1. Crossovers: Basic Knowledge

1.1. Active and Passive Filters

There are two very basic principles for crossover construction. One of them is the active filter, the other one the passive filter. For information about active filters, please check out paragraph 4 of this manual.
This paragraph will only cover passive filters for applications such as loudspeakers etc.

1.2. Passive Filters - The Components

There are three basic components to build a passive crossover from: Resistors, Capacitors and Inductors. All these components have different characteristics concerning impedance (Complex resistance), frequency and proportionality.

1.3. The Resistor

The resistor is the easiest to understand: it provides a constant resistance to al the frequencies applied. This is the theory. In practice, however, different resistors have different side components in form of inductances and capacitances - see fig. 1:

Fig. 1 - Replacement circuit for a simple resistor

Depending of the build style of the resistor, there are not only purely resistive components to be found. If considering for example the old ceramic high power resistor (white block), they certainly do have a small amount of inductance enclosed due to the way the resistive wire is wound within the resistor. MOX resistors do suffer from these problems a lot less.

However, it is important to note that these side capacities and inductances are of minor importance to the frequency crossovers, simply because their inductance values are considerably smaller than the ones of the voice coil of the loudspeaker for example. The parasitic capacitance and inductance are of high interest when building a power amplifier with emitter resistors - here the parasitic impedances can make the amplifier unstable and destroying the loudspeaker connected to the amp.

Again, for crossover purposes, the resistor provides a constant resistance across the audible frequencies.

1.4. The Capacitor

A different story altogether is the capacitor. Plotting the transfer function of a capacitor one can see that its impedance is frequency dependent - see fig. 2:

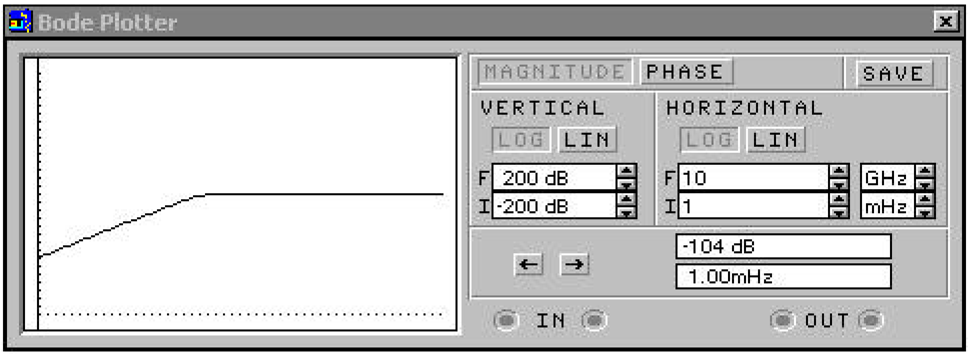

Fig. 2 - Bode Plot for a Capacitor

This type of filter is called High Pass filter - as it lets pass the high frequencies; High Pass filters attenuate the low frequencies. The formula for the reactance of the capacitor is:

$$X_C = \frac{1}{2\pi f C}$$

Note that $\omega = 2\pi f$, and due to its complex contribution to the reactance, I prefer to see the reactance written like:

$$X_C = \frac{1}{j\omega C}$$

Note that the capacitive reactance is inversely proportional to frequency - a rise in frequency indicates a drop in reactance. Again, there are parasitic side effects within a capacitor; fig. 3 shows this:

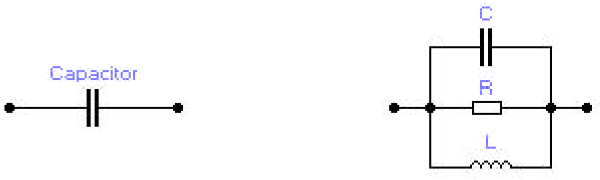

Fig. 3 - Replacement circuitry for a simple capacitor

For crossover purposes, the parasitic inductance can be omitted completely as it is of very small importance to the final result. The resistive part, however, can be significant: Having for example a capacitor in series with a tweeter, and realising that the tweeter needs a resistive network to attenuate the level so that it fits with the midrange driver, then the resistive part of the capacitor should be included as otherwise the tweeter is attenuated too much. But how do we measure the resistance of a capacitor, as its DC resistance goes towards infinity ? Some people suggest measurements done at 1 kHz. Pure convenience, think others, and hint towards measurements at the actual crossover frequency of the tweeter to provide accurate results. If you have the measurement instruments needed for that - go ahead. Otherwise you might just forget about this parasitic resistance and adjust the resistive network using your ears.

1.5. Inductors

The final component is the inductor. Again, its reactance changes with frequency, and the transfer function of an inductor can be seen in fig. 4 as follows:

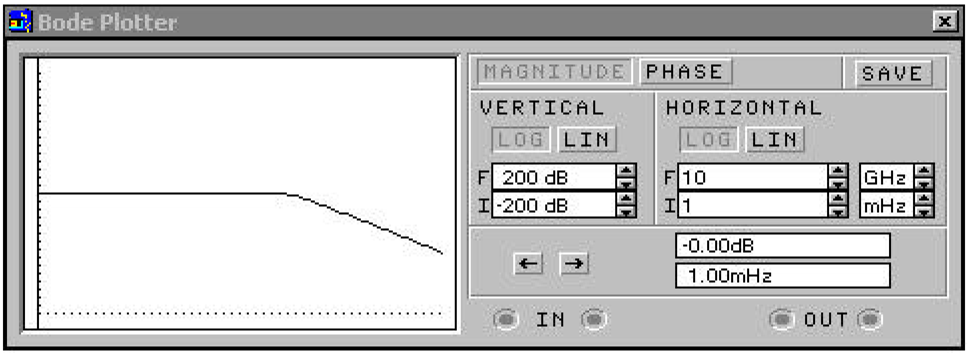

Fig. 4 - Bode Plot for an Inductor

This type of filter is called Low Pass filter - as it lets pass the low frequencies; Low Pass filters attenuate the high frequencies. The formula for the reactance of the inductor is:

$$X_L = 2\pi fL$$

Again, as the reactance includes complex components, many people - including me - prefer the complex notation form:

$$X_L = j\omega L$$

Note that in the case of the inductor, the value of L and the frequency are proportional to each other - if L rises, the reactance rises as well and vice versa.
And exactly the same as the two previous components, inductors do have parasitic capacitance and resistance. The parasitic capacitance can be omitted for crossover construction, but the resistance is of utmost importance - using for example an inductor in series with a low frequency drive unit, the amount of resistance changes the whole cabinet construction due to its influence on RE, the DC resistance of the drive unit (See Paragraph 8 for drive units and their parameters).

The replacement circuit for the inductor can be seen in fig. 5 on the following page:

Fig. 5 - Replacement circuit for the inductor

1.6. Examples

Having had a look at the three components and its functions, a simple filter can be calculated using an ordinary calculator. For example, we want a simple low pass filter with a reactance of 3 Ω at 1000 Hz. What is the value for L ?

1) $3 = 2\pi fL$
2) $L = 3/2 \times \pi \times 1000$
3) **L** = 0.00047 Henry = **0.47 mH**

Another example:

High pass filter, f = 5000 Hz, reactance = 10 Ω

1) $10 = 1/(2\pi fC)$
2) $(2\pi fC) \times 10 = 1$
3) $20\pi fC = 1$
4) $C = 1/20\pi f$
5) **C** = 0.000003183 = **3.18 μF**

Always remember that the results are calculated in standard units - R in Ohms, C in Farads and L in Henry.

2. The Crossover Construction

Having had a look at the basic operation principles of single components, one might come up with the idea to daisy-chain two or more components. Steady. First comes the single component again. As seen in the Bode Plots, they provide a certain amount of attenuation. This amount is of huge importance, as we ought to know about it. Well, thankfully it is very simple: Single component crossovers (i.e. one inductance or capacitance) are called first-order networks and have a slope of 6 dB per octave. This means that when the reactance is at a certain value at a given frequency f, it will be half (or double, depending if it is a high or low pass filter) at 2f. If we connect two inductances in series, the slope is not going to change, as we simply have changed the value of the inductor. If we, instead, connect a capacitor, as shown in fig. 6, we change the slope:

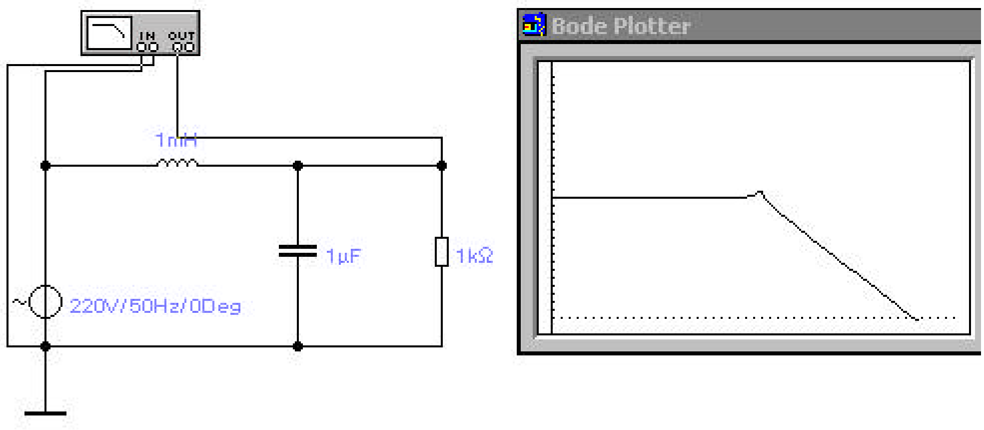

Fig. 6 - A Second Order low pass filter

Daisy-chaining another inductor would increase the filter order to third - and another capacitor would change it to fourth order. Higher orders are as well possible but will not be used for crossover constructions.

The higher the order of the filter, the higher the attenuaton at 2f (or ½f depending of the filter type - low pass or high pass). Here comes an overview over the filter slopes:

Filter Order	Filter Slope
1st Order	± 6 dB/Octave
2nd Order	± 12 dB/Octave
3rd Order	± 18 dB/Octave
4th Order	± 24 dB/Octave

2.1. DeciBel and 0.707

In terms of crossover construction, many of the above formulae must be thought of again. This is due to the fact that crossovers must bring their reactance in concordance with the drive units resistance and reactance - this includes DC resistance and AC reactance due to the voice coil impedance for example. Now what does all this mean ?

If we have, for example, two filters, a high pass and a low pass filter, and we want to add the two filter responses together and achieve a linear transfer function, what is the most important aspect ?

The most important aspect is that the two filter branches have the same slope - very important to achieve a linear transfer function. But there are other factors: For example -how big should the attenuation be at the frequency where the two filters meet ? Simple logic would suggest that if both filter branches are at half their magnitude at the crosover frequency, the signals add up to a perfect linear transfer function. Well, it's not that simple…
Some filters do indeed require a 6 dB attenuation at the crossover frequency. Then again, some don't. Why ?
Going back to the introductory part one notices that there are j's in the equation. Now, this complex component adds the so called phase shift to the signal; in other words, how much is the current lagging behind the voltage or vice versa. Other books will inform you a lot better about this than this article - this just keeps it simple.
We know now that phase shifts play an important role when adding two signals together.

But before going into detail about adding the signals, take a step back and take a close look at the Bode Plot in fig. 6. Noticed that little hump next to where the attenuation zone starts ? This is not quite what we were aiming for - a linear transfer function. So what went wrong ?

Going back to the formulae for the reactance of the inductor and the reactance for the capacitor we find that each value of inductors and capacitors has its own resonance frequency. If we are now combining two components, an inductor and a capacitor, the resonance frequency of the combination of these two components can be found by using the following equation:

$$f = \frac{1}{2\pi(LC)^{0.5}}$$

Looking at above equation, one can see that we can trade the two values for L and C to whatever value we want - as long as the product, sometimes called the LC product, remains constant. However, the ratio between L and C is of very high importance, which prohibits to change the values of L and C. If ratio and product are defined, the values for L and C are pretty much restricted.
However, this is what went wrong in fig. 6 - the values clearly give the desired crossover frequency, but the quality of the crossover region is affected due to improper choice of the L and C values. However, sometimes these slight deviations are of useful nature, be it just to boost the output a little more at that frequency because of irregularities of the drive unit for example.
This is where the Q-factor comes - it describes basically the ratio between energy stored at resonance and energy dissipated at resonance. Differenct values for Q therefore have different shapes at the knee of the crossover frequency. To calculate the value of Q for a second-order LC filter, use the following formula:

$$Q = \left[\left(R^2C\right)/L\right]^{0.5}$$

Filter Name	Value of Q
Linkwitz - Riley	0.49
Bessel	0.58
Butterworth	0.707

For further information on crossover filter design consider paragraph 2 of this paper. There, lots of information about the different filter shapes, delay times and signal addition properties can be found.

Acknowledgments

1) Vance Dickason, *Loudspeaker Cookbook,* 5th ed., Audio Amateur Press

2) John Borman et al., *The Loudspeakers and Headphones Handbook*

3) Martin Colloms, *High Performance Loudspeakers*

4) Bill Waslo, *The IMP Loudspeaker Measurement System*

5) JAES Magazines