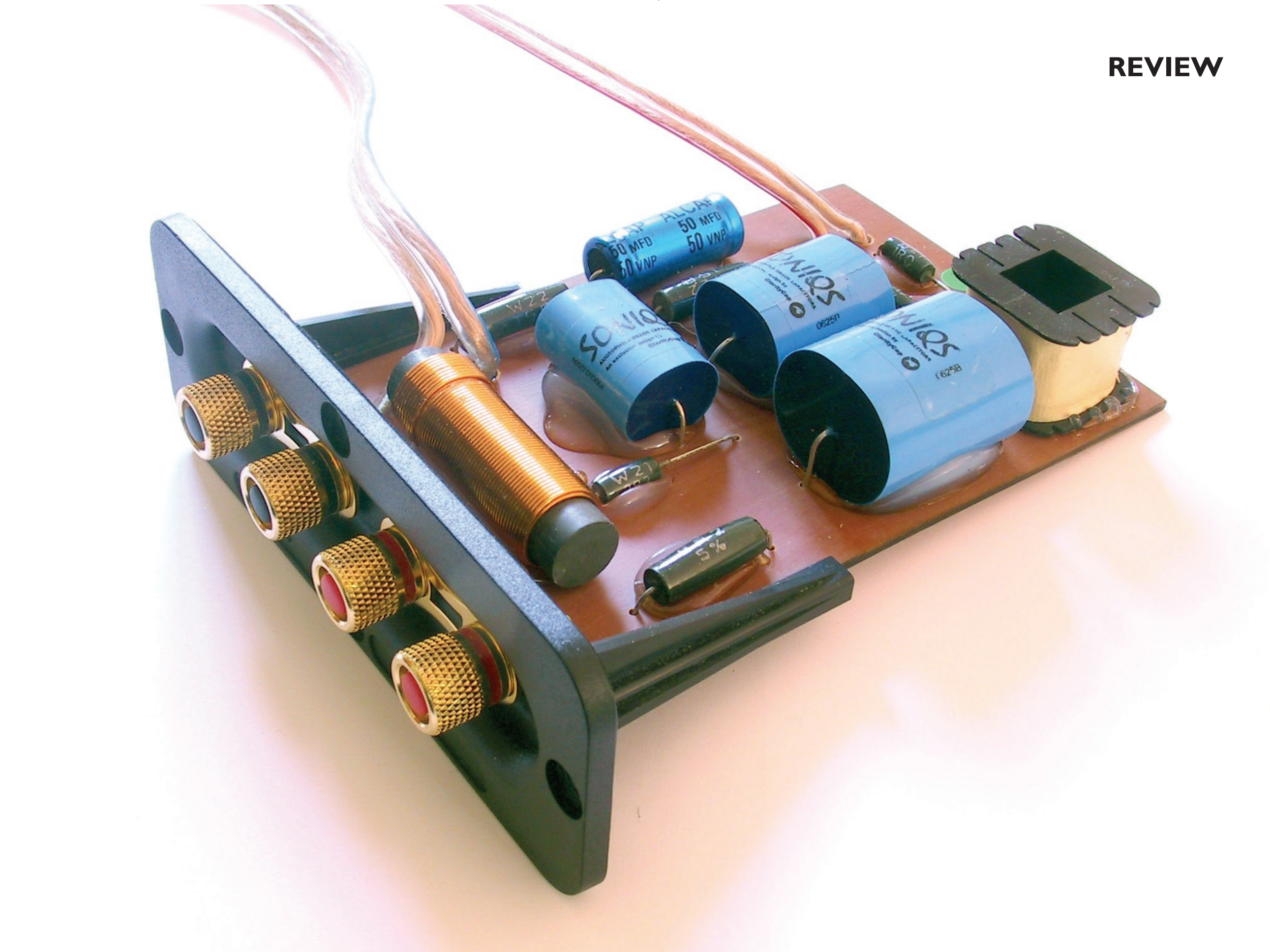


Designing Speakers

Part 6 Crossover Design

Crossovers are the 'bête noir' of loudspeakers, but do they really cause more problems than they're worth? Peter Comeau explains...

Of all the aspects of loudspeakers Crossover Design is possibly the most contentious. Do you stick with the First Order brigade who claim that anything else mucks up the phase response, or do you join the Fourth Order protagonists who argue that drive units need to be tightly bandwidth limited to avoid acoustic distortion?

If you don't know what I'm talking about then don't worry, I'm about to explain all.

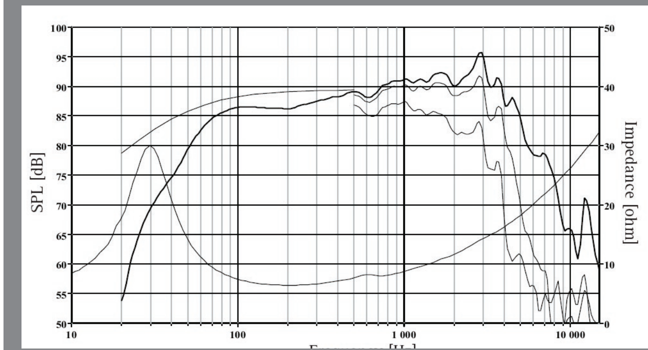
FIRST ORDER

First of all why do we need to crossover at all? To see why you really need to have a listen to one of the full range drive units that are the 'fave rave' of the DIY speaker fraternity. Listen to a Fostex or a Lowther in comparison to a two-way speaker and you'll be immediately aware of the lack of bass power and treble extension, as well as honky, clappy, tubey, papery colorations in some areas of the midband.

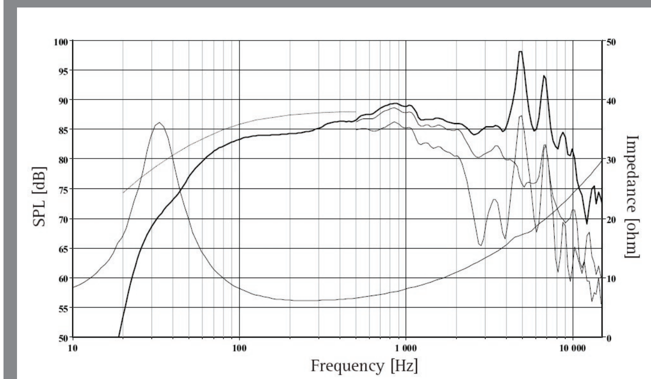
Now before I get a raft of letters and e-mails from DIY speaker builders I will own up to a liking for full range drivers and their coherence through the midband. But for most listeners their colorations and bandwidth limitations rule them out.

So why can't we make a full range drive unit that really works well? The problems lie in the physics of turning electrical impulses from your amplifier into acoustic energy in the room. If you have read the previous articles on enclosure design you will have realised that, to do a good job, bass units need

'Breakup' modes are caused when the drive unit stops behaving like a piston. Part of the diaphragm starts to move independently and this can be audibly noticeable.
You can see the 'breakup' modes as ripples in the frequency response that match with those in the impedance graph.



Look at the graph and you'll see a kink in the impedance plot which matches the beginning of dips and peaks in the frequency response at 600Hz.



By comparison a very stiff, cast magnesium cone stays pistonic over a wide frequency range and pushes the 'breakup' modes higher in frequency. However the rigidity of the cone eventually results in a strong resonance at 5kHz. This resonance can be successfully 'dialled out' by clever crossover techniques.

to be relatively large. This makes diaphragms heavy and the large dimensions narrow the area of sound dispersion as frequencies get higher.

If you look at full range drive units you will see that they have lightweight diaphragms (which restrict bass power and extension) and emit high frequencies in a narrow beam (so they have to be pointed towards the listener).

Another problem is that drive units do not maintain their pistonic performance over a wide frequency range. For a cone this means that although the whole drive unit is moving at low frequencies, at midrange frequencies the centre portion of the cone starts moving independently of the outside of the cone, and at high frequencies only the very centre of the cone is moving.

The behaviour as the cone 'breaks up' is part and parcel of its acoustic character. Too many 'breakup' modes and you hear lots of colorations. There again if there is just one, severe, 'breakup' mode it can be clearly heard as a resonance.

To avoid hearing the colorations and distortions due to this less than ideal drive unit behaviour we should feed musical energy to drive units over the useable part of their frequency bandwidth.

So, for example, if we have an 18cm bass/midrange unit with a relatively coloration free bandwidth up to 2kHz then we can cross over to a 25mm dome treble unit that can do a much better job of driving treble energy into the room from 2kHz upwards.

FIRST ORDER

So far so good. This is the basis of the classic 'two-way' loudspeaker. The problem then becomes just how do we cross over from one drive unit to the other?

The simplest method is to use an inductor in series with the bass unit and a capacitor in series with the treble unit. The inductor increases in impedance as the frequencies rise, resulting in less treble energy 'getting through' to the bass/midrange unit. The capacitor increases in impedance as the frequency drops, so less midrange energy is fed to the treble unit whilst all the high frequencies are 'let through'.

We call this a 'first order' crossover. It is the simplest, and the easiest to manage, type of electrical crossover and has many adherents. Its two primary attractions are that it is easy to experiment with and there is no phase shift between the drivers throughout the crossover region.

For these reasons many DIY speaker builders stop there. They can tinker with the values until they get good performance just by listening to the results. All you need are two 'perfect' drive units and a handful of inductors and capacitors.

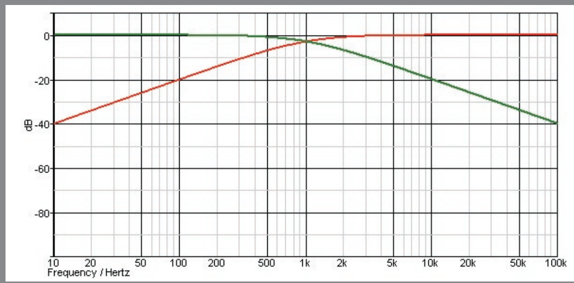
So why aren't all speakers made this way? Well the problem is that there are very few 'perfect' drive units that meet all the first order requirements. Look at the graphs and you'll see that the drive units have to behave impeccably for at least three octaves beyond the crossover frequency. In other words unless they are free from colorations, resonances and distortions and have a smooth frequency response over the majority of the audio band you will not be able to design a clean, transparent sounding loudspeaker.

As for the attractions of 'linear phase' this demands that the drive units maintain their frequency and phase response for three octaves beyond the crossover frequency. Think about it. If you cross over at 2kHz your bass/midrange unit has to have a bandwidth up to 16kHz. Even worse your treble unit has to be useable down to 250Hz!

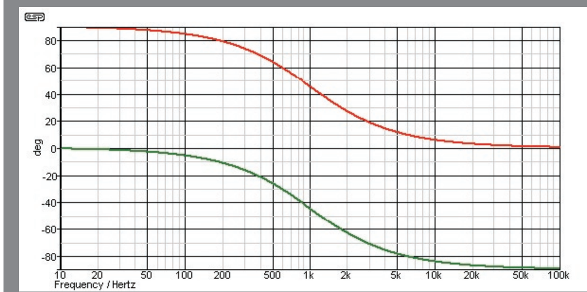
Now drive units with this sort of behaviour are few and far between. The upshot is that using first order crossovers with normal drive units results in performance restrictions. You may be aware of colorations from the bass midrange unit through the upper midrange and treble region and you will certainly notice distortion from the treble unit at lower frequencies.

Furthermore if you can measure the frequency response you will find huge deviations from what the theory tells you. This is because the theory is based on the drive unit having a linear impedance beyond the crossover frequency.

If you look at a typical bass unit impedance you will see that, due to the inductance of the voice coil, the impedance rises rapidly through the midrange. This means that, in combination with your series



First order slopes are very gentle at just 6dB/Octave attenuation below the crossover frequency. So the use of first order crossovers requires exemplary drive units with good behaviour over a very wide frequency range.



Phase response from first order filters is electrically in perfect synchronisation (HF red, LF green). But the phase response of real drive units will not be such a good match.

crossover inductor, the impedance increases dramatically as the frequency goes up. In fact it often goes up so fast that, in combination with the falling response of the drive unit, the resulting 'acoustic' crossover approximates to a third order slope!

Worse is to come with the treble unit. Common sense dictates that, in order to have a wide bandwidth, we should choose a treble unit with a very low fundamental resonance (F0). But sling a series capacitor in series with these types of treble units and you will find that the midrange output drops dramatically through the crossover region.

It's all because the electrical crossover slopes are too shallow. To compensate for the droop in at mid to high frequencies from the treble unit you lift its sensitivity and then it sounds too 'bright' in the treble range. For these reasons it is easier to work with real drive units using higher order crossovers.

SECOND ORDER

The next step up from first order is, of course, second order. Here we add a second 'leg' to each inductor and capacitor. The series inductor to the bass unit now has a capacitor across the bass unit. This capacitor 'shunts' some of the treble energy away from the drive unit (remember – a capacitor's impedance falls as the frequency gets higher).

Similarly there is an inductor across the treble unit to 'shunt' away some of the midrange energy. The overall result is a 12dB/Octave electrical slope. So far, so good, but the theory of second order crossovers shows that the phase shifts by 180° through the crossover region. This means that we have to reverse the connections to the treble unit.

Now this would be all well and good if we could maintain the phase response of the bass unit and treble unit either side of the crossover. But real-world drive units don't behave like this and very often the combined phase response of the electrical output of the crossover and the acoustic performance of the drive unit result in phase discrepancies which wreck the smooth crossover we are aiming for.

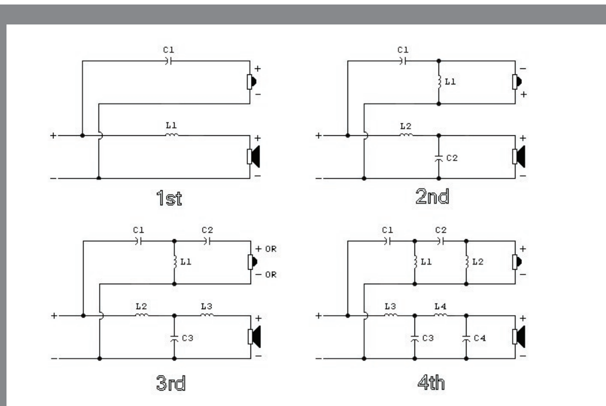
THIRD ORDER

Typically the use of second order electrical crossovers combined with the falling response and phase and impedance characteristics of real drive units results in a third order acoustic performance. So it is best that we concentrate our energies by looking at the benefits a third order crossover gives us.

Let's start with slopes. A third order slope is 18dB/Octave so, at last, we are starting to be able to 'hide' the out of band colorations and distortions of our drive units. Now we only have to make sure that our drive units behave themselves for little over an octave either side of the crossover frequency!

Phase response is, in theory, shifted by 90° through the crossover region but this, as we'll see when we start measuring 'real' loudspeakers, isn't the problem that it first appears to be. Theoretically we need to add a third element to each crossover leg – another series inductor leading to the bass unit and a second capacitor in series with the treble unit. You can see that there is a 'block/shunt/block' action going on here which increases the rate at which electrical energy is filtered to the drive units.

However, as we have said, there isn't always the need to add this third element. For example the impedance



Diagrams of electrical 1st order, 2nd order, 3rd order and 4th order crossover networks. These are theoretical electrical crossovers. Practical circuits designed to work with real drive units may differ from these, but the basic arrangement of the components will remain the same.

of many bass units rises so fast above the crossover frequency that they achieve a 6dB/octave acoustic slope naturally. Add this to the 12dB/Octave of a second order electrical crossover and, bingo, there is your third order acoustic crossover.

So you will often see what initially looks like a mismatch of second order and third order crossovers in commercial speakers, but bear in mind that you are only looking at electrical slopes. It is the final, acoustic slopes that we are more interested in.

ACTIVE CROSSOVERS

From third order we can go on adding elements to take us to fourth order electrical crossovers, but now things start to become rather unmanageable. Imagine, if you will, juggling the values of all those elements to try and achieve the desired acoustic crossover. As you change the value of just one component it can affect the performance so much that you need to adjust the values of all the other components to 'balance' the result.

It is difficult enough doing this with third order crossovers. Adding the complexity of a fourth element in each leg is asking for trouble. In addition, as the filter slope increases, the 'ringing' of the filter becomes worse. Unless carefully managed this affects the transient response and adds 'hardness' and 'sharpness' to the sound through the crossover region which can become fatiguing.

Every time we add elements to the crossover the reflected impedance to the amplifier runs the risk of looking worse. The swing of capacitance to inductance through the crossover region can upset even the most well behaved amplifiers. So it is in our interest to try and keep the overall system impedance looking fairly benign, otherwise the speakers will sound very different in character depending on the amplifier they are partnered with.

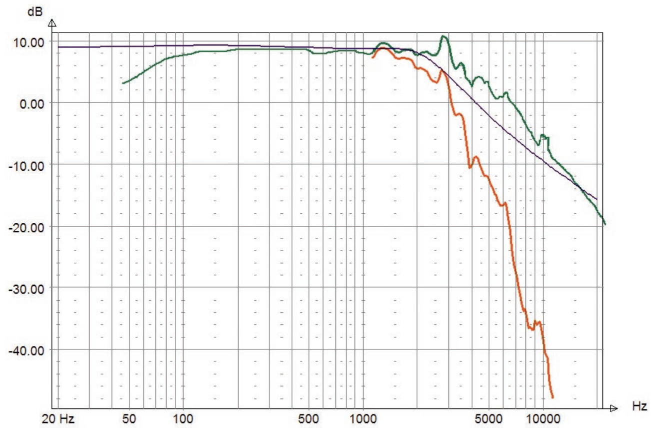
For these reasons the role of higher order crossovers is often kept in the electronic domain. There is a persuasive argument for coupling a power amplifier to each drive unit and putting the crossover in the preamplifier section. To start with the amplifier can control the drive unit more accurately if it doesn't have the impedance of the crossover in the way. Then we can build a high slope into an electronic crossover, with fewer problems than attempting it with passive components, and achieve the desired acoustic response by 'mapping' the drive unit characteristics to the required filter slopes in an 'active' crossover design.

If speaker designers had their way then I suspect that most speakers would be 'active' designs. But the complexity, and expense, of adding an amplifier for each drive unit and moving the crossover design into the preamplifier are often beyond the amateur designer's capabilities. Commercially it is something of a non-starter as it moves the 'mix and match' approach that is typical of the separates hi-fi market into a 'system' approach from each manufacturer. That is why you are likely to find successful active speakers only from the 'system' brands such as Bang & Olufsen and Meridian.

CALCULATIONS

OK, so where are the calculations, you know, the ones to select the right values for our crossover elements? Sorry to disappoint you, but they don't exist! Yes, I know that you can look up spreadsheets and calculators that give you theoretical values for a given crossover frequency. But look at what they ask you. What is the impedance of the drive units?

Indeed, just what is the impedance of the drive units? A bass unit may be 8 Ohms at 250Hz but it is likely to have an impedance of 22 Ohms at 1kHz. It is a variable, not a fixed, impedance and your crossover calculator cannot possibly take a guess at the component values for an impedance that varies with frequency.



Combine a drive unit with a first order natural roll-off (green) to a 2nd order crossover (blue) to achieve a 3rd order acoustic crossover (red).

So just how do you get started? The old way, and for many the best way, was to take the prototype speaker into a measurement chamber with a bucketful of crossover components and start plugging in values until the response looked reasonable.

Then you took the prototype speaker and crossover into the listening room and fiddled about with it until it sounded half reasonable. Then back into the chamber again to find out what damage you had done to the desired frequency response and so on.

This process of iteration between measurement and listening is very time consuming, but it is a path you have to follow if you want to design accurate, clean, transparent speakers. To do it by listening alone is very, very frustrating as you really don't know where you are in terms of ironing out problems.

SHORTCUTS

Occasionally we see speakers come in for review that have, fairly obviously, been designed by ear without recourse to, or perhaps ignoring, the requirements for a smooth frequency response. Generally they have one or two 'problem' areas which show up on audition, perhaps a 'gap' in the upper midrange which leads to a 'dulled' presentation of detail or a 'peak' in the treble region that makes them overbright.

Let me tell you it is much easier to iron out all the frequency response anomalies and then 'fine tune' the acoustic performance than to just 'play it by ear'.

Now this may be a disappointment to you budding speaker designers, but don't become downhearted and give up yet. Next month we'll look at ways that you can use a computer to run your own measurements, and you don't even need a measurement chamber!

We will also look at how you can 'shortcut' your crossover design to cut the months of iteration between measurement and listening.

Next month: Measurement techniques