A case for extreme-slope crossover networks

By

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TIME ALIGNMENT OF DRIVERS

It is considered common knowledge that all of the drivers in a two or three way loudspeaker should be time-aligned such that the sound generated by each driver reaches your ears at the same time. It is also considered common knowledge that crossover networks should not contain filters that have slopes greater than 12 or 18 dB / Octave or phase errors will cause time delay distortion. I hope to present evidence here that will show that this is not really true.

Loudspeakers that use direct radiator drivers having small displacements can be time-aligned at some point in space at a given frequency, but little can be done to time-align the drivers in a loudspeaker using horn-loading where each driver will have drastically different path lengths. In the case of the Belle Klipsch, used here as the subject of study, even the woofer is horn-loaded making the path length differences between drivers several feet.

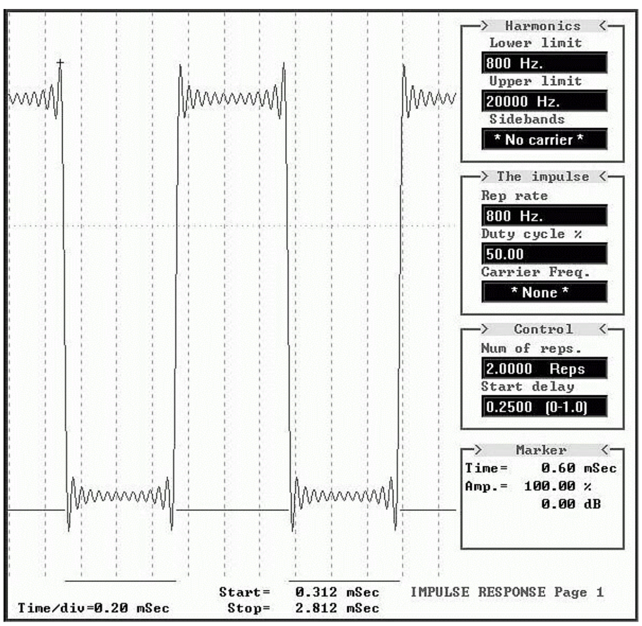


Figure 1

The first factor to consider is how important it is that all of the frequency components of a waveform arrive at your ears at exactly the same time. It is known that any complex waveform can be analyzed in terms of the phase and amplitude of many individual sine wave harmonics summed algebraically. The term used for this is Fourier analysis. A perfect square wave, for example, can be constructed from a fundamental sine wave and all of its odd order harmonics in decreasing amplitude. Figure 1 shows how a computer program constructs an 800 Hz square wave with the harmonics limited to no higher than 20 KHz. Note that the square wave shows ringing on both the top and bottom. This is with no filter or loudspeaker at all in the analysis.

Consider figure 2, which is a single driver, in this case, a JBL 2426h mounted on an Altec 811b "Voice of the theater" horn generating an 800 Hz square wave. The driver is connected directly to a McIntosh Mc50 power amplifier with no crossover or other filters of any kind between them. Figure 3 shows the same situation with the microphone moved to a slightly different position in the room.

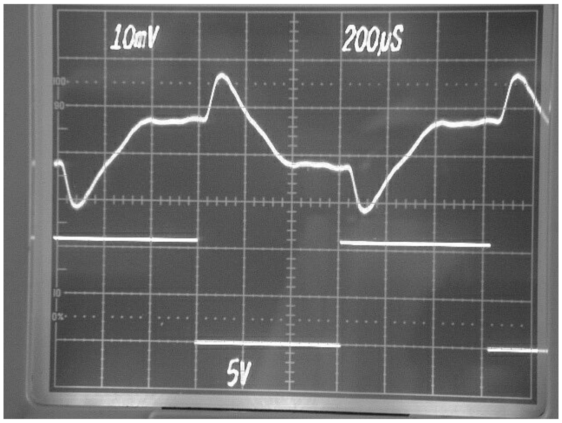


Figure 2

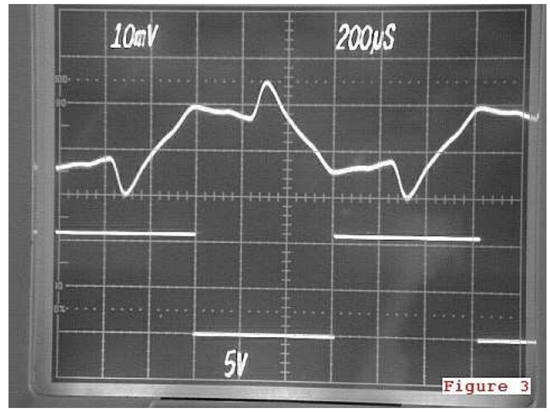


Figure 3

This driver and horn are considered to be a "wide-range" combination and will reproduce the harmonics of the 800 Hz square wave to at least 10 KHz. Clearly the acoustic waveform is a far cry from what we would like a square wave to look like. Clearly then, the harmonics of the square wave are not reaching the microphone in the correct alignment to create the square wave. This leads one to conclude that maybe precise phase and time-alignment in any loudspeaker is more of a dream than a reality. This is further demonstrated by the fact that simply moving the microphone results in yet a different waveform.

TONE BURSTS AND DRIVER INTERFERENCE

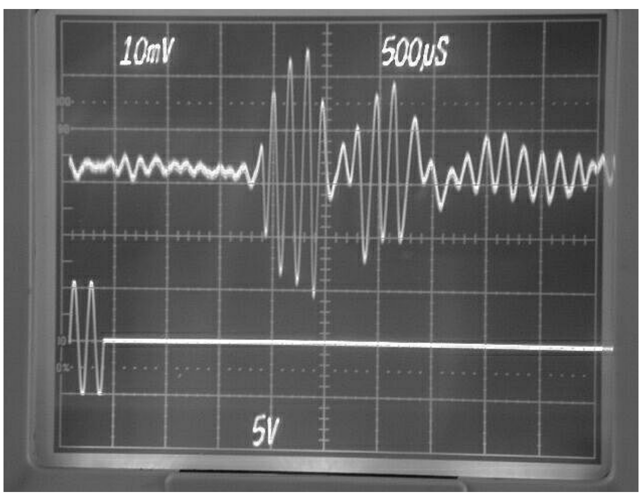


Figure 4

If two drivers mounted at two different distances form your ear, or in this case, a microphone, are given short burst of sound having a duration less than the propagation time difference between them, two distinct bursts will be seen. Figure 4 shows a 6 KHz burst being reproduced by the Altec / JBL combination shown earlier generating the 800 Hz square wave and a Beyma CP25 tweeter. The crossover network being used is a conventional 12 dB / Octave filter set (2nd order Butterworth) with a crossover at 7500 Hz. Two individual bursts can be seen. The first burst in time is from the tweeter, which is closer to the microphone.

It is debatable if the human ear can perceive the difference between this situation and a single burst, but if it could, I would think the effect would be that of a “smearing” phenomenon. In this case, the two drivers are not producing sound at the same time so there is no interaction between them.

If the duration of the tone burst is increased such that it is longer than the propagation time difference between the two drivers, the two bursts will overlap. Both resulting bursts can then interact with each other causing the sound from the two to acoustically add together. The phase and amplitude of these two sounds become random at different places in the room. This causes the sum to be different at different locations in the room as well. Figure 5 and 6 show this situation with the microphone position chosen to show a summation in one spot in front of the speaker and a near total cancellation in another spot. The burst is 5 KHz.

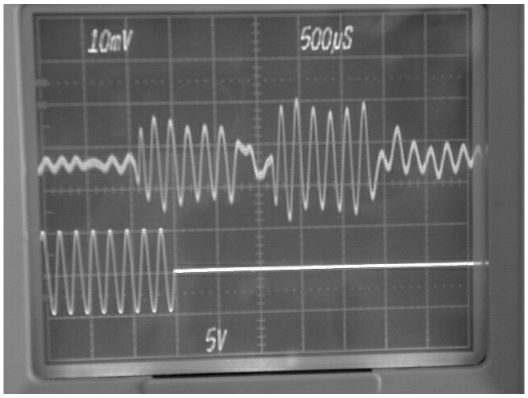


Figure 5

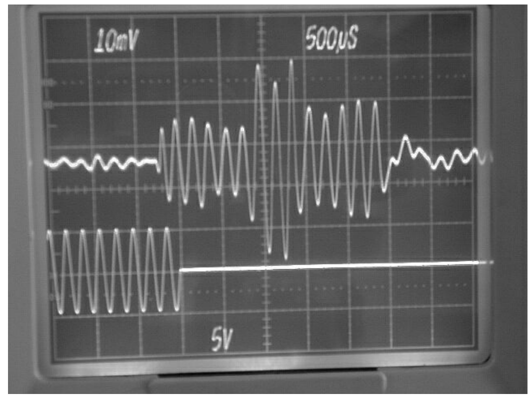


Figure 6

A PROPOSED SOLUTION

With a horn-loaded speaker, It is not aesthetically pleasing to mount a tweeter such that its driver is the same distance from your ear as the midrange driver. A midrange driver mounted on a horn could be a foot or more behind the tweeter. Furthermore, it is virtually impossible to do this when the woofer is also horn-loaded. The woofer driver would need to be placed in a tunnel cut in the listening room wall! Clearly this is not a practical solution. In truth, even direct radiators can only be time aligned at one point in space in front of the speaker. Sounds produced by separate drivers will go out of time alignment as soon as a listener moves off axis in either the vertical or horizontal plane. A more reasonable solution would be to somehow see to it that only a single driver will generate each harmonic component of the total waveform being reproduced. This can be done by limiting each driver to only a precise range of frequencies with virtually no overlap at all using a crossover network having extremely rapid stopband frequency slopes. The only overlap would then be within a narrow segment at the crossover frequency. Two such networks have been developed for the Belle loudspeaker having stopband slopes on the order of 120 dB / octave extending down to approximately 25 dB. This was assumed to be adequate to remove any tendency for adjacent drivers to interact. These networks, though designed for the Belle are applicable to any loudspeaker no matter if it uses direct radiators or horn drivers. The squawker / tweeter network is particularly general in nature and useful for application in other speakers. The woofer / squawker network is somewhat more specific to the Belle as will be explained later.

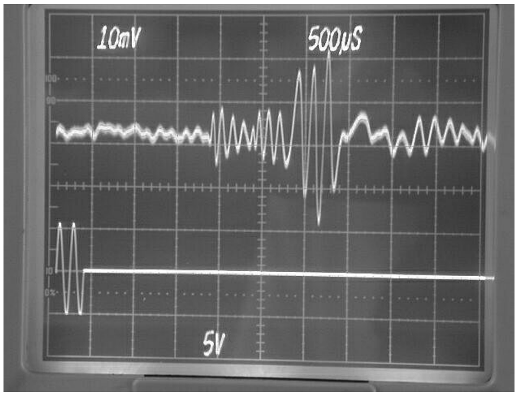


Figure 7

Figure 7 shows the same 6 KHz tone burst as figure 4 but using the 7500 Hz extreme-slope squawker / tweeter network to be described. Note that the first burst, the one from the tweeter, is greatly reduced and that virtually no additional ringing is introduced by the network despite that the burst is very close to the filter stopband "notch" frequency. The earlier experiments with a single driver demonstrate that possible ringing is probably not important anyway!

TOTAL DELAY

It would seem logical that there must be limits to how far components of a waveform can be out of time-alignment before the listener begins to find it noticeable. It is also questionable how this would be perceived by the listener other than hearing two separate clicks from the steps of a tap dancer, for example, in an extreme case. The total delay of the driver path differences plus the delay added by the crossover networks must be below this limit. Research done by Blaeurt & P. Laws [1] on tolerable “Group delay” indicated that these limits vary with frequency. The most sensitive frequency range seems to be around 2000 Hz where the limit was found to be slightly less than 1 millisecond. Above and below there, the limit becomes less stringent. The limit at 700 Hz, where I have chosen to cross over from woofer to tweeter, appears to be about 2.7 mSec. To complicate this issue, there is a question relating "group delay" in filters with acoustic "time delay". The two are NOT the same thing and I doubt if they can be directly added together!

The group delay in a filter, which is defined as the rate of change in phase with a change in frequency, comes to a peak just as the skirt attenuation begins. This puts the maximum group delay error contributed by the crossover network, which I will assume to at least be proportional to true time delay, right at the crossover frequency. This would seem to provide a means to partially control the delay at the frequency where both drivers are sounding. The lower the frequency and the sharper the skirts of a filter, the more group delay it has.

The crossover frequencies for the drivers used to modify my Belle speakers were chosen to be 700 Hz and 7500 Hz. The frequency response of the Belle woofer was found to extend solidly up to 700 Hz. The Altec 811b horn and JBL driver I am using are specified to be operated no lower than 800 Hz. The actual specifications for the JBL 2426h driver recommends a crossover at 800 Hz with a slope of 12 dB / octave or greater. It also states that it may be used down to 500 Hz at reduced power; the reason being that low frequency energy coming through the crossover network will cause damage due to excessive diaphragm motion. At extremely low frequency, the diaphragm motion can become large enough to cause it to actually hit the phasing plug. The extreme-slope crossover described here limits any energy below 650 Hz to at least 25 dB below the level applied above 700 Hz. This allows the driver to be operated to full power below the 800 Hz limit. The Altec 811b horn throat matches this driver perfectly and has no problem reaching down to 700 Hz. Impedance measurement on the driver mounted to the horn indicated good loading by the horn to even lower frequency. The attenuation plot of the 700 Hz extreme-slope crossover is shown in figure 8.

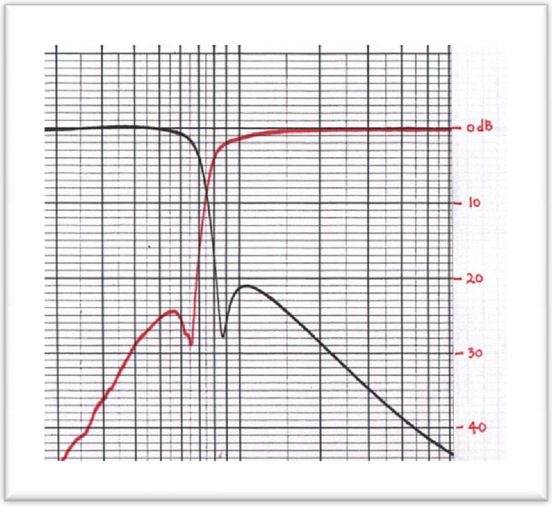


Figure 8

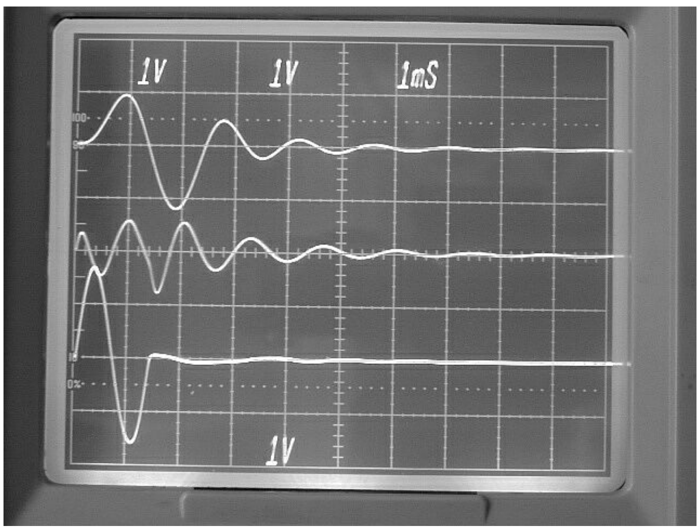


Figure 9

The 700 Hz crossover was designed to have higher group delay in the highpass (squawker) channel than it does in the lowpass (woofer) channel. This is because of the higher ultimate rejection of the squawker filter. Computer analysis shows approximately 2.5 mSec group delay in this filter as compared to 2.0 mSec in the woofer filter. The difference is about .5 mSec which would correspond to about 7 inches of difference in delay time if the two types of delay were the same, but they are NOT! Figure 9 shows simultaneously the response of both network outputs to a single cycle input burst of 700 Hz. The top trace is the woofer channel. The middle trace is the response of the high frequency channel. The bottom trace shows the input burst. All three traces are chopped and triggered externally from the gate pulse that is triggering the input burst. It is quite obvious that the time delays do not approach the computed 2 mSec group delay numbers however. If I were to do the design of this network now, I would make the high and low filters symmetrical like the 7500 Hz network. I do not believe that it is possible to correct for propagation path length differences between drivers using crossover network group delay differences.

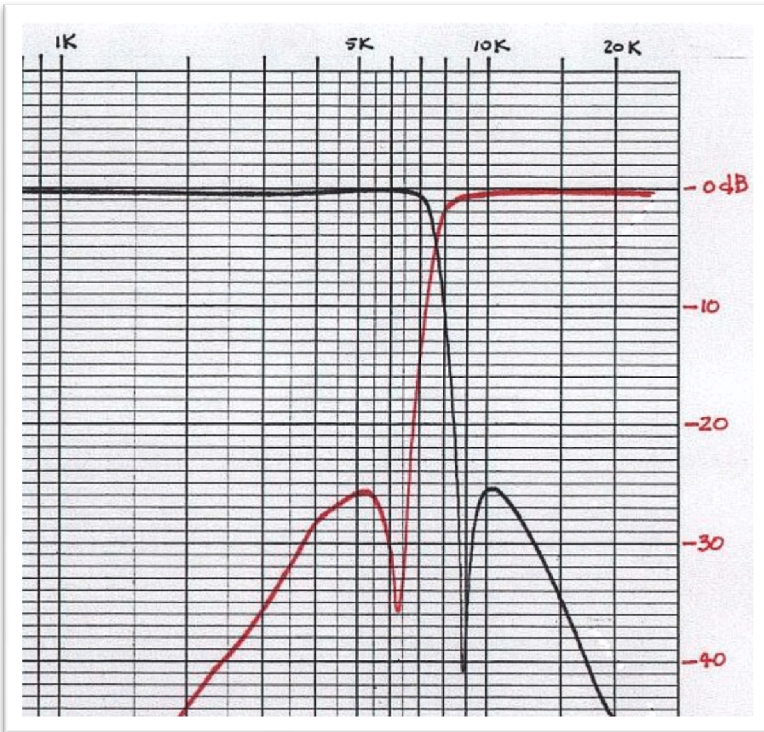


Figure 10

7500 Hz was chosen for the squawker / tweeter crossover because published curves seem to show that the Altec horn begins to lose its wide dispersion above that frequency. The plot of the 7500 Hz squawker / tweeter crossover in figure 10 shows equal ultimate rejection between the two channels. The two filters are simply the inverse of each other and also have equal group delay peaks of about .28 mSec. at the crossover frequency

RINGING IN THE FILTERS

Ringing, as shown by the computer-drawn Fourier analysis of the 800 Hz square wave in Fig 1, can be simply a function of how many individual frequency elements of a waveform are summed and not solely a filtering phenomenon. A filter with a sharp skirt does have a tendency to cause unequal group delay within its passband causing some distortion. The acoustic output of a wide-range driver alone, when reproducing a square wave, should be the ultimate situation. A single sound source with no filters to distort the waveform fed with a virtually perfect square wave still produces a waveform that is anything but square! The addition of a filter, even one with such a sharp skirt, might make things worse but its contribution to the problem is insignificant by comparison.

Fourier analysis was done using computer models comparing the 7500 Hz extreme-slope crossover and the 2nd order Butterworth version. The findings seem to indicate that so long as no harmonic or the fundamental of a square wave or impulse falls directly on the group delay peak at 7500 Hz, there is little difference in their performance. Experiments using signal generators and an oscilloscope on the networks alone verified the computer models. The 700 Hz woofer / squawker crossover has similar group delay peaks in each filter at the crossover and could potentially cause problems considering the harmonics of 700 Hz are clearly audible. To test this, a signal generator was used to slowly sweep both square waves and narrow pulses over the 700 Hz crossover frequency and up. The nature of the sound was noted carefully by ear. No difference was noted no matter what frequency was used. The frequency was also swept around the 7500 Hz crossover. At this frequency, the second harmonic is so high that I was unable to even hear the difference between a sine wave and a square wave. The narrow pulse was used in an effort to excite ringing. Here, the harmonics are so high that the pulses sound the same as sine waves, but not as loud. Only the second harmonic of 7500 Hz at 15 KHz is within the audible range. A considerable amount of research by others seems to show that a change in phase and amplitude of any single frequency within the range of the tweeter is not a factor [3]. You simply can't hear it!

Figures 11 and 12 show the acoustic 800 Hz square wave output of the complete speaker using the 7500 Hz extreme-slope crossover and the 7500 Hz 2nd order crossover, respectively. Aside from the loudness being set slightly higher on one, there is little difference between them.

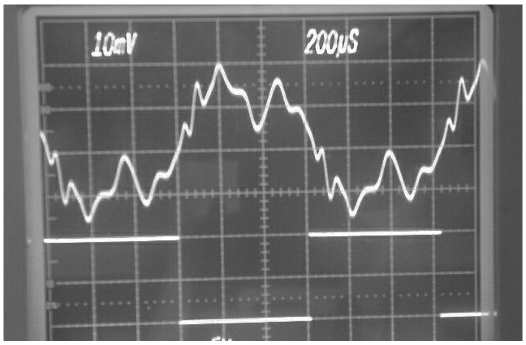


Figure 11

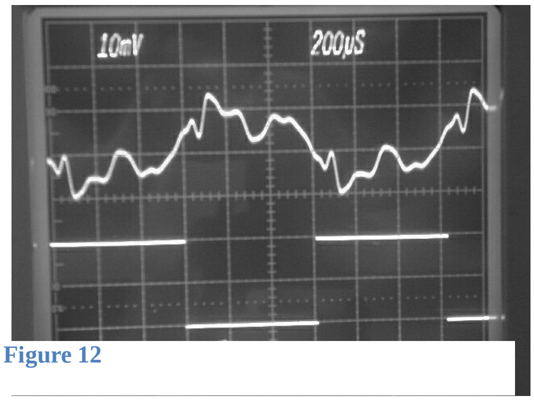


Figure 12

Sibilance on female voices is often blamed on ringing filters. Listening tests comparing sibilance heard through the loudspeaker and through good quality stereo headphones (Grado SR225) showed virtually no difference. Headphones also use a single driver and no filters making them a good reference for comparison. Sibilance is a real thing and is often recorded on CDs. I do not believe that it is generated by the crossover network filters.

It is my conclusion that the distortion caused by the sharp slope filters is insignificant compared to the benefits created by eliminating the interaction of adjacent drivers and the lobeing that it produces in the dispersion. Tests using background hiss from an FM tuner set between stations, (Muting off) or pink noise from a test CD demonstrate a smoother distribution of the sound over the listening area using the extreme-slope crossovers than when using the usual gentle slope networks. If there is a major disadvantage to the extreme-slope crossover it is in its complexity and expense. As with all filters, high quality parts need to be used in their construction. It is even more critical to use quality parts with such sharp filters. Component losses tend to show up most prominently at the passband corners. In this case, that would be at the crossover frequency where adjacent drivers must sum their outputs. Low quality parts will cause a dip in the response at that point.

MODIFYING THE BELLE

The Belle is one of the best loudspeakers available for home use and one of the few that utilize horn loading of drivers over the entire spectrum. With some help from a subwoofer below about 70 Hz, the woofer is hard to beat. The high end is probably its weakest area. The squawker horn, having rather poor dispersion, was the first candidate for upgrade. Altec "Voice of the Theater" 811 horns have an excellent reputation, so a used set was purchased to replace the Klipsch K501 horn. They have far better dispersion and sound a lot better than the K501. The Klipsch K55V driver was replaced with a wide range JBL 2426h driver in hopes of making the speaker two-way. The 700 Hz extreme-slope crossover was designed and built first for use in the two-way configuration. This turned out to be unsatisfactory due to poor high frequency performance. The combination sounded very dull. A three-way system is definitely required.

The tweeter used by Klipsch (K77M) is the old venerable ElectroVoice T-35 which seems to have been around since George Washington was camping out at Valley Forge! I used it for a long time with the 7500 Hz extreme-slope crossover with very good results. It was replaced later with a Beyma CP25. The Beyma tweeter, with its aluminum voice coil and bi-radial horn, will go higher than the T-35 and has better dispersion. It also seems to have higher sensitivity and may need to be attenuated by an "L" pad.

The Altec horn is taller than the Klipsch K501 horn and would not fit under the beautiful woodwork top section of the Belle. I did not want to damage any of the original parts of the speaker in any way, so a raiser was constructed to raise the top section by exactly 3/4 of an inch. This also provided a cross-member on which to attach the bottom of the Altec 811b horn mounting flange. The 4 screws holding the top section were replaced by longer ones to extend through the new raiser and the top cover mounting strips. The details are shown in figure 13.

Figure 13

Figure 14

The top mounting flange of the horn was attached to another cross- member through a 1/2 inch spacer. The cross-member was simply wedged between the top section baffle mounting strips and the board attached by Klipsch under the top to stiffen it. No screws were used to hold it in place. Only shims were necessary. The original Klipsch tweeter was mounted, vertically on its own panel, to the right of the Altec horn in the same way until it was eventually replaced by the Beyma CP25. See fig 14.

Figure 15

Figure 15 shows the Beyma CP25 tweeter mounted in the grill cloth frame constructed to replace the original front horn mounting board. The frame is fastened to the front of the Belle top section using the original mounting strip holes and screws. The Beyma tweeter horn is too large to be mounted on the same cross-members as the Altec horn.

Figure 16

The finished assembly, before the grill cloth was put on, is shown in figure 16.

THE DESIGN OF THE NETWORKS

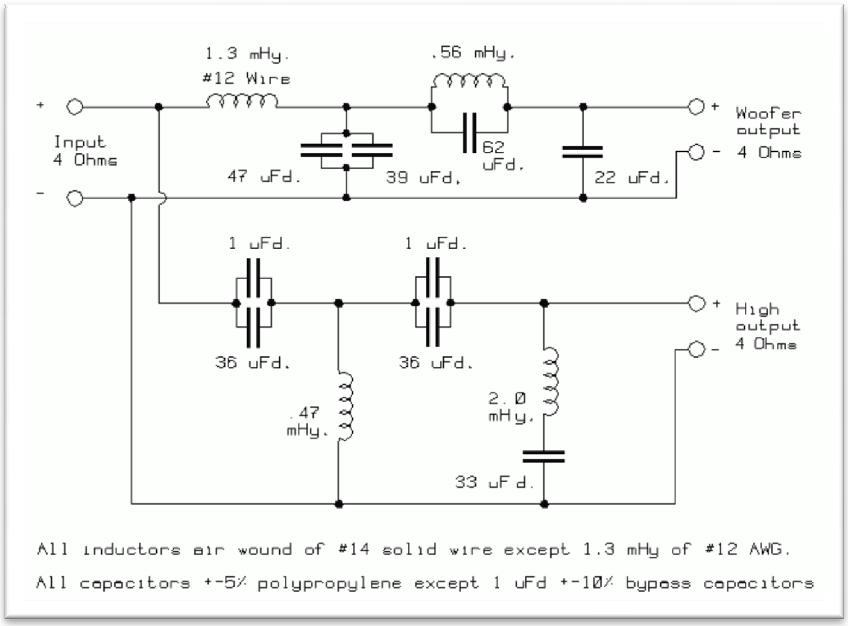
These networks should be considered to be in a different class than most crossover networks used in loudspeakers. These designs utilize microwave filter syntheses techniques and are really "diplexers" having a flat resistive input impedance over their entire frequency range, including the crossover area. They are NOT simply "elliptic function" filters. The filters are singly terminated filters synthesized using a professional filter design package [2]. This technique allowed the total elimination of one element by the careful choice of passband ripple. The lowpass and highpass sections must not be separated or grafted onto other filters. The parts used to construct them must have close tolerances and low loss. Mutual coupling between inductors must also be avoided.

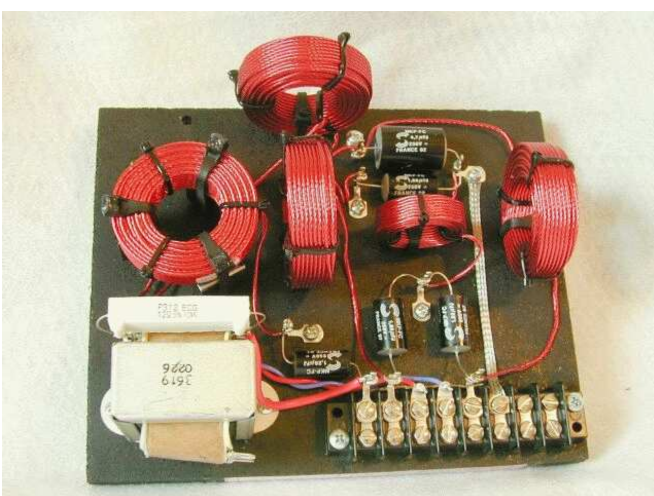
700 Hz crossover

THE WOOFER / SQUAWKER NETWORK

The extreme-slope network designed to crossover from the woofer to the squawker is a 4 ohm design to match the 4 Ohm woofer in the Belle. Both the low and high frequency channels must see resistive 4 ohm loads. When both output ports are terminated in 4 Ohm resistive loads, the load impedance seen by the amplifier is an extremely stable resistive 4 Ohms over the audio spectrum including at the 700 Hz crossover.

At 700 Hz, virtually all of the losses associated with the inductors are a function of the DC resistance in the wire. AWG #14 solid wire was used throughout except for the 1.3 mHy inductor directly in series with the woofer. It was wound of AWG #12. All the inductors are air-core and fastened to the board using plastic cable ties. Inductors having laminated iron or ferrite cores were not used because they tend to change inductance with signal level degrading performance. This is the low level beginning of classic core saturation. It is usually ignored. All capacitors were Solen metalized polypropylene "Fast" capacitors. These capacitors have far less loss than the paper in oil capacitors often used in crossover networks. Paper in oil capacitors are unacceptable for a filter having such rapid attenuation slopes. Their value tolerance is also usually inadequate. The series connected capacitors in the high frequency channels were further bypassed with 1 uFd Harmony brand "bypass" capacitors to ensure an extremely low loss path all the way to 20 KHz and beyond. The part values for a 700 Hz crossover are shown on the schematic diagram.





7500 Hz Crossover

THE SQUAWKER / TWEETER NETWORK

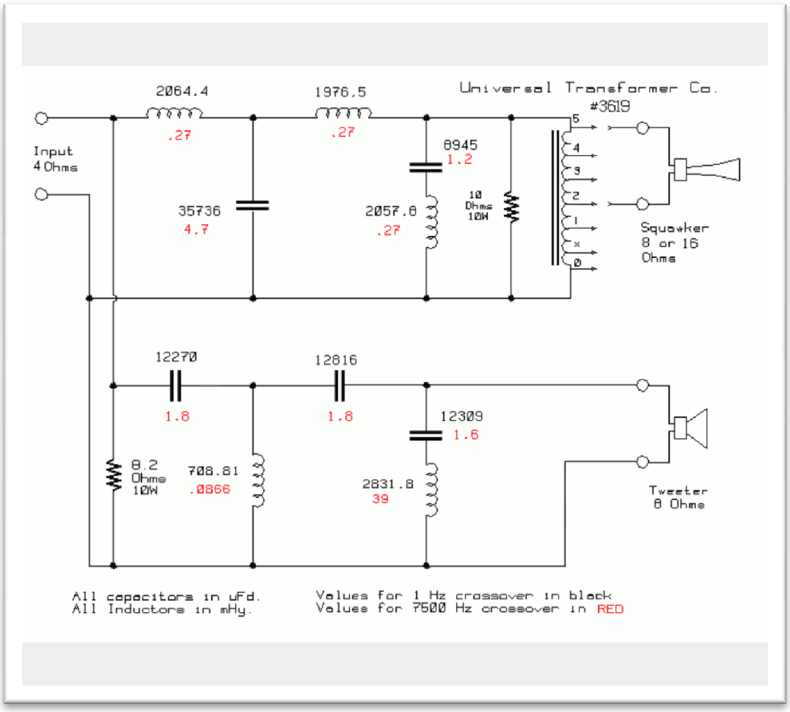
The network designed to transition between the squawker and tweeter is an 8 Ohm design to accommodate the 8 ohm tweeter. It is a design less specific to the Belle loudspeaker and suitable for use in other speakers. To provide the correct 4 ohm load to the 700 Hz network that is feeding it, an 8.2 ohm resistor was connected across the input. This does not create any loss in speaker efficiency but rather just draws more current from the amp at a lower voltage level. This is what constitutes the lower impedance. The efficiency of the entire speaker is set by the woofer efficiency. The squawker sensitivity is attenuated with an autotransformer, or autoformer as it is often called, in keeping with the Klipsch tradition. This is with good reason. An autoformer reduces the level without divorcing the amplifier's damping factor from the driver as a resistor pad would do. The difference is quite audible [4]. I believe this is because it transforms the back EMF generated by the driver up creating even tighter control by the amp than even a direct connection would provide. The autoformer used here is a special design having tighter coupling and heavier wire than the ones used by Klipsch. It also provides an additional tap and greater core area. The squawker driver can be connected between any two of these taps, not just from one tap to common (tap 0) which provides only 3 dB steps. A large number of possible intermediate settings can be made. Either 8 or 16 ohm drivers can be used without any modification to the network. A table of voltage (turns) ratio settings and approximate attenuations are given below.

Turns ratio	Between taps	Approximate attenuation
.825	5 - x	2.6 dB
.775	5 - 1	3.4
.710	4 - 0	3.8
.645	5 - 2	4.6
.535	4 - x	6.2
.500	3 - 0	6.7
.460	4 - 1	7.4
.355	2 - 0	9.5
.320	3 - x	10.4
.245	1 - 0	12.5

An autoformer, while performing its attenuation function, transforms the impedance of the driver up by the square of its turns ratio. This is the impedance that would be seen by the network squawker filter. To bring this impedance back down to the necessary 8 Ohms to properly terminate the squawker channel of the crossover, a 10 Ohm 10W swamping resistor is connected across the autoformer. As it happens, 10 Ohms works well for both 8 and 16 Ohm drivers as most have similar efficiency and therefore transform back to the same impedance. The loss in this resistor can simply be considered as absorbing the extra power that is not needed by the driver. The 10 Ohm value ensures a load mismatch of no worse than 1.25:1 (10:8) to the filter no matter how low the squawker level is set. At normal settings of about 6 dB, the impedance match is much better.

In this network, frequency is high enough that losses other than those caused by DC resistance in the wire alone creep into the inductors. The use of "Litz" wire, which is made from many strands if fine wire insulated from each other, yields about a 3:1 reduction in loss over solid wire. All the inductors are of AWG #14 Litz except the small .086 mHy inductor which is a .10 mHy of #16 Litz wire. All of the turns on the outer layer except one were removed to get down to the needed value.

The most important consideration by far in the construction of this network is the position of the three large inductors near the autoformer. Coupling between them totally destroyed the response in an early prototype. Most literature describing how to mount inductors for minimum coupling show them sitting at right angles to each other. This is not enough! What is not normally mentioned is that they MUST also be mounted precisely on center with each other. They can NOT both be mounted on the same surface if the absolute minimum coupling is needed. This is why the .27 mHy inductor associated with the squawker filter "trap" is sitting atop three spacers. It is also why the other .27 mHy and the .39 mHy inductors are positioned as they are. I cannot stress this point enough! Capacitors in this network are also polypropylene "Fast" capacitors.



The schematic diagram for the 7500 Hz network shows two sets of values for each part. One set is given for the 7500 Hz crossover that I describe here. The other values are the precise calculated values for a crossover frequency of 1 Hz and 8 Ohms. To design a network at a different frequency the following formula can be applied:

V2 = V / F

Where:

V2 is the final value in uFd or mHy.

V is the value specified on the schematic for that component.

F is the frequency of the desired crossover (in Hz).

For the 7500 Hz example, the first shunt capacitor in the lowpass squawker channel (the one closest to the input) would be:

35736 / 7500 = 4.76 uFd.

The first shunt inductor in the tweeter section would be:

708.81 / 7500 = .0945 mHy.

The calculated values in the 7500 network described here were carefully rounded off, one at a time, to those actually used by computer analysis while observing the cumulative effect. Without this tool, every effort should be made to keep each component as close to the calculated value as possible. The error should be kept well below +-5% for each component and hopefully to no more than +-2%.

To scale the design to a different impedance:

C = V * (8 / Z)

L = V / (8 / Z)

Where Z is the desired impedance.

LEVEL SETTINGS AND OTHER VARIATIONS

The proper phasing of the squawker drivers need to be determined by trial. With the squawker connected one way, a dip of about 6 dB appeared in the frequency response at the 700 Hz transition. This was easily fixed by reversing the squawker connections the other way. The polarity of the tweeter does not seem to make a difference. This is probably because the delay difference between the squawker and tweeter is several wavelengths.


Figure 17

The two networks were constructed on two separate boards because of their size. The JBL driver takes up so much room inside the Belle that one needed to be mounted on each side of the driver. Figure 17.

The squawker autoformer settings were adjusted using instruments but the listener's ear and your listening room will dictate the final settings. These will also depend on what drivers are used and if equalization is to be employed. With the squawker and tweeter drivers described, the autoformers were set between taps 0 and 3 with the tweeter running wide open. These are high level settings because two parametric equalizers are being used to flatten the response. Without the equalizers, the squawker would be better operating at a lower level, such as between taps 0 and 2. The Beyma tweeter should also be provided with an adjustable "L" pad to bring its sensitivity in line with the Belle woofer. The original K77 (T-35) tweeter sounded best running wide open.

The load impedance provided by the Belle woofer horn was measured with a vector impedance meter. The impedance was found to rise from 4 Ohms to about 5.7 +jX 4 Ohms at 700 Hz. This can be compensated for by a "Zobel" network consisting of a 5.6 ohm resistor in series with about 80 uFd connected across the woofer driver. This resulted in a very nice resistive 4 Ohms across its useful range. Experiments seemed to show no difference in the performance with the Zobel connected. I plan to experiment with it more at a later date but conclude that it is not necessary.

The original Belle horns and drivers could still be used with these networks if the high crossover network frequency is changed. The woofer / squawker transition can remain at 700 Hz considering the "AB" network used in the Belle by Klipsch for a while crossed the two even higher by natural horn rolloff. The K55 squawker driver will not reach up to 7500 Hz requiring that the squawker / tweeter crossover network be scaled down in frequency to no higher than 6000 Hz. Both the Beyma and the K77 (T-35) will reach below 6000 Hz. If a lower crossover frequency is considered, power handling capacity could become a factor. The Beyma CP25 will handle much more power than the original tweeter.

MORE ABOUT GROUP DELAY AND TIME DELAY

There seems to be widespread confusion cornering "time delay" and "group delay". Time delay is typically the time it takes for a sound to propagate through the air from a source to your ears. Sound travels at a constant rate making time delay quite predictable and understandable. Group delay, on the other hand, is really just a means to specify phase linearity. It is the rate of change of phase with frequency at some specific frequency. That is, group delay is the derivative of phase. The two types of delay are quite different and can NOT be treated as equal and can NOT simply be added together as if they were. It is very frustrating to read technical papers where the authors do not make a clear distinction between them. The Blaeurt & Laws paper [1] cited here, and by many other writers, is clearly referring to "group delay", not "time delay". A paper done by Paul Klipsch [5] is primarily concerned with time delay but mentions group delay so casually as to leave the reader thinking they are equal. The main conclusion in both cases seems to be that neither type of distortion is offensive to the ear. In the case of group delay, the Blaeurt & Laws article finds that it can be heard only through headphones, using narrow pulses and by listeners "trained" to know what to listen for. As concluded by Daniel Shanefield [6] of Western Electric Co., it appears that it is not important at all when reproducing music.

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I would also like to acknowledge the many contributors to the Klipsch web site forums (www.klipsch.com) for the vast spectrum of ideas that are discussed and to the Klipsch management for their tolerance of all of it with no interference!

UPDATE

The crossover networks described here are still in use but the woofer / squawker network has been totally redesigned to utilize the voice coil inductance of the K33 woofer driver without the use of a Zobel network to bring the impedance to a resistive 4 Ohms. The true impedance of the K33 is about 6 Ohms in series with 1 mHy inductance. The new design is designated ES700 and is available from ALK Engineering.

The squawker / tweeter network is extremely critical with respect to placement of the inductors and is **NOT** recommended as a do-it-yourself project. This network is also available from ALK engineering as the ES7500.

More experiments have been done using separate CW signals generators mixed together at the proper frequencies and levels to simulate a square wave having continuously changing phase relationships of the harmonics. This writer was unable to hear any changes in the character of the resulting sound no matter how the waveform changed with random phase of the harmonics. It is my belief that the human ear is totally deaf to the phase relationships between the components of a complex waveform.

Experiments were also done plotting the phase versus frequency of the acoustic output of a loudspeaker. This rate of change in phase of the entire speaker is many times that of even an extreme-slope network making any phase errors in the network a totally moot point.

REFERENCES

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[4] The Trouble with Attenuators
Paul W. Klipsch
Audio Craft November 1958 Page 26

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The Journal of the Audio Engineering Society
Volume 20, No 8, October 1972

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EQUIPMENT USED

Tektronix 7704a oscilloscope with 7A26, 7A16A and 7B85 plugins
Wavetek 188-S-1257 function generator
Wavetek 166 pulse generator
Old Colony Mitey Mike II calibrated microphone
Hewlett - Packard 4800A vector impedance meter