# SPEAKERLAB TECHNICAL REPORT № 1

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## A GUIDE TO CROSSOVER DESIGN

P. J. Snyder

Most speaker system builders buy the raw speakers from a supplier and then build the enclosures from wood themselves. When it comes to crossovers, those who wish to buy a ready-made one are usually faced with only a very limited selection and have little to go on in choosing the right one. Those who wish to build their own have difficulty finding parts and information on how to build them.
We hope that this report will provide some of the needed information.

### WHY CROSS OVER?

Just about every high quality speaker system in use today has at least two speakers, a woofer and a tweeter. Two speakers can divide the audio spectrum between themselves and each do a better job. One specializes in low frequencies, the other in highs. The crossover network routes to each speaker the part of the spectrum it can reproduce best.

After speakers and enclosure, the most important single factor in speaker system performance is the crossover network. A properly designed crossover can bring out good sound even from cheap speakers, and is absolutely necessary to obtain from high quality speakers their maximum performance.

The most significant advantage of a good crossover is its ability to reduce intermodulation distortion in the speakers to very small proportions. Intermodulation distortion is the worst from of distortion in speakers and is what gives the speaker its generally accepted status as the "weakest link" in the stereo reproduction chain. This distortion is generated by motion of the woofer voice coil in its magnetic field, which cannot be made perfectly uniform. The woofer's sensitivity changes as the coil moves from regions of high field to low field, and any mid or high frequencies being reproduced by the woofer are modulated by the low frequency that caused the cone motion. This form of distortion is particularly objectionable because it does not occur in nature and is very discordant to the ear. The cure is to exclude the mid and high frequencies from the woofer and have them reproduced by one or more other speakers. A crossover which achieves this will make a vast improvement in sound quality. The speaker designer who takes the trouble to incorporate the right crossover in his design will find that the results repay his diligence immensely.

This first issue of the SPEAKERLAB TECHNICAL REPORT covers the basic principles of parallel section crossover networks. Parallel section crossovers have a separate section for each speaker, which makes it possible to tailor a network for any possible combination of speakers.

### TWO WAY, 6 DB PER OCTAVE CROSSOVER

The simplest form of crossover network is shown in Figure 1. It is called a two way system because the frequency spectrum is divided into two parts, above 1670 Hz and below 1670 Hz. The low frequency section is merely an inductor which acts as a low pass filter and the high frequency section is a capacitor

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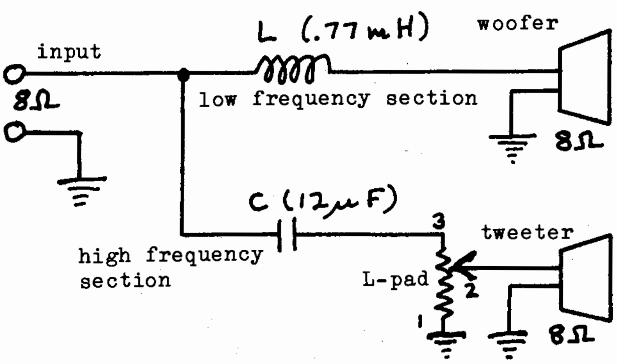



FIGURE 1. Two way, 6 dB per octave crossover. The ground symbol merely indicates a common connection point inside the speaker system.

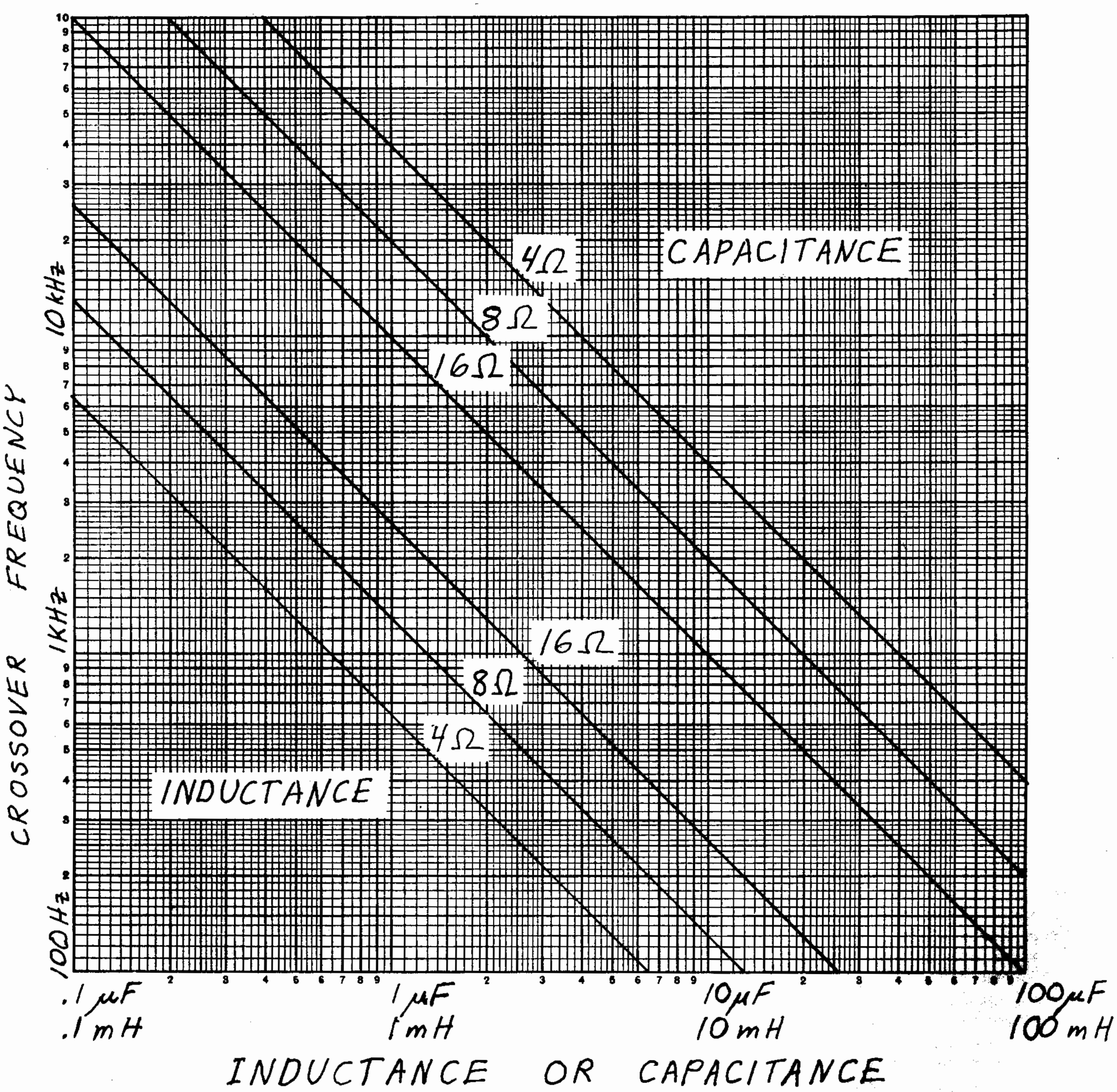



Figure 2. Capacitance and inductance values for 6 dB per octave crossover sections. Use the upper three lines to determine capacitance and the lower three lines to determine inductance.

which acts as a high pass filter. The value of the inductance of the low frequency section is determined by the formula

$$L = \frac{R}{2\pi f}$$

where $L$ is the inductance, $f$ is the crossover frequency, and $R$ is the impedance of the woofer.

The value of the capacitance in the high frequency section is determined by the similar formula

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

Here $C$ is the capacitance, $f$ is the crossover frequency, and $R$ is the impedance of the tweeter. In both formulas the frequency is in hertz (Hz) and the impedance is in ohms (Ω). Capacitance is in farads (F) and inductance is in henries (H).

Both of these formulas are expressed in graphical form in Figure 2 on the preceding page. Once the crossover frequency and impedance have been chosen, the required parts values may be read directly from the graph.

At the crossover frequency the signal to each speaker will be 3 dB down, and each speaker will be radiating half power compared to what it radiates in the center of its frequency band. Thus the total radiation from both speakers at the crossover frequency will equal the power radiated at the other frequencies, and there will be no hole or peak in the frequency response.

This type of network has a rather gradual cutoff beyond the crossover frequency. It is called a 6 dB per octave crossover because outside its desired frequency band each speaker receives 6 dB less signal for each octave beyond the crossover frequency.

## 12 DB PER OCTAVE CROSSOVER

A crossover network with a sharper cutoff characteristic, 12 dB per octave, is shown in Figure 3. Unfortunately the parts values for the 12 dB crossover are not given by one simple formula as in the case of the 6 dB unit. However, the two systems have this in common: each consists of two sections, one for the woofer and one for the tweeter. The two sections are fed in parallel from the input terminals. All the crossover systems discussed in this report share this feature; each speaker is driven by a crossover section for the part of the spectrum allocated to that speaker, and all the sections are connected to the input terminals in parallel.

Crossover networks may be made for speaker systems of any complexity by connecting appropriate sections in parallel.

Each section passes only signals of frequencies falling in its share of the audio specturm. It blocks out signals of other frequencies. If the impedances of all the speakers in a system are the same, the impedance of the whole system at the input terminals will be the same as that of the speakers. At any given frequency, only one speaker is drawing power; the other speakers are isolated from the input by their crossover sections. (Right at a crossover frequency, of course, two speakers will be drawing partial power.)

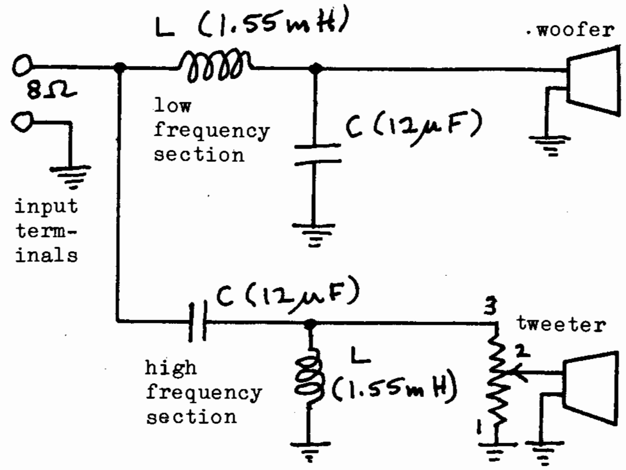



Figure 3. Two way, 12 dB per octave crossover. The parts values shown are for an 8 ohm system crossing over at 1160 Hz.

## OTHER CROSSOVER TYPES

Even steeper rolloff characteristics can be obtained with more complex networks. Figure 4 shows an 18 dB per octave system. This type is rarely used, however, except for special applications.

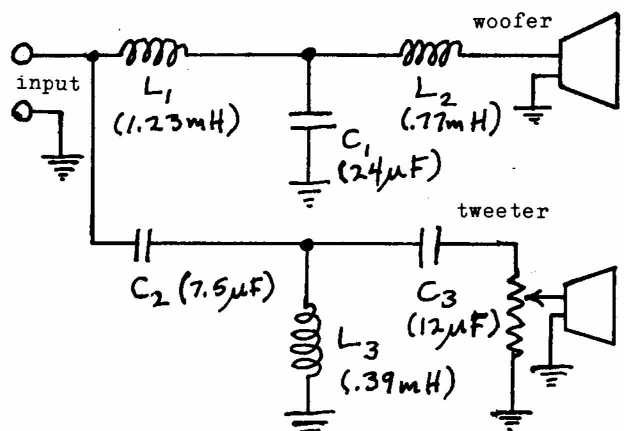



FIGURE 4. Two way, 18 dB per octave crossover. The values shown are for an 8 ohm system crossing over at 1670 Hz.

THREE WAY CROSSOVER SYSTEMS

The crossovers described so far have all been two way systems. Three way crossover networks use sections similar to those already presented for the woofer and tweeter, plus a third section of an inductor and capacitor in series for the midrange. A typical three way system is illustrated in Figure 5.

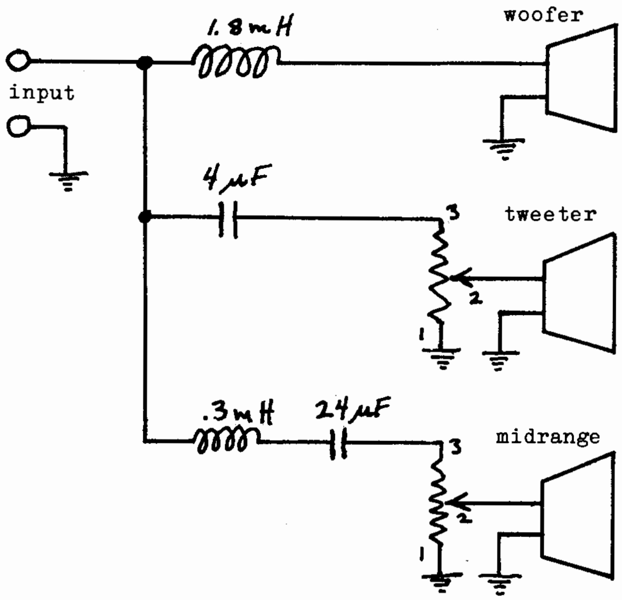



FIGURE 5. Three way, 6 dB per octave crossover. The parts values shown are for an 8 ohm sytem with crossover frequencies of 710 and 5000 hertz.

The system of Figure 5 is a 6 dB per octave three way crossover. A 12 dB per octave system appears in Figure 6. Note that while true 12 dB sections are used for the woofer and tweeter, the midrange section is of the same type as is used in the 6 dB system. The cutoff slope of this type of section lies between 6 and 12 dB and depends on how many octaves wide the midrange band is.

While it is possible to build true 12 dB midrange sections, they are generally regarded as impractical because two inductors and two capacitors are required.

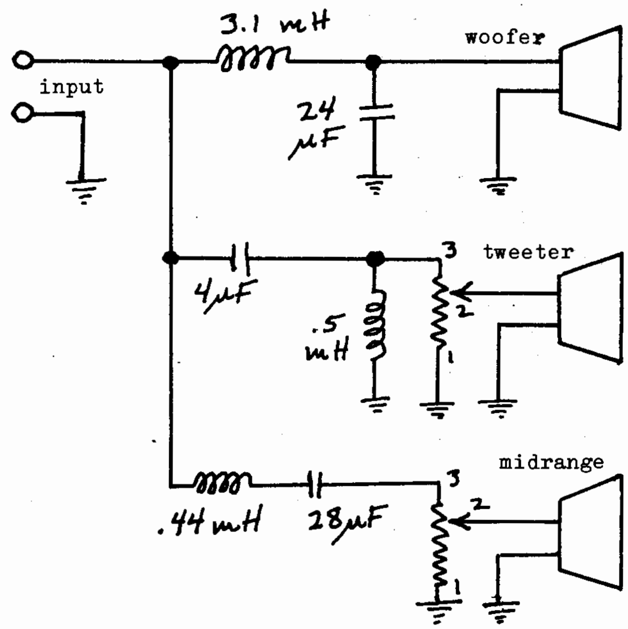



Figure 6. 12 dB per octave three way crossover. The parts values given are for an 8 ohm system with crossover frequencies of 590 and 3500 Hz.

FOUR WAY CROSSOVERS

Four way, five way, and even more complex crossover systems may be assembled by putting addtitional sections in parallel. The extreme high and low frequency sections are either 6 or 12 dB per octave networks as described for two way systems. The other sections are midrange type networks. A typical four way system with crossover frequencies of 250, 1300, and 8000 Hz is shown in Figure 7.

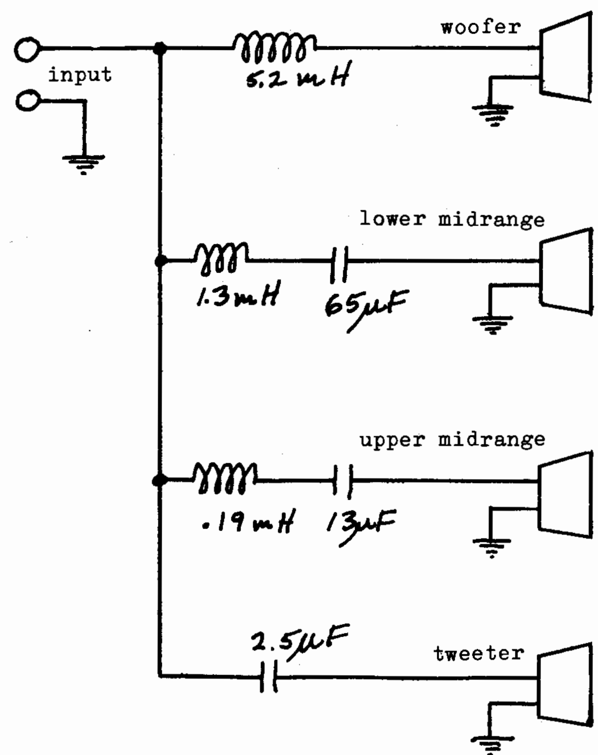



FIGURE 7. Four way, 8 ohm crossover system with crossover frequencies of 250, 1300, and 8000 Hz. The speakers for four way systems are often called woofer, midrange, tweeter, and supertweeter.

## SPEAKER IMPEDANCE

All the speaker systems shown in the Figures as examples have had a woofer, tweeter, and midrange of the same nominal impedance. It is not necessary that all the speakers of a system be the same impedance, however. Since the crossover is designed with a separate section for each speaker, it is only necessary that each section be selected for the impedance of its corresponding speaker. Thus for example one may use an 8 ohm woofer, 4 ohm midrange, and 16 ohm tweeter in the same system provided that one makes the woofer crossover section for 8 ohms, the midrange section for 4 ohms, and the tweeter section for 16 ohms.

If you have speakers which have unknown impedances you can determine the impedances by measuring the voice coil resistances. Speaker AC impedance is generally 30 to 50% higher than the voice coil DC resistance. Thus 8 ohm speakers will usually have resistances of 5 to 6 ohms; 4 ohm speakers, 2.5 to 3 ohms; and 16 ohm speakers, 10 to 12 ohms. This is not a hard and fast rule and speakers with DC resistances outside the ranges stated are often found. A safe approach is to measure the DC ohms and use the next higher standard impedance value as the speaker impedance. Using this rule, a speaker with a 9 ohm DC resistance would be considered a 16 ohm speaker.

British-made speakers use a two number impedance rating system, for example "10/15 ohms." The first number is the DC resistance and the second is the nominal impedance; so this speaker would have a 16 ohm rating by our system.

Some speaker system designs use more than one woofer, or more than one tweeter or midrange. If two woofers of the same impedance are used, they may be wired in series or parallel (usually parallel). The load impedance on the crossover will then be double (series) or half (parallel) the impedance of one woofer. If four woofers are used, they may be wired in series-parallel which results in a combined impedance equal to the impedance of a single woofer. In these cases where woofers (or whatever) in combination are used, the impedance of the combination should be used for the corresponding crossover section.

When the different sections of a speaker system have different impedances, the system impedance which is presented to the amplifier will vary with frequency. This is of no consequence so long as the system impedance never dips below the amplifier's minimum safe load impedance. The latter is 3 ohms or less for nearly all transistor amplifiers rated for use with 4 to 16 ohm speaker systems.

The speaker system impedance will equal the impedance of the woofer section at low frequencies, the tweeter section impedance at high frequencies, and so on. The speaker system builder should rate his system impedance the same as the lowest impedance section. This is the most conservative approach because low impedance loads put the heaviest strain on amplifiers.

## L-PADS

The L-pads shown in most of the examples are used to set the level of the midrange and tweeter relative to the woofer. Midranges and tweeters are generally more sensitive than woofers and it is usually necessary to "cut back" the signal going to them in order to obtain uniform frequency response. The L-pad is a special kind of volume control which maintains a constant impedance load on the crossover regardless of the control's setting. An ordinary volume control or potentiometer varies its input impedance as the setting is changed. This is unacceptable because it would cause the crossover frequency to change.

Although the L-pad is a three terminal device and is represented by the same symbol as an ordinary potentiometer, it actually contains two variable resistors inside. As one varies the signal level to the speaker, the other equalizes the load impedance on the crossover.

L-pads are wirewound to enable them to handle the high power levels at which speakers operate. When connecting up L-pads it is necessary to wire the terminals properly. The terminal numbers shown in the figures correspond to the numbers on the terminals of the L-pads supplied by Speakerlab. For other types consult the manufacturer's instructions packed with the unit.

If the tweeter and midrange are less sensitive than the woofer, L-pads cannot be used to equalize the speaker sensitivities. L-pads can only reduce midrange and tweeter sensitivities, not increase them. Usually the only time the woofer section is more sensitive is when two woofers in parallel are used. Then it may be necessary to use multiple tweeters and midranges as well.

The proper technique for adjusting L-pads is as follows. First, set all the L-pads to minimum (full counterclockwise). Turn the balance control on your amplifier all the way to one side so you can adjust the L-pads one channel at a time. Turn up the midrange L-pad until the midrange and woofer sounds "blend" so that it is difficult to tell which sound is coming from which speaker. Then do the same with the tweeter L-pad. When the L-pads are properly adjusted you will not be able to hear the "highs" and the "lows" separately; the music will sound all as one. Improper adjustment of the L-pads puts a step in the frequency response to which the ear is very sensitive. It makes the different frequencies sound separated.

## COILS AND CAPACITORS

Coils for use in crossover networks come in two styles, iron core and air core. The iron core type are generally less costly because they use less copper, the most expensive material. They also are inherently self-shielded and less susceptible to hum pickup. However they add some distortion to the signal because of the nonlinear magnetic properties of iron. The latter causes the inductance of iron core coils to vary as the signal level varies. Inductance increases with increasing signal amplitude until saturation is reached, then decreases.

Air core coils do not suffer from this shortcoming because they are made without iron. Air core coils will pick up hum if mounted near a source of AC magnetic fields, such as a power transformer or turntable motor, but this is easily avoided. Crossovers are usually mounted inside speaker enclosures where there are no sources of hum.

Capacitors suitable for use in crossovers are also of two types, solid dielectric and nonpolar electrolytic. Solid dielectric capacitors have two plates separated by a dielectric of paper, mylar, or oil-impregnated paper. Nonpolar electrolytic capacitors have two aluminum plates separated by an electrolyte-soaked gauze. Passing AC current through the capacitor forms a very thin insulating anodic film on each of the plates. These films are the dielectric in an electrolytic capacitor.

Solid dielectric capacitors provide superior stability and lower power loss compared to electrolytic capacitors, but are much larger and more expensive for a given capacity. Crossovers with a low woofer crossover frequency require large capacitances and usually only electrolytics are practical in such a case.

Nonpolar electrolytics are available in only a few standard sizes and it is often necessary to wire units in parallel to obtain the desired capacitance value. The capacitance of a parallel combination is equal to the sum of the capacitances of the individual units. The voltage rating of the combination is the same as that of the lowest-rated unit.

Unfortunately nonpolar electrolytics are not stocked by all electronics parts houses and may sometimes be difficult to obtain. Speaker builders have tried to "synthesize" a nonpolar electrolytic by wiring two DC (polarized) electrolytics in series back-to-back, but this does not work. DC electrolytics are made with a dielectric film on only one plate, and when the AC audio signal passes through them it begins to form a film on the other plate also. The second film has two bad effects. First, it reduces the capacitance to a low value, changing the crossover frequency. Second, it is very weak and is easily punctured by strong signals, causing pops, clicks, and sound level variations in the midrange or tweeter. The unsuspecting speaker builder ends up with mystifying "bugs" in his system that he can never track down.

Whether of the air core or iron core type, the coils must be made with low series resistance to avoid power losses in the coil itself and to avoid changing the effective damping factor of the amplifier. This second consideration requires lower resistances than the first, so it is the determining factor.

The amplifier damping factor is equal to the load impedance (usually 8 ohms) divided by the Thevenin equivalent source impedance of the amplifier. The latter is nearly always .5 ohm or less for transistor amplifiers, resulting in damping factors of 16 or greater. A high damping factor is desirable because it gives the amplifier "tight control" over woofer cone motion at very low frequencies. Interposing any resistance between the amplifier and woofer, either by long speaker wires or by a coil, has the same effect as higher amplifier source resistance and lower damping factor. It changes the woofer bass response and in an extreme case causes a "boomy" peak in the frequency response.

The coil resistance should be no more than a tenth of the woofer impedance in order to avoid these effects.

## POWER HANDLING CAPABILITY

The power capability of a crossover is determined by the voltage rating of the capacitors, the power rating of the inductors, and the power rating of the L-pads. Capacitor voltage rating required for a given power level is determined by the formula

$$V = \sqrt{2RP}$$

$R$ is the system impedance rating in ohms, $P$ is the power level, and $V$ is the capacitor voltage rating. Table II gives the power levels obtainable with common impedances and capacitor ratings.

While capacitors must stand off the full speaker system power, inductors and L-pads need handle only the power going to their corresponding tweeter or midrange speakers. This is only a fraction of the system power. How great a fraction of the power it is will depend on the choice of crossover frequencies and the frequency distribution of the energy in the audio signal. Table III shows the maximum power which may be expected in a midrange or tweeter section versus crossover frequency.

For midranges, use the lower crossover frequency to determine the power which the midrange inductor, L-pad, and midrange speaker must handle. For tweeters, use the upper crossover frequency to determine the power which the tweeter and its L-pad must handle.

TABLE II

Effect of capacitor voltage rating on crossover power handling capability

| Voltage Rating | Power Handling Capability 4 ohm | 8 ohm | 16 ohm |
|---|---|---|---|
| 10 V | 12 W | 6 W | 3 W |
| 25 V | 78 W | 39 W | 19 W |
| 50 V | 312 W | 156 W | 78 W |
| 100 V | 1250 W | 625 W | 312 W |

TABLE III

Frequency distribution of power in music

| Frequency | 300Hz | 600Hz | 1200Hz | 2400Hz |
|---|---|---|---|---|
| Maximum percentage of power above that frequency | 50% | 25% | 10% | 5% |

For example in a three way system with crossover frequencies of 600 and 2400 Hz, the midrange components will have to be capable of handling 25% of the system power, and the tweeter components 5% . So for a system power rating of 50 watts the midrange inductor, L-pad, and speaker must have ratings of 12.5 watts. The tweeter and its L-pad must have ratings of 2.5 watts.

The woofer and its inductor should be rated to handle the full system power, 50 watts.

Ratings for the speakers, inductors, and L-pads may be obtained from the manufacturer's specifications. Several power rating systems are in use; any may be used so long as it is used consistently. The difficulty arises when one component is specified in DC power and another in "program material" power. The problem is complicated by the fact that none of the speaker power rating methods correspond to any of the amplifier power rating methods.

The most common speaker and speaker comtem component rating method is "watts program material." It equals 2.5 times (approximately) the "watts RMS" or "watts DC." ("Watts RMS" and "watts DC" are the same in speaker ratings.) A speaker system rated at 50 watts program material may be safely used with an amplifier rated at 50 to 100 watts RMS per channel. This is possible because all those extra amplifier watts are used as reserve power to avoid clipping. A 100 watt RMS per channel amplifier playing music at full output (just on the verge of clipping the music peaks) will actually be putting out only 10 to 20 watts of average (RMS) power.

Thus a 20 watt RMS speaker system may be safely used with a 100 watt RMS amplifier to play music. For reproducing sine waves in the laboratory it's a different story. For sine waves all the ratings are the same and the amplifier running at full 100 watts capability would burn out the speaker system in a very short time.

We are discussing here the maximum power rating of a speaker system, of course. There is also the minimum power required to drive it. Here most speaker makers use the same system and specify required power in terms of minimum amplifier power in watts per channel RMS. The minimum power required is determined simply by the woofer used. Most woofers available require 20 watts or less, and a few 30 watts. Generally the heavier the speaker's magnet, the more efficient it is and the less power it requires.

MOUNTING

The most convenient method of mounting crossover networks is to glue the capacitors and inductors to a board, then fasten the board inside the speaker enclosure. A suitable glue is silicone rubber "bathtub caulk," such as General Electric type RTV-108. Do not pass metal nails or screws through the coils because currents induced in the metal will change the effective inductance values. For the same reason mount the crossover at least three inches from any other large metal mass, such as a speaker frame. A metallic enclosure should not be used to house a crossover containing air core coils unless there are generous clearances inside.

The L-pads may be mounted on the same board as the crossover, and the board mounted over a recess in the back of the speaker enclosure so that the control knobs are accessible at the back. Alternatively the L-pads may be mounted where convenient and connected to the rest of the crossover by wires.

WHICH TYPE OF CROSSOVER TO USE

This report has so far told you how to build the different kinds of crossovers, but not which kind to use. The choice of crossover design will depend on the overall design of the speaker system and also on the goals of the designer. Here are a few general suggestions for different types of speaker systems.

(1) Two way systems with cone speakers. The chief virtues of the two way system are simplicity and economy. A 6 dB crossover is usually chosen in accord with these virtues (it has the fewest parts) and the crossover frequency depends primarily on the frequency range of the tweeter. Most cone tweeters require crossing over in the span 1000 - 7000 Hz, and 1670 Hz is a popular point. The cone tweeter should have response to one octave below the crossover frequency because of the 6 dB network's gentle rolloff.

(2) Three way cone systems. Three way systems are not much more costly than two way and have considerably lower distortion. In a two way system the midrange frequencies are reproduced by the woofer and suffer distortion from the woofer cone motion caused by the lows. The "cleaner" sound obtainable from the three way setup is well worth the additional cost to most people.

Common crossover frequencies are 350 to 1000 Hz for the lower one and 3000 to 7000 Hz for the upper one. Good examples are 350, 550, or 710 Hz for the downside and 5000 Hz for the upper crossover point. The lower the woofer crosses over the better, but as you go down in frequency the cost of the midrange speaker and of the crossover network go up.

Here again the speakers should have response one octave beyond their crossover points if a 6 dB network is used. This condition is fairly easy to meet.

A very successful three-way system uses a 12" woofer, a 5" midrange, and a 3" tweeter with crossover frequencies of 710 and 5000 Hz. Such a system can be assembled in a 1.7 cubic foot walnut box for about $70.00 and will overshadow anything commercially available at up to three times the price.

(3) Four way cone systems. Here the builder is getting out on the frontiers of speaker design. Superb results can be obtained but some experimentation and adjustment may be necessary. A recommended system might consist of a 12" or 15" woofer, 5" midrange, 3½" tweeter, and 2" supertweeter. Appropriate crossover frequencies are 250 Hz, 1300 Hz, and 8000 Hz. This is the combination of Figure 7. 6 dB per octave filter sections are adequate.

(4) Two way system with cone woofer and horn tweeter. A system with one or more horn speakers is very desirable because of the superior distortion and transient response characteristics of horns. However, they are much more costly. The crossover frequency is determined by the low end capability of the horn. The crossover point is set as low as possible so that as much of the spectrum as possible will be reproduced by the horn. 500, 700, and 800 Hz are popular crossover frequencies for two-way systems. A 12 dB per octave crossover is recommended to sharply restrict the amount of energy going to the horn below the crossover point. Horns are easily overloaded by signals below their rated cutoff frequency.

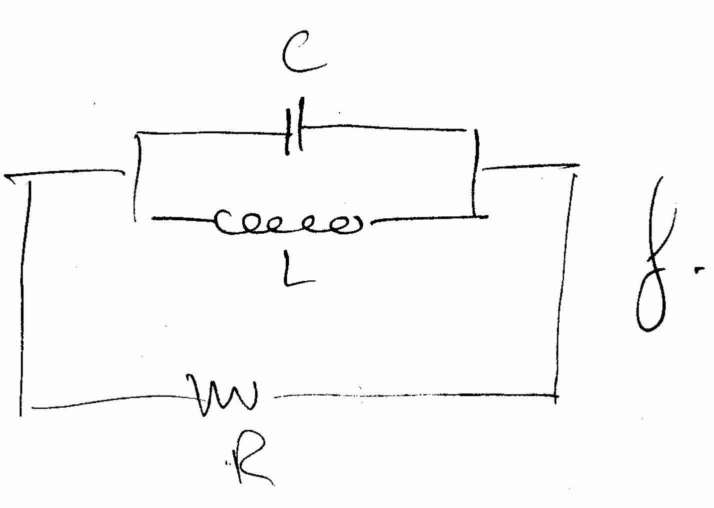
If the crossover system of Figure 3 is used with 8 ohm speakers, the part values will be 2.2 mH and 18 microfarads for an 800 Hz crossover, or 3.3 mH and 28 microfarads for a 500 Hz crossover.

(5) Cone woofer, horn midrange, horn tweeter system. This type of system is the finest possible that can be contained in a reasonable size enclosure (2 - 3 cubic feet). It can easily provide reproduction as good or better than the speaker systems used as monitors by recording studios. The lower crossover point should be about 350 Hz to have the lower midrange frequencies reproduced by the midrange horn. 5000 Hz is a good choice for the upper crossover frequency. That assigns 3½ octaves to the midrange horn and 2 octaves to the high frequency horn.

A 6 dB per octave crossover will suffice for this system if you use one of the large midrange horns available with response down to 200 Hz. The part values, for 8 ohm speakers a and the crossover network of Figure 5, will be 3.7 mH for the woofer section; .28 mH and 52 microfarads for the midrange section; and 4 microfarads for the tweeter section.

(6) Horn woofer, horn midrange, horn tweeter system. The all-horn system represents the ultimate in the present state of the art in accurate sound reproduction. Listeners to music reproduced through a good all horn system tend to compare what they hear to the original performance, rather than to renditions by other speaker systems. Unfortunately relatively few stereo fans have all horn systems because of their cost and size. The low frequency horn is necessarily large, even when constructed in folded form. Probably the majority of all horn systems in use are owner-built because of the prohibitive cost of the commercial product.

The all horn system may be built with the same crossover as recommended for system (5) above. In fact, a good way to work up to an all horn system is to build system (5), then later construct the low frequency horn and substitute it for the woofer section.



# MORE NOTES ON CROSSOVERS

by Pat Snyder

## 1. 12dB/octave crossovers.

Page 3 of the "Guide to Crossover Design" (Report No. 1) gives the formulas for inductance (L) and capacitance (C) for 6dB/octave crossover sections. There are some formulas that may be used to 12dB/octave sections as shown in Figure 3 of the Guide. The formulas are:

$$L = \frac{R}{\sqrt{2}\,\pi f}$$

$$C = \frac{1}{2\sqrt{2}\,\pi f R}$$

These formulas hold good for both highpass and lowpass sections. The formulas are similar to those for 6dB/octave sections except that inductance is 1.414 times the 6dB/octave value and capacitance is 0.707 times the 6dB/octave value.

## 2. Midrange sections.

Highpass and lowpass 12dB/octave sections may be cascaded (the output of one feeding the input of the next) to give a 12dB/octave midrange section with no difficulty. Use the formulas above to calculate the parts values. However, for midrange sections in 6dB/octave systems (similar to that shown in Figure 5 in the "Guide") a special formula is necessary. The midrange inductor and capacitor interact and shift the crossover frequencies so that the simple formulas on page 3 of the "Guide" may not be used to calculate their values.

The correct formulas are:

$$L = \frac{R}{2\pi (f_H - f_L)}$$

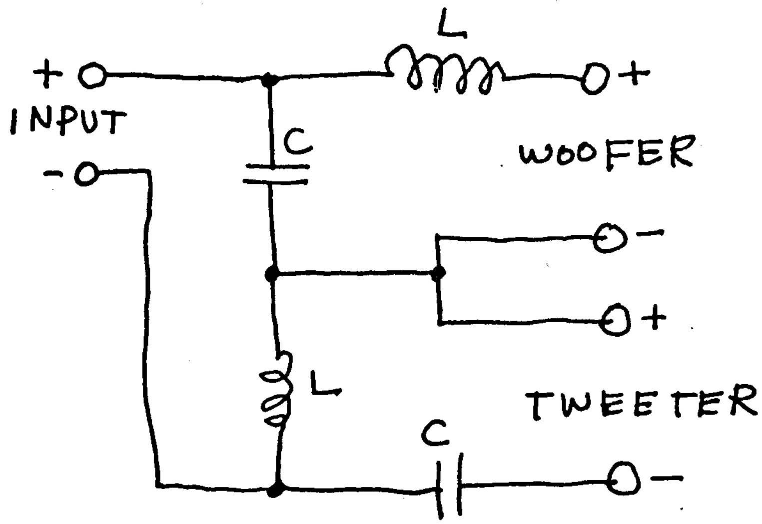
$$C = \frac{1}{2\pi R}\left(\frac{1}{f_L} - \frac{1}{f_H}\right)$$

where $f_H$ = higher crossover frequency

$f_L$ = lower crossover frequency

## 3. Series-connected crossover networks.

Like every other aspect of stereo, the series-connected crossover has its own band of devoted followers. I am not one of them, but for those interested here is the most popular series configuration. Note that compared to the parallel-wired network, the inductances are cut in half and the capacitances are doubled.

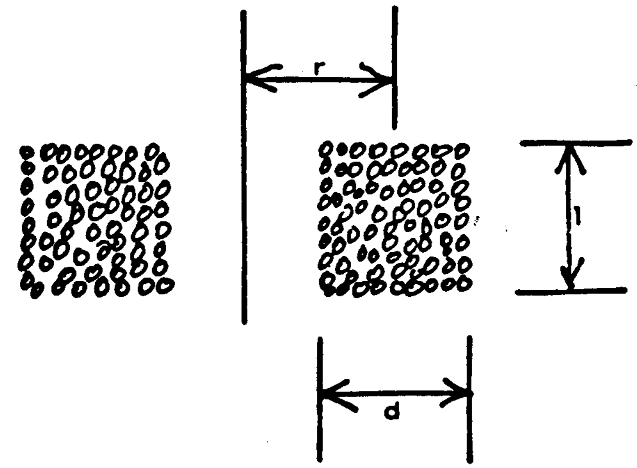



$$L = \frac{R}{2\sqrt{2}\,\pi f} \qquad C = \frac{1}{\sqrt{2}\,\pi f R}$$

4. <u>Coil winding formula</u>.

A popular formula for air-core coils gives

$$L = \frac{.0008\ r N^2}{6r + 9l + 10d}$$




**Cross-Section of Coil**

where L = inductance in millihenries (mH),
N = number of turns,
r = mean radius in inches,
l = length of coil in inches,
d = depth of coil in inches.

Our experience is that the formula is only approximate, giving inductances within about 30% of the desired value. We use an inductance bridge (ESI model 250DA) to determine the exact number of turns necessary to get a desired inductance value. This is the tough part - getting the right values. The number of turns of wire required changes with different batches of wire and different winders; variations in thickness of insulation and winding technique (wire tension, layer compactness) change the outer diameter of the coil, which affects the inductance.

We have found that coils of about the shape shown (with r = l = d) give the most inductance for the least resistance and least weight of wire.

5. Coil winding jig.

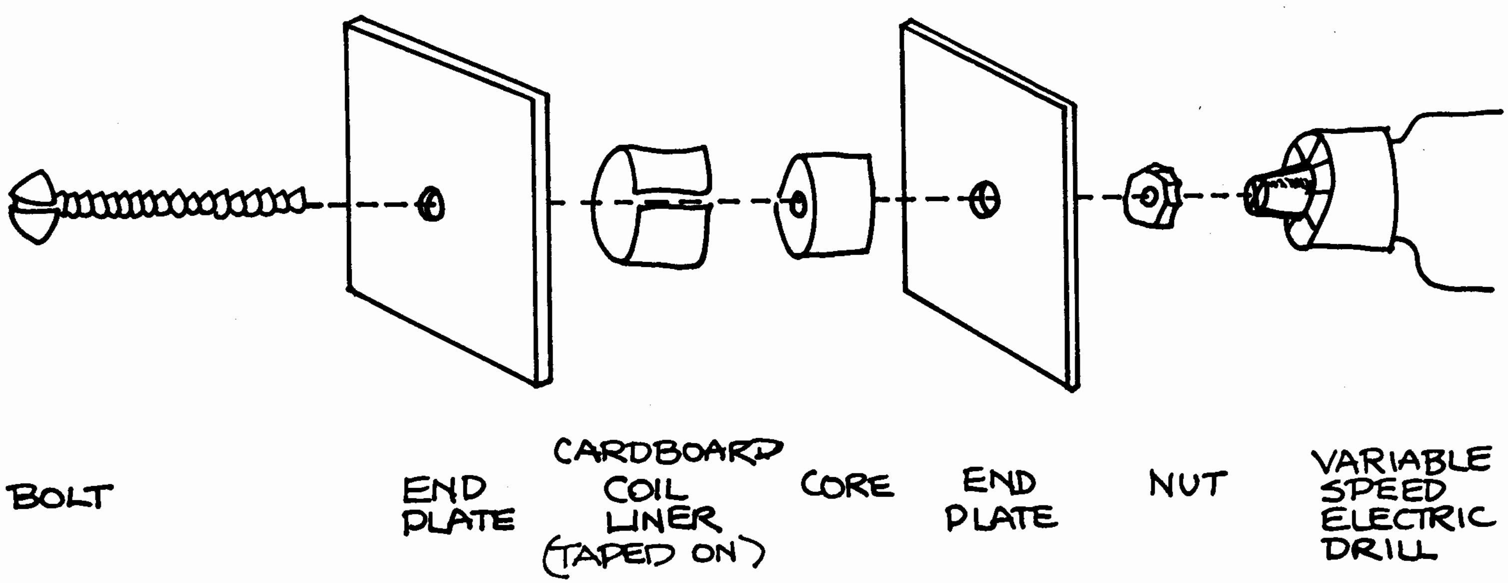
Make the core out of broomstick or dowel about 1" long by 1" diameter. Bolt is ¼" by 3" or so. End plates are masonite or ¼" plywood. Wrap a cardboard coil liner around the core and hold it with PVC electrical tape before winding the coil. The liner enables you to get the coil off the core after winding. Put a paint spot on one side of the winding jig and go slowly so you can count the turns. Hold the coil together with electrical tape after winding. You can reuse the coil form as many times as you like since it is not left trapped in the coil after winding (except the cardboard coil liner becomes a permanent part of the coil). Use silicone rubber glue to mount the coil.

6. Winding your own coils.

Wind your own coils out of magnet wire -- copper wire which has a thin lacquer or nylon insulation. Magnet wire is available at electronic hobby stores and electronics distributors.

7. Coil series resistance.

The other important consideration for a coil, besides finding the correct inductance, is to keep



the coil's internal series resistance small to prevent significant power losses in the coil itself. We stick to a guideline that the coil DC resistance should be less than one-tenth the speaker's impedance. This insures an insertion loss of less than 1 decibel. The resistance is determined by the length of wire you use and its gauge (thickness). For air -core coils under 1mH you can safely use gauge 19, and probably get away with wire as small as gauge 22 (larger gauges correspond to smaller wire thicknesses). To keep the resistance low for coils with much more wire, that is, with many more turns, will require wire of greater thickness (smaller gauge). The largest wire we use is 15 gauge, for a 5.0 mH coil.



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