Crossover Networks

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Crossover networks are used in multi-way speaker systems to split the input signal into separate frequency bands to be fed into special-purpose speakers designed to cover a specific range of frequencies. Special-purpose, or hi-fi speakers as they are sometimes called, are commonly known as woofers, squawkers or midrange, and tweeters, to signify the range of frequencies which they cover.

The use of crossover networks in a multi-way system becomes essential when such speakers are used so as to limit their response to be in the range of frequencies within which their response is smoothest. A woofer, for instance, designed to cover only the low frequencies has its response 'rolled off' in the mid or upper mid frequency region so as to allow another speaker – a squawker or a tweeter – to take over.

The use of specialised speakers for different frequency ranges is also essential as it is difficult to have a single speaker to cover the full audio frequency range satisfactorily. A speaker which covers a wide frequency range is known as a fullrange. The response of a fullrange is, however, peaky and is subject to greater harmonic distortion than a multi-way speaker system utilising special-purpose speakers with a well designed dividing network to give a smoother and wider response.

However, if the crossover system is ill-designed or not made properly, it would ruin the overall performance of the speaker system rather than improve it, regardless of the enclosure design and the quality of the loudspeakers used. It is obvious therefore that a crossover network forms a critical part of a speaker system

Crossover systems may be either of the active type or the passive type, utilising a combination of inductances and/or capacitances to form low pass, high pass or even band pass elements. We shall be concerned only with the passive type of crossover networks as these are the most commonly used. The two basic rules for designing a crossover network are:

1. The loudspeakers should have a usable response extending to above the tentative crossover point and all the loudspeakers should have similar sensitivities in this region.

2. The crossover network design should be as simple as possible.

In a two-way speaker system which comprises a woofer and a tweeter, a two-way corssover is used. This basically comprises a low pass and a high pass section and is most often connected in parallel as shown in Fig. 1. The circuit

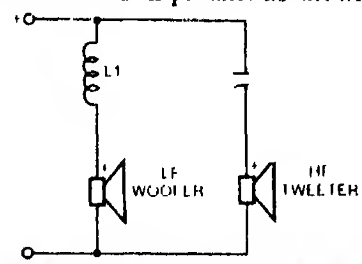


Fig. 1: 6dB/octave, 2-way crossover network.

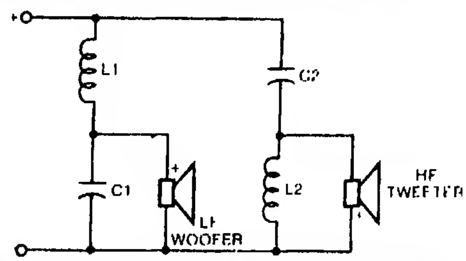


Fig. 2: 12dB/octave, 2-way crossover network.

shown in Fig. 2 is similar to Fig. 1 but has two elements in each section. The two circuits differ in their attenuation rates. The first circuit has an attenuation rate of 6 dB/octave while the second has an attenuation rate of 12 dB/octave on account of the additional filter elements used. The attenuation rate gives us the rate at which the response of the filter rolls off. Greater the attenuation rate of a filter, sharper the cutoff. Fig. 3 shows another two-way circuit with an even larger number of filter elements and having an attenuation of 18 dB/octave. The attenuation rate increases as the number of reactive elements in a section is increased.

In hi-fi systems, either 6dB/octave or 12dB/octave filters are used. Some designs utilise a combination of 6dB and 12dB/octave sections. Such arrangements are known as asymmetric filters. Attenuation rates above 12dB/octave

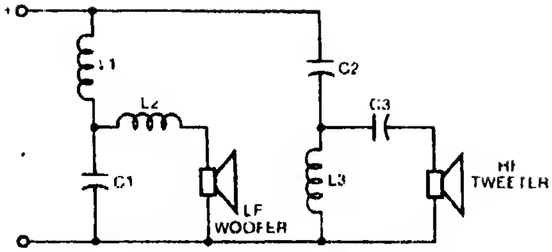


Fig. 3: 18dB/octave, 2-way crossover network.

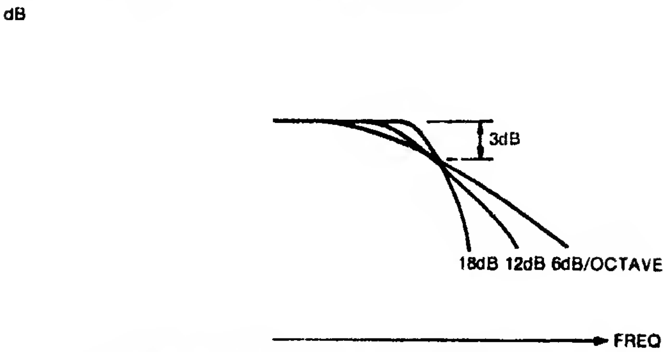


Fig. 4: Comparison of 6dB, 12dB, and 18dB/octave rolloff rates.

are rarely used as besides making the filter very complicated, a very fast roll off rate can very often introduce transient problems in many speakers. A 12dB/octave filter is the one most commonly recommended for use in hi-fi systems on the ground that a 6dB/octave filter is 'very slow' and not suitable for hi-fi systems. Paradoxically, in many cases (which shall be dealt with later), a slow action filter can be made to give better results than the fast acting one through a careful study of the speaker response and desired crossover frequency.

Mathematical representation

The capacitance and inductance values can be determined from the following formulae, for a given crossover frequency and loudspeaker impedance!

$$C = \frac{1}{2\pi f_o Z} \quad \text{.... 1.}$$

$$L = \frac{Z}{2\pi f_o} \quad \text{.... 2.}$$

where Z is effective impedance of the speaker, f_o is the crossover frequency, L is inductance in milli henry, C is capacitance in micro farad.

This gives the reactance values for a 6dB/octave filter. In case of filters having two reactive elements per section as in the 12dB/octave filter, the reactance value of the elements is $\sqrt{2}$ times the effective impedance Z of the loudspeaker. This means that in a 12dB/octave filter, both inductances and capacitances have the same value. These results and formulae are applicable to the parallel circuits shown in Fig. 1 for the 6dB/octave filter and Fig. 2 for the 12dB/octave filter for two-way systems.

These results can be extended to a three-way corssover system which is utilised when a three-way speaker system comprising a woofer, a squawker and a tweeter is used. The mid-range of frequencies forms a band between the lows and highs and logically requires a bandpass arrangement to function in the filter. The bandpass is designed by establishing the upper and lower frequencies of the bandpass filter and using a series combination of a low pass filter formed by an inductor and a high pass filter formed by a capacitor. The component values for these can be determined using the same method as described above. The circuit arrangement for a three-way crossover network of 6dB/octave and 12dB/octave types are shown in Figs. 5 and 6 respectively.

For example, in the case of a three-way system using a 6dB/octave network, first of all the value of the required series inductance is determined using equation 2 after substituting in this the frequency at which we wish to crossover to the squawker, say f_1. The inductance obtained, L1, acts as a low pass filter and blocks higher frequencies—in this case, above f_1Hz with an attenuation rate of 6dB/octave. One octave is referred to as a doubling of frequency, hence an octave above f_1Hz is twice this frequency, say, $2f_1$Hz. This theoretically implies that the signal would have undergone

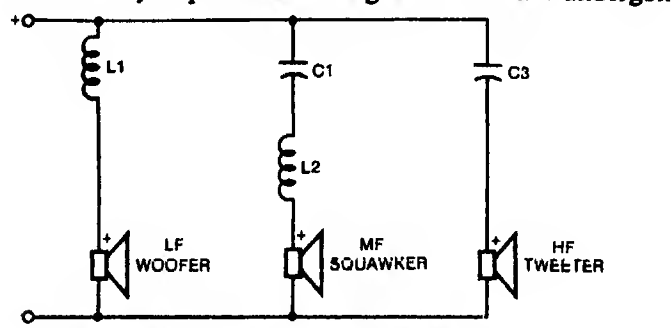


Fig. 5: 6dB/octave, 3-way crossover network.

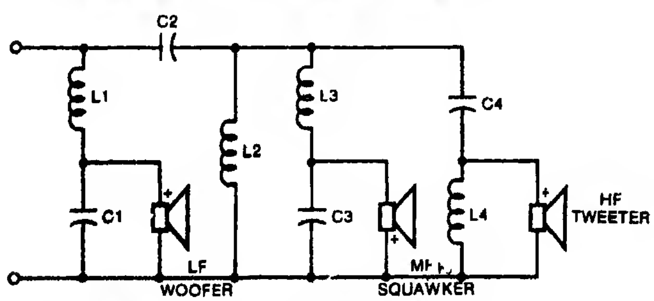


Fig. 6: 12dB/octave, 3-way crossover network.

an attenuation of 6dB at $2f_1$Hz. Next, moving on to the mid-frequency arm of the filter, the value of capacitor C1 is determined using the lower crossover frequency, f_1Hz. Suppose we wish to roll the squawker over to the tweeter at f_2Hz, we substitute this in the relevent formula to get the required inductance L2. In the same way, the capacitor C3 may be found by applying the upper crossover frequency f_2 to form the required high pass filter for this section.

Proceeding in the same way, the component values in the

12dB/octave network can also be found. The only difference in this case is that the reactance required from each element is now $\sqrt{2}$ times the effective impedance of the loudspeaker. Hence the reactance formula given above is divided by $\sqrt{2}$ in the case of the capacitance and multiplied by $\sqrt{2}$ in the case of inductance. It will be noted that the bandpass element values will be similar to the low pass and high pass section values, except that their order of operation is reversed i.e., C1 which forms a bypass element in the low frequency section is of the same value as C2 which forms the high pass element of the bandpass section. In the same way, the series inductor L1 is the same as the shunt inductor L2. Similarly, in the upper frequency section, the inductor L3 has the same value as L4 which shunts the tweeter. Capacitors C3 and C4 also have the same value.

The practical view point

So far, we have looked at crossover networks on a purely theoretical or ideal stand-point. That is, we have imagined a purely resistive load remaining constant over the full frequency range. Moreover, we have assumed that the loudspeakers also have an absolutely flat response. But sadly, things do not work out like this in actual practice and many a constructor finds himself landing up with outlandish results in spite of the best design efforts. In the first place, the rated impedance of a loudspeaker is anything but within a narrow range of frequencies. Fig. 7 shows the impedance versus frequency plot of a typical loudspeaker. It will be seen that the impedance is never constant and is maximum at the resonance frequency of the loudspeaker, sometimes over four times the rated value. This gives birth to the golden rule never put the crossover point anywhere near the resonant frequency of the loudspeaker!

The rated impedance of a loudspeaker is usually defined as the lowest value above resonance and is about 15 to 20 per cent higher than the DC resistance of the loudspeaker. With further increase in the frequency above resonance, the impedance increases gradually as the loudspeaker becomes more and more mass controlled. Since many a crossover point lies way above the resonance and for that matter, where the impedance was the stated value, it is important to consider the effective impedance of the loudspeaker at the crossover frequency (which is likely to be somewhat greater than the stated minimum impedance) rather than the rated impedance, for purposes of crossover network design. For practical purposes, it is enough to assume an effective impedance

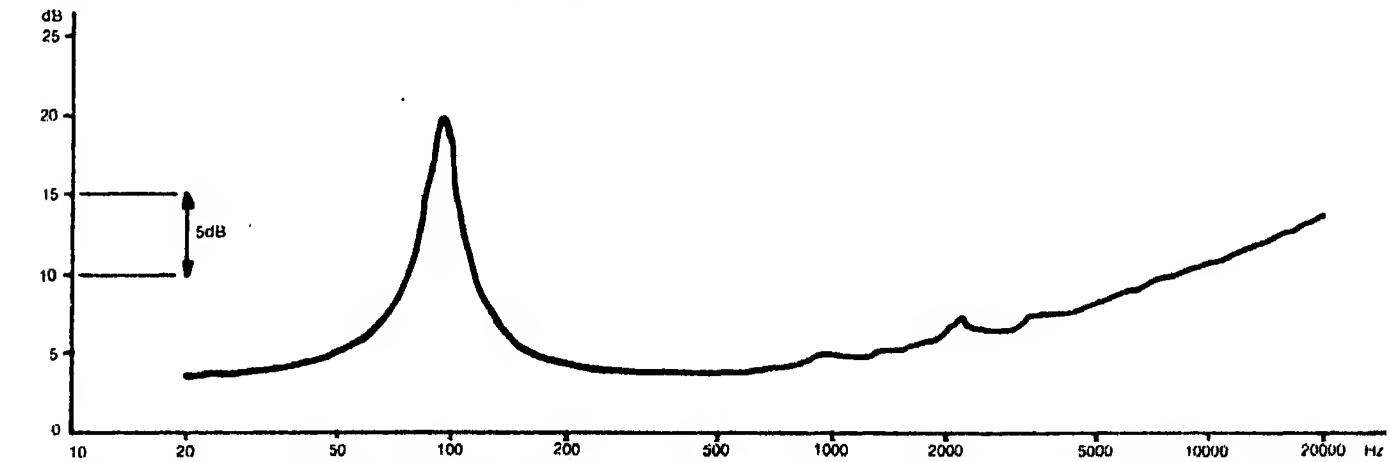


Fig. 7: Impedance curve of a typical loudspeakers.

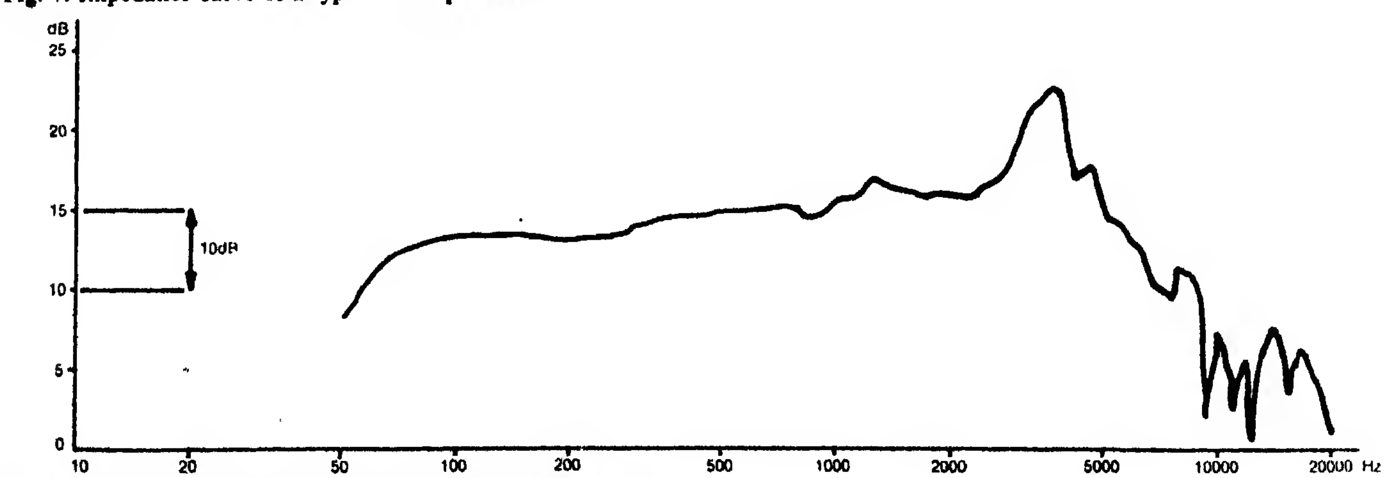


Fig. 8: Frequency curve of a 20 cm woofer mounted in a 20-litre sealed enclosure.

of 5 ohms when the rated loudspeaker impedance is 4 ohms; 10 ohms when the rated impedance of the loudspeaker is 8 ohms; and so on.

One important factor which dictates the choice of crossover frequency and effects the performance of the system to a great extent is the frequency response ranges of the component loudspeakers. Many manufacturers of loudspeakers are notorious for not releasing any response curves and thereby making things pretty difficult for the crossover designer. The reason why it is so important to have some idea of the frequency response of a loudspeaker when designing a crossover network is very obvious since we want a speaker to function upto a certain crossover point, it should have an acceptably smooth response at least up to that point. Rest assured, even the better loudspeaker will have a response curve which vaguely resembles a mountain range. Many manufacturers state the frequency range of the speaker, though the variation in terms of decibels (dB) may not be stated. From this the designer can know, to some extent, the response ranges of the speakers. The frequency ranges of all the speakers should be overlapping so as to be compatible for use in a multi-way system. Also, when selecting the crossover point, the speaker manufacturer's recommendations should be taken into consideration, as it is essential for the sensitivities of the speakers to be equal at the crossover frequency. If this is not so, a step will appear in the overall frequency response of the system which will indicate a sudden drop in the output due to a speaker having a lower sensitivity.

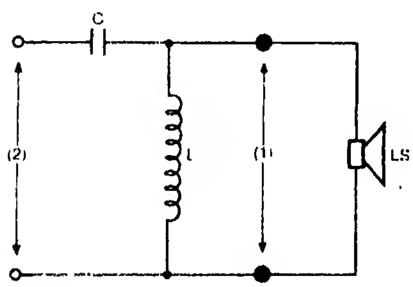
Simpler, the better

Very often, the crossover network can be simplified and at the same time made more effective by incorporating the basic response characteristics in the crossover design. For example, woofers generally have high inductance voice coils as part of their design to achieve a high energy product and power handling capacity. This inductance can be incorporated in the crossover network as part of the low pass filter, thereby reducing the size of the component and at the same time maintaining the constant resistance behaviour of the network. The cone texture of many woofers is also not conducive to mid and high-frequency output and helps in rapidly rolling off the highs, acting as a built-in corssover network. For this reason, it may not be always necessary to employ a very high cutoff rate in the low-frequency section of the filter, unless a very low crossover frequency is aimed at.

In general, if the lower crossover frequency is above 1 kHz, a 6dB octave filter in this section is quite sufficient, whereas if the crossover frequency is below 1 kHz, then a crossover rate of 12dB octave should be employed. In the same way, in the case of tweeters, if the crossover frequency is very high, say, above 6000 Hz, a 6dB octave filter will be quite adequate, but if we intend to operate the tweeter below 4000 Hz, a 12dB octave filter is a must because a slower acting filter passes through some lower frequency energy regions which could destroy the tweeter, besides introducing a good deal of distortion. In the case of mid-range speakers viz., squawkers, the bandpass section can sometimes be left out altogether, using instead a simple high pass filter and letting the natural response of the speaker do the rest. The ear, in fact, is the best judge and it is advisable to initially mount the crossover outside the enclosure and listen to the system. Changes can then be made as necessary before final assembly.

TABLE I
Power handling capacity measured as per DIN 45573/IEC 268-5 (See Fig. below) of Philips dome tweeter

LS Rated Impedance ohms	Frequency 3dB (kHz)	Net-work CμF	L(mH)	LS PHC measured at 1 (watt)	System PHC at 2 (watt)
4	2	12	0.35	4	20
	4	5	0 20	6	50
8	2	8	0.20	4	20
	4	3.2	0.35	6	50



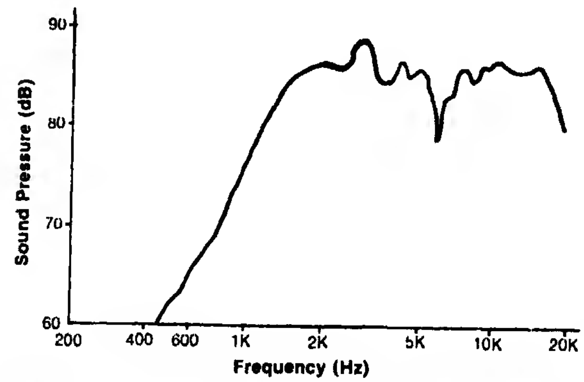


Fig. 9: Frequency curve of a Philips dome tweeter.

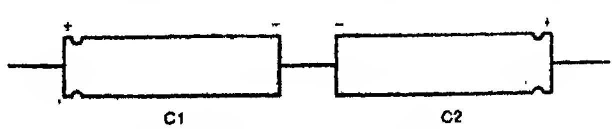
One final point which deserves some mention is that of the power handling capacity of all the loudspeakers which are to be used in a multi-way speaker system. Where the power handling capacity of the woofer is usually high and can be assumed to be handling most of the input power, the power capacities of the other speakers, in particular tweeters, is usually very low and requires prior attention while designing the network to ensure that the tweeter is not overloaded in the system. Tweeter coils are very light and usually wound with very fine gauge wire and can withstand at the most a couple of watts across the terminals. Of course, the high pass filter limits the amount of power input, but this depends on the crossover frequency. The lower the crossover frequency, the greater the energy transmitted across the filter, and hence lower the power the tweeter can handle in the system. In the event of tweeter power capacity falling short, either the crossover frequency should be adjusted viz., raised higher, or two tweeters of half the required impedance should be connected in series and used.

A speaker manufacturer usually gives the power handling capacity of a tweeter or a squawker with a particular high pass filter connected to the speaker, the details of which are usually given. This should be taken into account when designing the filter. Anyone who played around with speakers would probably be aware how an expensive tweeter may go to waste when too much power is sent across the little voice coils. Incidentally, it is impossible for a repaired tweeter to sound the same as before, as the response of a tweeter is effected by little things such as the size of the solder beads and the type and amount of adhesive, amongst other things. It is proper therefore, to get it repaired only from the manufacturer.

Construction

Crossover networks are easily assembled on tag boards or even terminal strips. However, for production purposes, a printed circuit board is most convenient. In all arrangements, it is preferable to have more than one inductor, spaced away from one another. The components for use in a crossover network should be so selected as to give minimum losses in circuit. These losses are caused by the power factor of the capacitors and the small but finite resistance of the inductor coils. Obviously, a bigger and more complicated network will have more losses than a simpler one on account of greater number of components.

The power loss occuring on account of a crossover network is stated in terms of insertion loss in decibels (dB). The insertion loss becomes a very important factor in high-power systems as at high-power levels, a considerable number of watts may be dissipated in the network itself. To ensure a low insertion loss, it is advisable to use a thick copper wire (18-22 swg) for all coils and capacitors with a low-power factor. Many manufacturers utilise 'cored' coils to reduce the amount of wire used and at the same time reduce the losses. The value of the capacitance required in most crossover circuits makes it necessary for only the electrolytic type of capacitors to be used. These are, however, polarised, i.e., have a positive and a negative terminal and cannot be used as such in filter circuits.



$$C = \frac{1}{C1} + \frac{1}{C2}$$

Fig. 10: Two electrolytic capacitors connected in back to back fashion to form a non-polarised capacitor.

For this purpose, two electrolytics may be wired 'back to back' as shown in Fig. 10 to obtain a non-polar capacitor. The resultant capacitance is given by the series law for capacitance viz., $1/C1 + 1/C2 = 1/C_T$. It should be noted that in this case the positive terminals of the two capacitors are facing outwards. In this way any desired capacitance can be obtained. It should be noted that the working voltage of the capacitor should be greater than the peak output voltage of the amplifier. Otherwise, a working voltage of about 40 volts is normally suitable for almost all purposes. In the high frequency section where a large capacitance may not be required, metallised polyester capacitors serve the purpose well. These have a low power factor and a low self inductance as well, and so do not generate any high impedances at high frequencies. If required, the two capacitors may be wired in parallel to increase the capacitance. Alternatively, it is also possible to wire a polyester capacitor across two 'back to back' electrolytics in the high frequency section of the filter to counteract the inductive effect of the electrolytics at very high frequencies, allowing part of the capacitance to be contributed by the polyester type capacitor.

For the inductances, air-cored coils are the best bet for the constructor as they can be easily constructed and are, performance-wise, the best. However, the DC resistance of the coils should be kept as low as possible and the thickness gauge of enamelled copper wire (within the budget) should be used. Generally, inductances below 1 mH may be wound with 22 swg, but inductances above 3 mH should be wound with 18 swg or even thicker wires. The size of the air core required to obtain maximum inductance with the minimum wire for a given diameter of the wire d in cm is given by the following formula:

$$a^5 = \frac{Ld^4 \times 10^9}{24.5}$$

where a is the radius of the former in cm
d is the diameter of the wire in cm
L is the required inductance in henry (H)

A little calculation gives the diameter, 2a of the former to be used.

(To be continued)