high-pass filter, do the calculations again using Rt in place of Rb and ignore L1, L2 & C1.

These formulae assume that the impedance of each driver is constant over its operating range. This is, of course, not the case – a moving coil loudspeaker will offer different impedances at different frequencies. There are two significant things going on here – firstly, it is a spring and mass system which, therefore, has a natural frequency of resonance. Secondly, because the voice coil is an inductor, its impedance increases proportionally with frequency.

The resonance of a bass driver is more often than not addressed mechanically, by operating it in a ported, tuned cabinet designed to suppress this resonance and possibly improve the driver's operating range. (Note that many bass driver models have been specifically developed for operation in a ported enclosure.) This still does nothing to ensure an even voice coil impedance, or tackle the natural resonances of mid-range and treble drivers, which brings us neatly on to the next subject.

Zobel Networks

You may think that crossover networks are complicated enough, without bothering with Zobel networks. You might have found that there are many loudspeakers on the market that don't use them. Without them, however, the crossover circuit cannot ever give its best performance, since the varying impedance peaks and humps over the drivers' working range unavoidably wreaks havoc with crossover operation. The difference between otherwise identical systems that have or do not have Zobel networks can be quite profound.



The Crossovers Designer of the Speaker Design suite of software, showing a freshly calculated second order crossover.

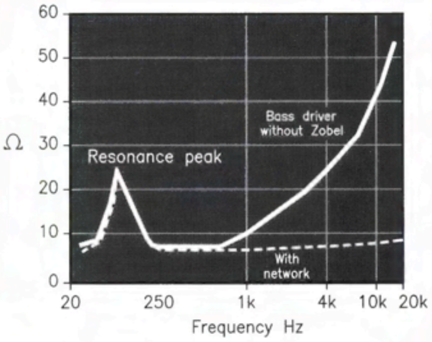


Figure 5. Bass driver impedance versus frequency plot.

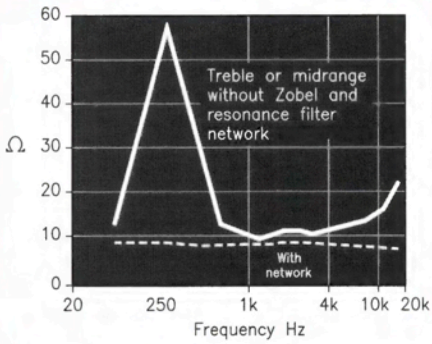


Figure 7. Treble or midrange driver impedance versus frequency plot.

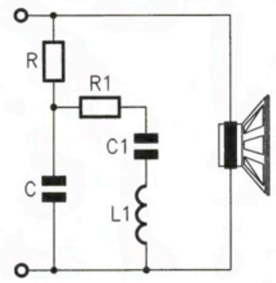


Figure 8. Zobel network with resonance correction filter.

Bass Drivers

Bass driver impedance typically remains more or less constant up 200 or 300Hz or so (ignoring the resonance region). Above this frequency, the impedance rises continuously, due to the inductance of the voice coil. Any crossover network designed on the basis that the impedance is 8Ω throughout and is purely resistive simply won't work properly. The effects of resonance and inductance on the impedance of a driver are shown in Figure 5.

Controlling bass resonance is usually a function of the enclosure, but a Zobel network is still required to compensate for the frequency dependent impedance rise at upper frequencies. All it has to do is provide an equal and opposite effect to that of the driver voice coil, which is effectively a resistor and inductor in series, so the basic Zobel network is simply a resistor and capacitor in series, as shown in Figure 6. The component values are related by:

$$R^2 = \frac{L}{C}$$

If the voice coil inductance is known, then the necessary simple circuit can be calculated thus:

$$R = \text{Voice coil DC resistance}$$

$$C = \frac{L}{R^2}$$

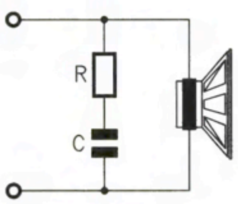


Figure 6. Basic Zobel network circuit.

Where Vl equals the inductance of the voice coil. Deriving the inductance may be awkward if no data is available, but it could be derived by a digital multimeter with an inductance range, or found by plotting a graph with the help of a signal generator, a resistor and a 'scope or millivoltmeter. Figure 5 also indicates what the impedance plot should look like after adding a Zobel network.

Treble Units

Things are not so simple for a treble driver. It too needs high frequency impedance correction, which can be done as simply as for a bass unit, but its main resonance occurs at a much higher frequency than that for the bass. The resulting impedance peak is bound to completely upset the behaviour of the high-pass section of the crossover network, usually in the most critical frequency range. The impedance characteristics for a typical tweeter or midrange unit are illustrated in Figure 7.

Resonance Correction Filters

The cancellation of the resonant impedance peak, by means of a more generalised form of Zobel network, requires a series tuned circuit of the same resonant frequency and Q to be connected across the Zobel network capacitor, in series with the Zobel resistor, the whole combination being in parallel with the tweeter. Although the effects of tweeter voice coil inductance can complicate the issue, the starting Zobel network is, nevertheless, found by a simple approach which is valid for bass drivers.

The complete circuit, comprising the Zobel network with resonance correction, is shown in Figure 8. While R and C are as Figure 6 unchanged, values for R1, C1 & L1 must be found. For this, you need Thiele/Small data for the driver, specifically Re (DC resistance), Fo (resonant impedance), Qms (mechanical Q) and Qes (electrical Q).

From these, the formulae for deriving the resonance damping components of the network in Figure 8 are:

$$Res = \frac{ReQes}{Qms}$$

$$Lces = \frac{Res}{2\pi FoQes}$$

$$Cmes = \frac{Qes}{(2\pi FoRes)}$$

$$L1 = CmesRe^2$$

$$C1 = \frac{Lces}{Re^2}$$

$$R1 = \frac{Re^2}{Res}$$

Figure 7 illustrates the corrected as well as the uncorrected impedance curves. Note that the elimination of the effect of the voice-coil inductance makes the driver's impedance closer to its DC resistance than to the nominal value of 8Ω, and this must be allowed for when designing the proper passive crossover network.

Thiele/Small data for tweeters is rarely published. This makes it impossible to design the necessary network without testing the treble driver. Briefly, this involves doing the following to derive these parameters:

$$Re = \text{DC resistance}$$

$$Fo = \text{Frequency of resonance}$$

$$Zo = \text{Impedance at the frequency of reasonance (high)}$$

$$Ro = \frac{Zo}{Re}$$

$$F1 = \text{Frequency below Fo where impedance} = \frac{Re}{\sqrt{Ro}}$$

$$F2 = \text{Frequency above Fo where impedance} = \frac{Re}{\sqrt{Ro}}$$

$$Qms = \frac{Fo\sqrt{Ro}}{(F2 - F1)}$$

$$Qes = \frac{Qms}{(Ro - 1)}$$

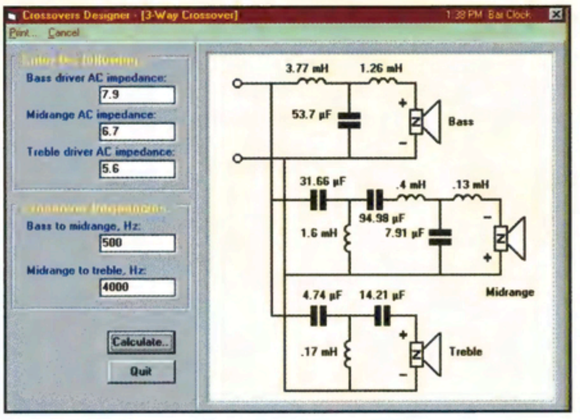
Network Components

The calculations invariably call for non-standard values for resistors and capacitors, i.e., values that do not precisely match any of those in the familiar E12 or E24 standard ranges for resistors, for example. This requires values to be combined in series and/or parallel to achieve the closest match. The type of resistors used will typically be high power wire-wound types, the capacitors most often non-polarised electrolytics or dual-polarity polypropylene, polyester, etc., as non-electrolytic types.

Generally, non-polarised electrolytics are suitable for bass and midrange pass filters, but treble band pass filters should really use polypropylene. Ideally, all of the capacitors should be high quality, 'audio grade' polypropylene, but these can very expensive and the space they will all take up can be absolutely huge. Separate cabinets that are extra to the proper speaker cabinets and containing nothing but crossover circuitry are not unknown!

Capacitors and Inductors

Maplin Electronics have just expanded their range of audio-grade polypropylene capacitors, and taken a number of ferrite-cored inductors specifically for loudspeaker crossovers.



The new version of the Crossovers Designer includes a three-way third order crossover section.

Specially developed for crossover networks in domestic and studio monitoring systems, the capacitors are also ideal for valve amplifiers. The inherently low dissipation and dielectric absorption properties of polypropylene, coupled with excellent mechanical stability, result in an extremely pure sound, with low self-inductance and ESR.

Values now include 100nF (Maplin Order Code VM87U), 220nF (VM88V), 330nF (VM89W), 470nF (VM90X), 680nF (VM91Y), 1·0µF (KR78K), 1·5µF (KR79L), 2·2µF (KR80B), 3·3µF (KR81C), 4·7µF (KR82D), 5·6µF (VM92A), 6·8µF (KR83E), 8µF (VP09K), 10µF (VM93B), 12µF (VM94C) and 15µF (VM95D). The rated voltage of all is 630V DC. Sizes range from 20mm long x 30mm diameter, up to 65mm x 49mm, which are not too big.

In addition there is a high grade, low loss general purpose range of 160V DC working, offering values of 1µF (JY78K), 1·5µF (JY79L), 2·2µF (JY80B), 3·3µF (JY81C), 4·7µF (JY82D), 22µF (VM86T), 33µF (JE14Q), and 47µF (JE13P). Using these, one could completely eradicate the less than ideal non-polarised electrolytics from the system.

The chokes are wound on ferrite cores, which are moulded to form the complete shape of the bobbin. Hence, there is a fair amount of ferrite material present (as opposed to a plastic former with a ferrite rod shoved up the middle), so the number of turns required is kept low, minimising unwanted DC resistance.

The new values are: 1·0mH (VM18U), 2·0mH (VM19V), 3·5mH (VM20W), 3·5mH, (VM21X), 5·5mH (VM22Y), 6·5mH (VM23A), 7·5mH (VM24B), 9·0mH (VM25C), and 12·0mH (VM26D). (Smaller values may be added to the range at a later date.) These are wound with enamelled copper wire in the order of 18 to 16swg, so the resistance should be pretty low. The bared ends are drawn out for connection, and PCB mounting is quite feasible.

Air-Cored Coil Formula

On the other hand, you could try making your own air-cored coils, and this is the formula to use:

$$L = \frac{0{\cdot}8 \times (N \times r)^2}{6r + 9cl + 10b}$$

Where L is in microhenries, N = the total number of turns, r = the mean radius of the coil, that is to say, of the former plus half the total thickness of wire wound on it, in inches; cl = the length of the coil in inches, and b is again the total thickness of all the layers of wire, in inches. To make L up to millihenries, divide it by 1,000 (multiply millihenries by 1,000 for the formula). Note that if cl is less than 1 or r is less than 0·1, the formula may not work properly.

Help!

Of course, you could take the pain out of all these calculations by resorting to using some form of computer software. This article was largely derived from the help files of the Speaker Design Suite, a complete set of speaker design applications for the PC running under Windows, originally compiled by Mosaic Software UK and distributed by Three Crowns Publishing. This software has been featured in Electronics before, but has since been upgraded during 1996 and has improved graphics and a few extra functions.

The package includes a Crossovers Designer, which is able to produce first, second and third order circuit diagrams and component lists from simple input data. When evaluating a second order filter, it actually implements the shift described earlier for the filter cut-off frequencies, and the component values in the resultant filter circuit diagram are adjusted accordingly. This is so that one of the drivers can be reverse-connected, as described earlier.

The Crossovers Designer also produces Zobel circuits and the necessary additions for resonance correction. A basic Zobel network for a tweeter can be calculated by the Crossover Designer given DC resistance, Re, and voice coil inductance. In order for it to make the resonance correction enhancement, more complete Thiele/Small parameters for the tweeter are required.

These can be derived by the Speaker Parameters part of the suite, in the same way as can be done for a bass driver (all drivers are held in a database), using the data entry process invoked by clicking on the 'Don't Know' button in this window. This leads on to entering the results of testing the driver, for which there is a 'how to' topic in the main help file. All you have to do is follow the instructions, and the program does all the calculations.

The 1996 revisions to the suite are mainly aesthetic, but include some significant changes as follows: both Speaker Parameters and Cabinet Maker can now handle metric as well as English imperial units of linear measure and volume. Speaker Parameters can run the Cabinet Maker directly, passing the calculated box volume. Cabinet Maker adopts the scaling mode (metric or imperial) that was last set by Speaker Parameters, and can generate three different enclosure styles where the panel ratios are optimised to reduce internal standing waves and resonances.

The Drivers Library (a database manager) can now run Speaker Parameters directly, passing the selected driver on clicking a 'run' button. It also prints all the Thiele/Small data along with the other information if the item detail print option is selected.

The response graph window in Speaker, Parameters can make up to six copies of itself for comparing different responses, each of which is re-sizeable and can print in colour, and can save its image as a bitmap or Windows metafile.

Last but not least, and of more relevance to this article, whilst the precise values of capacitors and resistors as calculated for the networks can be made up from standard value components, a specific value for an inductor may not be readily available. The Crossovers Designer includes a design option for producing multi-layered air-cored coils, so that you can make your own custom crossover chokes. There is also a drop-down list of readily available SWG wire sizes to select from when using this option.

To obtain your own copy of the Speaker Design Suite, just send £28.95 only to Three Crowns Publishing, PO Box 5773, Laindon, Essex SS15 5FJ.

Acknowledgements

I am indebted to the authors of Speaker Design, John Woodgate and Associates and Wilmslow Audio for help with this article. All drawings reproduced with permission from Three Crowns Publishing.

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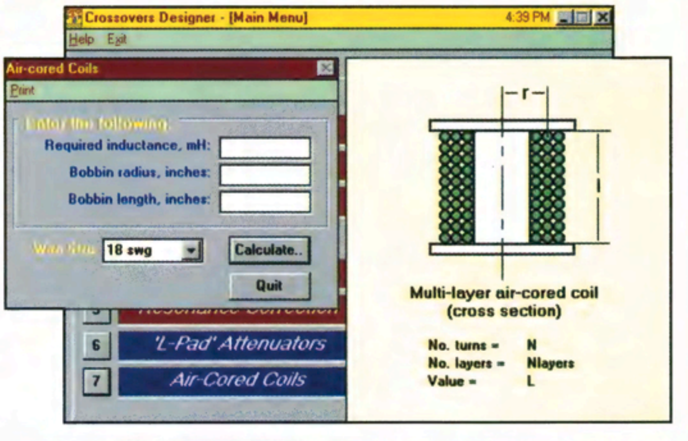

The seventh item on Crossovers Designer's menu is for winding multi-layered air-cored coils.