Its Just a Phase I Am Going Through

John Kreskovsky

Introduction

Over the years I have read and discussed many aspects of the design and implementation of crossovers for loudspeakers (I've been in this hobby for over 20 years). Issues such as transient response, square wave reproduction, crossover order, acoustic amplitude and phase response have all been touched upon at one time or another. However, some of the basic considerations of the requirements of the drivers used in a given system and how they interact with the crossover are often overlooked. A set of drivers is purchased and a crossover order is often chosen for reasons unrelated to the drivers' characteristics. For example, one commonly held belief is that a set of drivers, consisting of a woofer and a tweeter, that have a broad region of overlapping, flat frequency response are suitable for use with a simple first-order crossover. While this may be the case, there is more to it than that. In fact, as I will attempt to show, given that drivers for loudspeakers are minimum phase devices, which is generally true, the phase response of the drivers under consideration is probably the better defining quantity than the amplitude response. The reason for this is that while variations or irregularities in the driver's amplitude response through the useful pass band can generally be corrected with minimum phase equalization networks, the phase response of the driver across the same frequency range is not so much a function of the amplitude response in the pass band, but a stronger function of the natural high and low frequency rolloff characteristics of the driver. Recognition of this is key in the understanding the successful design and integration of the drivers in even a simple two-way speaker system. Of course with today's CAD programs and their optimizers the designer can proceed blindly without consideration of many of these and related effects and still achieve reasonable results. This is perhaps one of the drawbacks of such programs. I do not believe that the designer should rely on a CAD system to hide his ignorance of the physics involved. It will generally lead to sub optimal results.

Expectations: The fallacy of the full range driver

Before getting into the details of crossover-driver interaction I would like to show what might reasonably be expected from an ideal loudspeaker system composed of a single full range driver. The ideal system is defined to be one with flat on axis frequency response and suitable wide bandwidth. A simple but direct measure of the fidelity of such a system can quickly be seen in the ability of such a system to reproduce a square wave at different frequencies. It is accepted that the reader understands that the perfect loudspeaker would have a bandwidth from 0 Hz to infinity. Such a system would have, by definition, no phase shift and would reproduce any signal applied at the input perfectly as its output. However, such a broad frequency range is clearly unobtainable. So what would be reasonable? Several manufacture (who shall remain nameless) market so called full range drivers and make significant claims for the ability of the devices to provide a high level of fidelity. For the propose of analysis I have chosen to model a simple full range driver as a system with –3db points at 50 Hz and 25000 Hz. At the low frequency limit I have

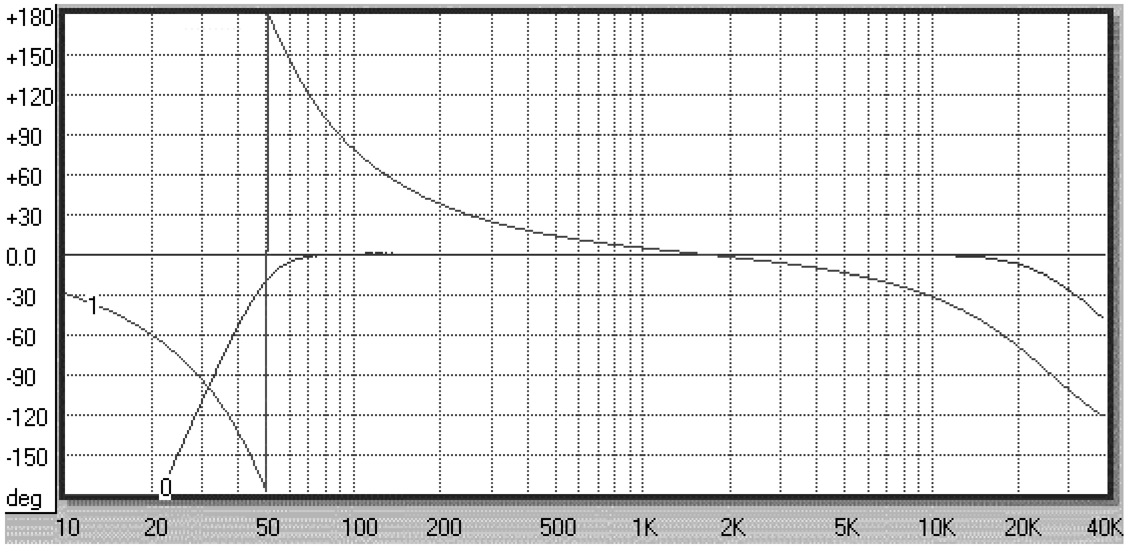

Figure 1. Hypothetical full range transducer amplitude and phase rersponse.

assumed the rolloff of the system to follow a 4th-order Butterworth characteristic. At the high frequency limit I have chosen a second-order rolloff. This would seem to be a reasonable representation of a very high quality, full range driver. The amplitude and phase characteristics of such a transducer are shown in Figure 1. As can be seen, while the amplitude response is indeed flat, there is considerable phase variation across the audio band. Note that this is the minimum phase response of this system, which is the phase is given by the Hilbert transformation [1], an integral relationship which relates the amplitude response to the phase and the phase to the amplitude response.

The response of this system to square waves of 100, and 1000Hz is presented in Figures 2-3. Figure 2 shows what some might consider a surprising result. Obviously the system response shows very poor reproduction of the input signal. One might be tempted to ask, “How can this be?” After all, the fundamental frequency of the square wave is 100 Hz, a full octave above the low frequency cutoff of the system and in an area where the amplitude response is flat! The key here is that the answer for the poor reproduction lies not in the amplitude response but in the phase response. A square wave can be thought of as represented by it’s Fourier series which consists of a sine wave series of the fundamental plus the odd harmonics with ever decreasing amplitude. However, each term in the series must also have the correct phase in relation to the other terms in the series. The phase shift introduced by our theoretical full range driver destroys the phase relationships and results in the distorted output.

Figure 2. Resopnse of the system shown in Figure 1 to a 100 Hz square wave input.

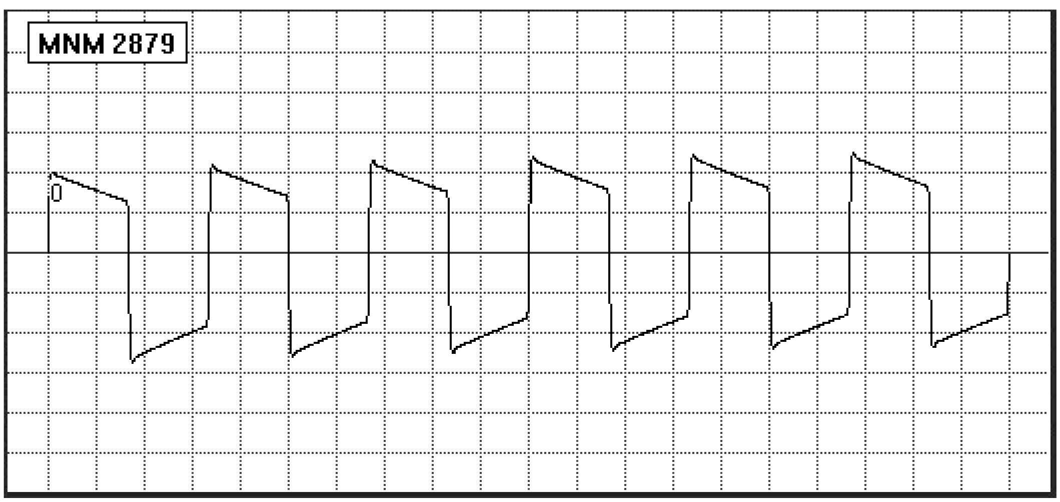

Figure 3. Response of the system shown in Figure 1 to a 1K Hz square wave.

Figure 3 shows the response of the same system to a 1K Hz square wave. While the response is now recognizable as an approximation to a square wave, there is still a great deal of distortion. That this distortion is in fact due to the low frequency cutoff of the system is demonstrated in Figure 4. This shows the response of a system with the same high frequency rolloff as the system of Figure 1, but which is now flat to 0 Hz. As is clearly evident in the figure, the reproduction of the square wave is excellent.

So what can be concluded from these figures is that even fairly wide bandwidth full range drivers are not capable of accurately reproducing square waves at relatively low frequencies even when the frequency of the wave is well above the low frequency cutoff of the system. The result improves to a degree as the frequency increases, but there are still problems in the response. This is, perhaps, one reason that impulse and step response

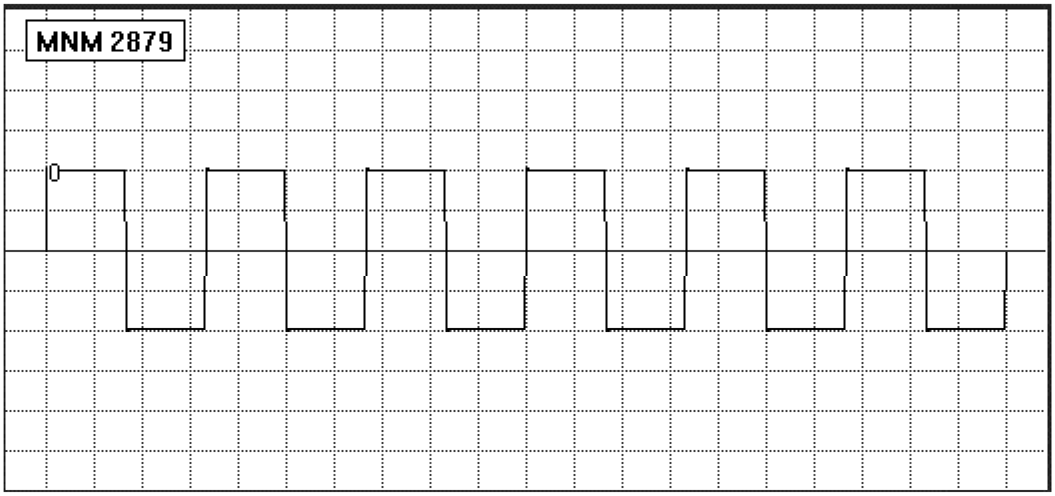

Figure 4. Response of a system having the same high frequency response as that of the system in Figure 1, but flat 0 Hz, to a 100 Hz square wave.

measurements are often presented to demonstrate the performance of full-range drivers as opposed to square wave response. These response measurements are a better test of the damping and high frequency characteristics of a driver than its phase coherence.

One other point should be noted before moving on. Simply choosing a system with a second-order low frequency rolloff can significantly improve the result. Figure 5 shows the 1K Hz square wave reproduction of a system similar to that of Figure 1 but with a second-order low frequency rolloff. As can be seen, the result is much better than shown in figure 3 owing to the lower phase shift across the audio band.

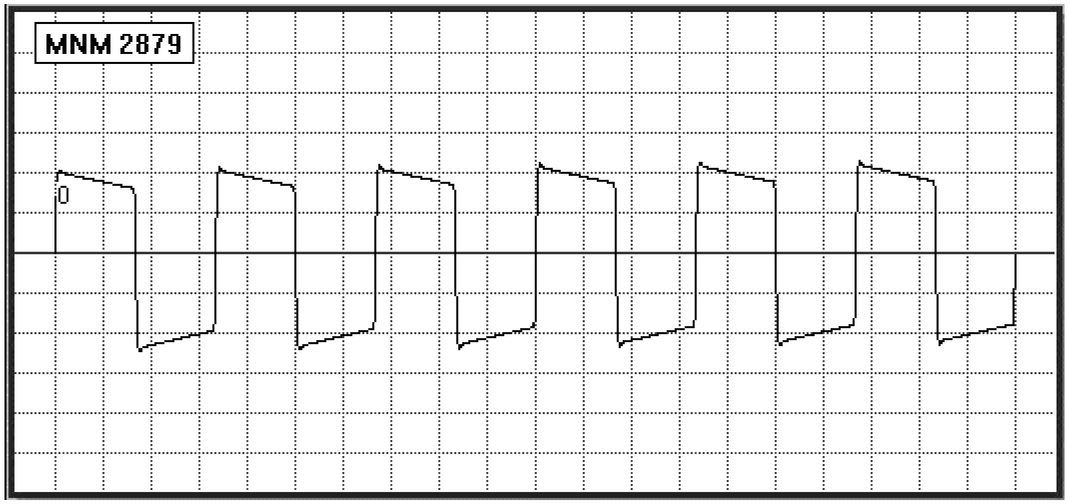

Figure 5. 1K Hz square wave response for a system similar to that of Figure 1 but with a second order low frequency roll off.

Limited Bandwidth Drivers and Crossovers

From the presentation given above it should be apparent that perfect transient response, or perfect reproduction of the input signal as the acoustic output of a loudspeaker, is a physical impossibility without some type of complex processing of the input signal to compensate for the phase distortion introduced solely by the bandwidth limitation of the system. This is a simple physical reality, no matter what anyone claims. While it is possible to design systems that ***appear*** to have good square wave reproduction, true phase coherence is simply not possible without addressing the driver-induced phase shifts, regardless of the type of crossover used in a system. Crossovers can be designed that yield a flat amplitude and minimum phase response through the crossover region, but we are still left with the phase variations at the frequency limits of the resulting loudspeaker.

In any event, let's move on. I will assume that you, the reader, have basic knowledge of simple crossover designs. For example I assume you are familiar with the fact that, of the standard crossover designs, only the true first-order crossover *can* yield perfect transient response and an output with has perfect fidelity with respect to the input. As the order of the crossover increases, more and more phase shift is introduced. Phase shift itself is not so much the problem, but rather the way the phase varies with frequency. If the phase were to vary linearly with frequency, then it would be the result of a constant delay and the signal would remain unaltered, just delayed. However, in all the commonly used crossover filter, whether Butterworth, Linkwitz-Riley or Bessel, and regardless of order the phase shift introduced by each high-pass or low-pass section varies in a manner that is not linear with phase. This results in a delay that varies with frequency and usually destroys the fidelity of the output with respect to the input. Never the less, the phase and amplitude response of the filter sections is what controls how the filter outputs sum and determines the final response of the system. And how each driver's inherent phase and amplitude response interacts with it's filter section is what determines the final acoustic characteristics of the crossover and the summed acoustic response of the system.

Ok, but how does all this affect the choice of crossovers for a given pair of drivers? We will start by defining a modeled set of drivers. For the woofer the model used is a 4^{th}-order bandpass response with Butterworth rolloff characteristics. The –3db points were chosen as 50 Hz and 8000 Hz. This represents an idealized response of a mid/bass unit in a vented enclosure. If anything, the –3db points assume a wider useful bandwidth than may be expected in practice. For the tweeter, the response model has a second-order Butterworth bandpass characteristic with –3db points taken at 750 and 25000 Hz. Again, this is a very reasonable model based on tweeters currently available. The raw woofer and tweeter data are shown below in Figure 6. For these models the phase data represent the case when the driver's minimum phase acoustic centers are aligned. The woofer amplitude and phase are given by curves 0 and 1. The tweeter data is given by curves 2 and 3. The data show that even though there is a relatively wide overlap where

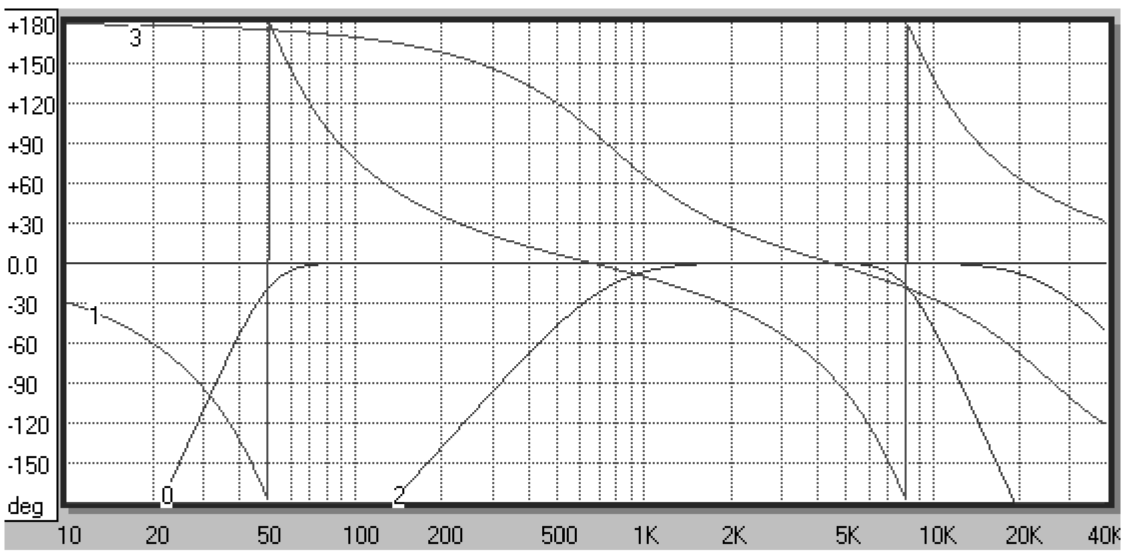

Figure 6. Modeled woofer and tweeter response data: 0 - woofer amplitude, 1 - woofer phase, 2 - tweeter amplitude, 3 - tweeter phase.

both drivers have flat amplitude response, the phase response varies greatly, and differently for both drivers throughout this region. So what are the implications of this with regard to crossover design? The first thing that is apparent is that even though it may be possible to closely match the amplitude response to a given target function over a reasonable frequency range, it may be impossible to match the target phase response. At first glance this would appear to imply that it might be impossible to develop crossovers that accurately sum to flat response. In fact there is a degree of truth to this. However, it is not quite that bad. The important result is not specifically how well the phase of the final acoustic high-pass and low-pass filter sections match the target function's phase response, but how well the *difference* in phase between the two acoustic filter sections matches the *difference* in phase between the target filter functions. Then, for the high-pass and low-pass filter sections to sum correctly, there must be a suitable wide frequency range to both sides of the crossover point where this phase difference remains close to the theoretical phase difference of the target functions. Obviously, as the order of the crossover increases the frequency range over which the phase difference must be close to the theoretical difference becomes narrower. The implication is that higher-order crossovers make it easier to achieve flat summed frequency response. To illustrate this point we shall examine several crossovers using our theoretical driver models.

First-order Crossovers

The obvious place to start is with the first-order crossover. Using the modeled drivers a crossover point of 2000 Hz was chosen. Figure 7 shows the amplitude response of the

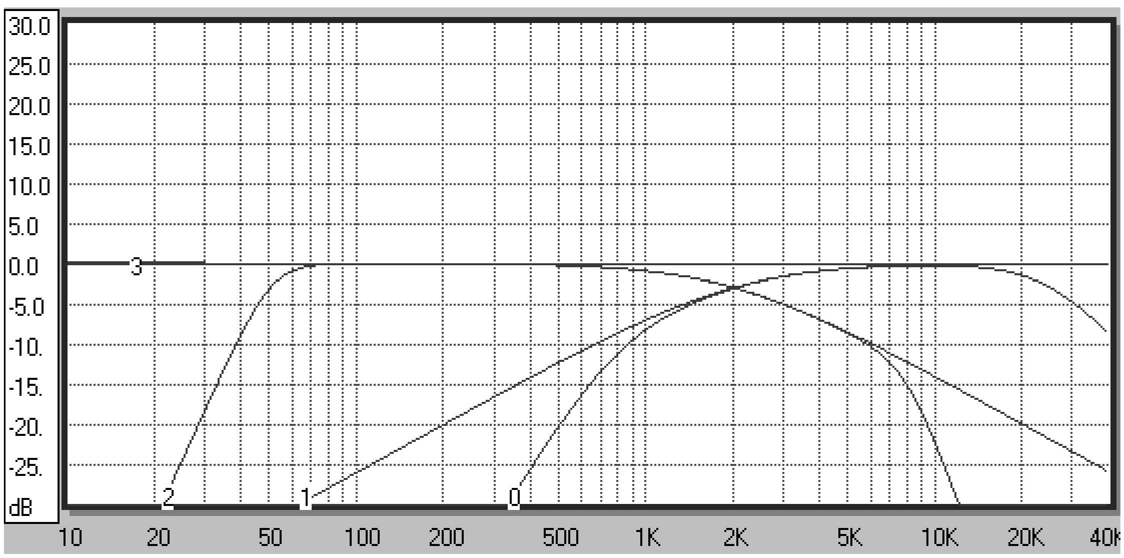

Figure 7. Theoretical 1st order Hp and Lp amplitude response curves and combined driver/filter amplitude response.

theoretical 1st-order high-pass and low-pass filter sections and the combined filter/driver amplitude response. The agreement between the high-pass filter and the target response is excellent to about 1400 Hz. The woofer response is in excellent agreement to about 6000 Hz. While the crossover point could have been chosen a little higher, (2450 Hz is the geometric mean of the driver f3 points), the present choice serves well to demonstrate the desired effects. If all were as should be, we would expect the summed response of these two filter sections to yield fairly flat response between 1500 and 6000 Hz, with perhaps some small deviation slightly above and below this frequency range. However, when looking at the phase response, shown in Figure 8, it is apparent that this will not be the case. Curves 0 and 1 in Figure 8 show the desired target phase response for the summed response to be almost flat. Of note is the constant 90-degree phase difference between the ideal high-pass and low-pass filter sections. In contrast, the phase response of the combined tweeter/HP filter section is given by curve 2 and that for the woofer by curve 3. Obviously, not only is the phase difference between the woofer and tweeter greater than

90 degrees at the crossover point, but the phase difference is not constant either. The result is that the summed on axis response is far from flat, as shown in Figure 9. When the woofer and tweeter are connected with the same polarity there is a broad dip in the response. When the tweeter polarity is reversed the response in the crossover region is elevated. Neither result is acceptable although the dipped response ***is*** a minimum phase result, and could be equalized to a flat, minimum phase response. The observation that the response differs so greatly when the tweeter polarity is reversed is further testament to the phase problems. If the phase response were correct, the polarity of the drivers would not affect the response.

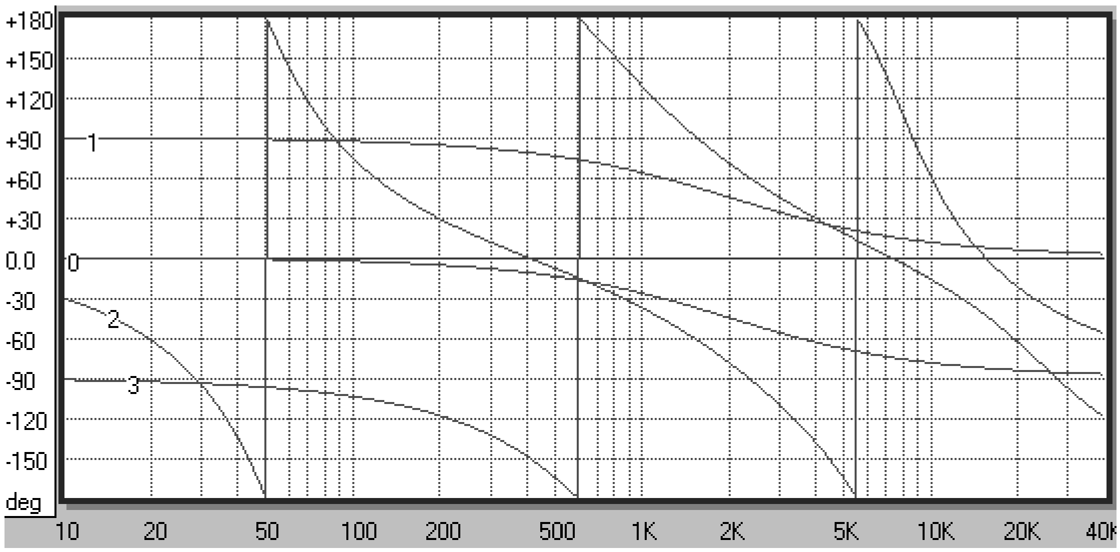

Figure 8. Phase response of theoretical 1st order crossover Hp and Lp filter sections (curves 0 and 1) and combined driver/filter phase response 2 - woofer, 3 - tweeter.

The amplitude result shown in Figure 9 can be improved upon by adjusting the offset of the tweeter to compensate for the incorrect phase difference between the woofer and tweeter at the crossover frequency. From examination of Figure 8 it can be determined that the phase difference at the crossover frequency is 150 degrees instead of the required 90 degrees. This can be corrected be offsetting the tweeter $60/360^{th}$ (or 0.1667) of a wavelength at the 2000 Hz cross over frequency; about 28 mm. The result is shown in Figure 10 for both normal and reversed tweeter polarity. In both cases the summed response at the crossover point is 1.0, but there are dip and peaks in the response to each side of the crossover point, depending on the tweeter polarity, and neither response is a minimum phase response. The problem continues to be the phase response. Looking again at figure 8 we see that while the phase difference at 2k Hz is 150 degrees, at, for example 1k Hz it is about 170 degrees, at 4k Hz it is about 165 degrees and at 8 K Hz

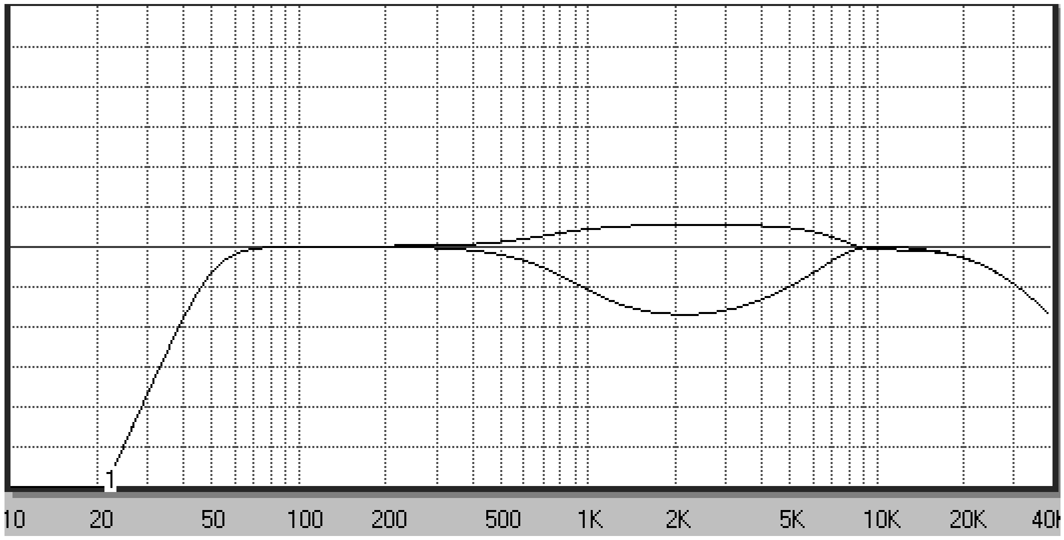

Figure 9. Summed response for 1st order crossover with drivers connected in phase (dipped response) and with reversed tweeter phase (elevated response). No driver offset.

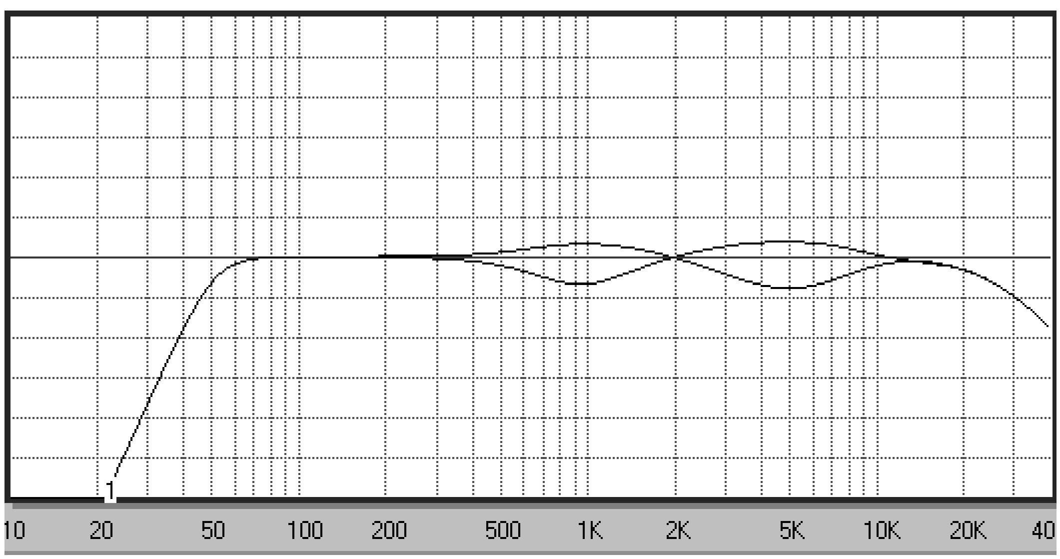

Figure 10. Summed response of 1st order crossover with tweeter offset my 28 mm; normal and reversed tweeter polarity.

is about 240 degrees. The offset of 28 mm corresponds to a constant delay of about 0.0833 msec. This delay then corresponds to a phase shift that varies linearly with frequency. Thus, while at 2K Hz the phase correction is 60 degrees, at 1k Hz it is only 30 degrees, at 4k Hz it is 120 degrees, and at 8k Hz it is 240 degrees. Thus, what happens is that while the phase is corrected at the crossover point, the slope of the tweeter phase response is increased and the correction is too small below the crossover point and too great above it. This is shown in Figure 11 where the phase response for the system, woofer, and offset tweeter is shown. Here we see that indeed the phase difference between the woofer at 2k Hz is 90 degrees. But at 1k Hz closer to 130 degrees and at 8k Hz the woofer and tweeter phase match. Also note that below about 700 Hz the system phase follows the woofer phase, above 5k Hz it follows the tweeter phase, with all the wraps due to the offset, and between those two limits the phase follows a contorted blending curve. Nowhere does the phase resemble the flat, zero phase shift of the ideal 1st-order crossover.

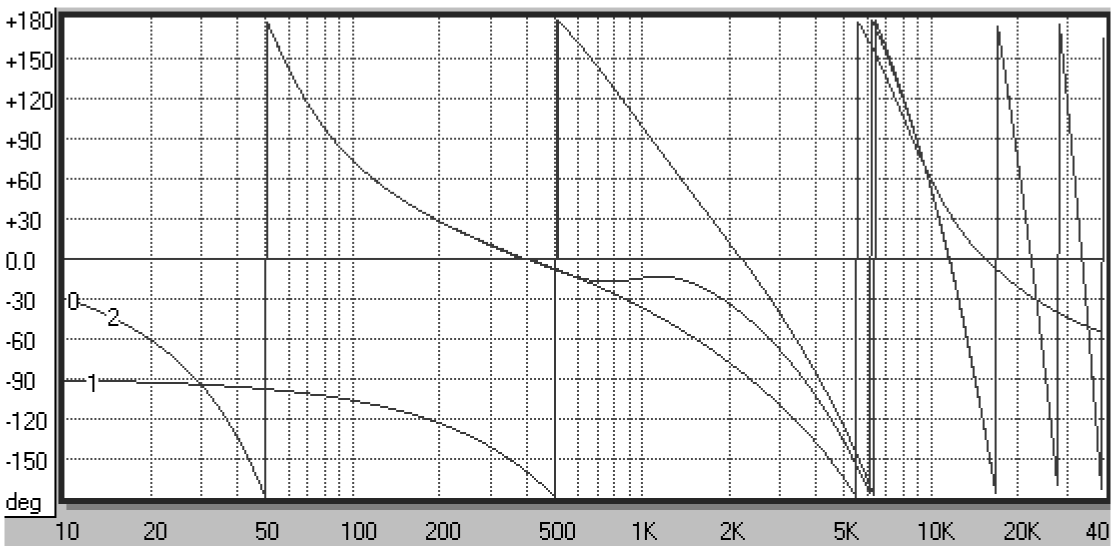

Figure 11. Phase response for 1st order system with tweeter offset. 0 - woofer phase, 1 - tweeter phase (note excess phase wraps due to offset), 2 - system phase (note that it follows the woofer phase to 700 Hz then breaks away to blend into the tweeter phase above 5K Hz).

Overall it once again becomes apparent that achieving a wide frequency range where the phase response is correct is a difficult task and again points to higher-order crossovers for their more limited range of overlap. Recalling the statements made in the introduction, it is not so much that the driver/filter amplitude response does not follow the target filter function. Rather the minimum phase response of the combination of the driver and filter is dominated by the rolloff characteristics of the drivers, as opposed to their amplitude response, in the crossover region. Furthermore, the consequences are the same whether a parallel or series crossover is used. The crossover elements may be adjusted for the flattest response but it will never be possible to achieve a true 1st-order system response that has both flat response and true 1st-order phase response, without equalization, as long as the driver bandwidth is limited.

Second-order Crossovers

The current popular choice of 2nd-order crossovers is the Linkwitz-Riley type. This crossover has flat summed response if the acoustic amplitude and phase responses of the driver/filter combinations match the target function closely and the drivers are correctly aligned, but it does not yield a minimum phase response. However, as with the 1st-order crossover the rolloff of the drivers will affect the acoustic phase even if the amplitude data matches the target response closely through the crossover region. Figure 12 shows the amplitude response of the target functions and the combined driver/filter response.

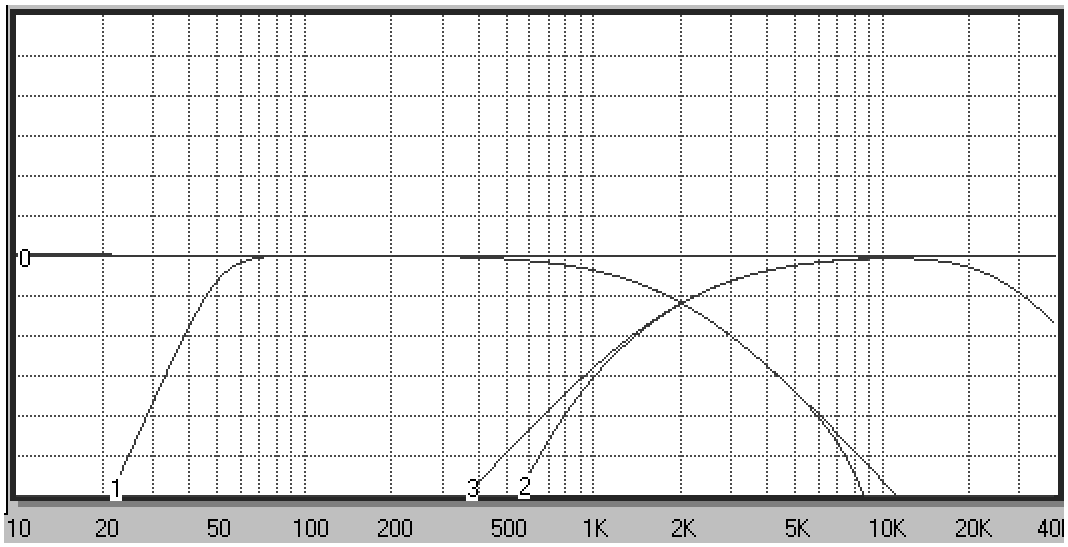

Figure 12. Theoretical Hp and Lp amplitude response curves and combined driver/filter response for 2nd order L-R crossover.

As with the 1st-order case, the amplitude response matches the target function very closely through the crossover region. However, the phase response, shown in Figure 13, shows the same dependence and divergence from the target phase as in the first-order case. Again, it is not so much that the phase does not follow the target phase, but rather that the phase difference between the HP and HP sections is not 180 degrees, and not constant. Also as with the first-order case, the driver offset can be adjusted to bring the phase into proper alignment at the crossover point, but the different rates of change in the phase of the HP and HP sections prevents perfect phase alignment throughout the crossover region. The summed amplitude response for this crossover with the tweeter connected with reversed polarity and offset 28 mm to achieve flat amplitude response at the crossover frequency (2k Hz) is shown in Figure 14. The individual driver responses and the normal polarity response are also shown for reference. Here we see that the summed response is indeed quite flat across the audio band with only small dips in the response to each side of the crossover point. This improvement in the summed response over the 1st-order network is due to the steeper rolloff of the 2nd-order filters placing less importance on the errors in the phase response away from the crossover point. Finally the phase response for this system is shown in Figure 15. Compared with the result for the 1st-order crossover shown in Figure 11, it is observed that the phase errors are significantly less in this case. The system phase follows the woofer phase closely below the crossover point and follows the tweeter phase closely above.

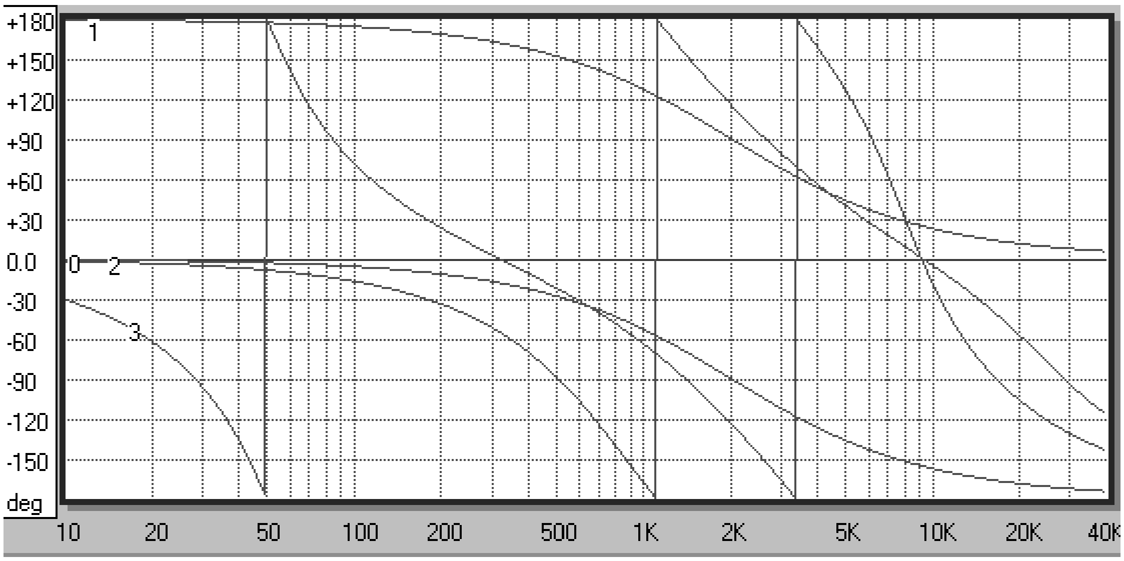

Figure 13. Theoretical 2nd order L-R phase response for Lp and Hp sections (curves 0 and 1) and combined driver/filter phase response (2-tweeter, 3 - woofer). Tweeter connected with normal polarity. No tweeter offset.

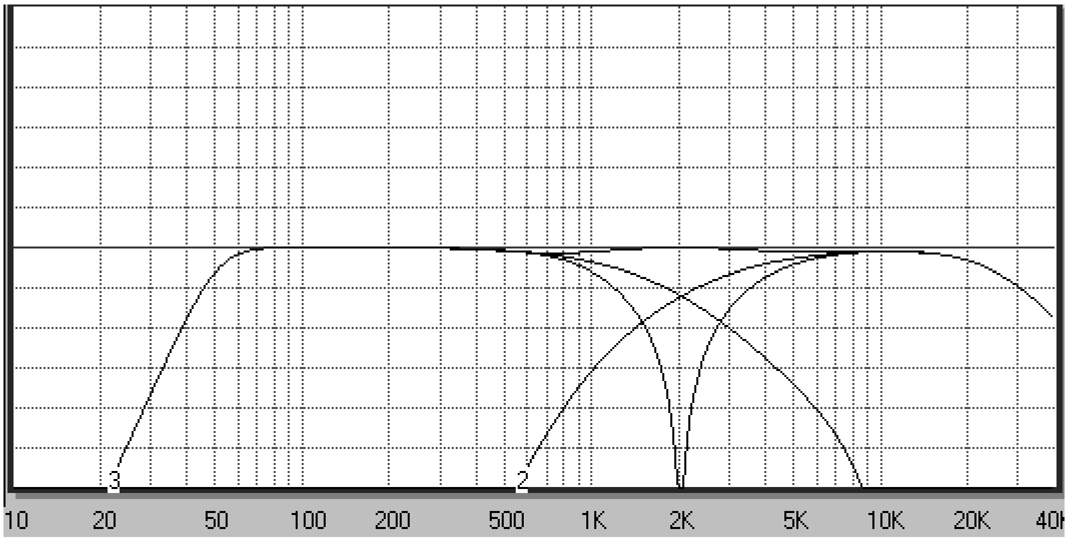

Figure 14. Summed response for 2n order L-R corssover with tweeter offset 28 mm with tweeter connected in normal and reversed phase.

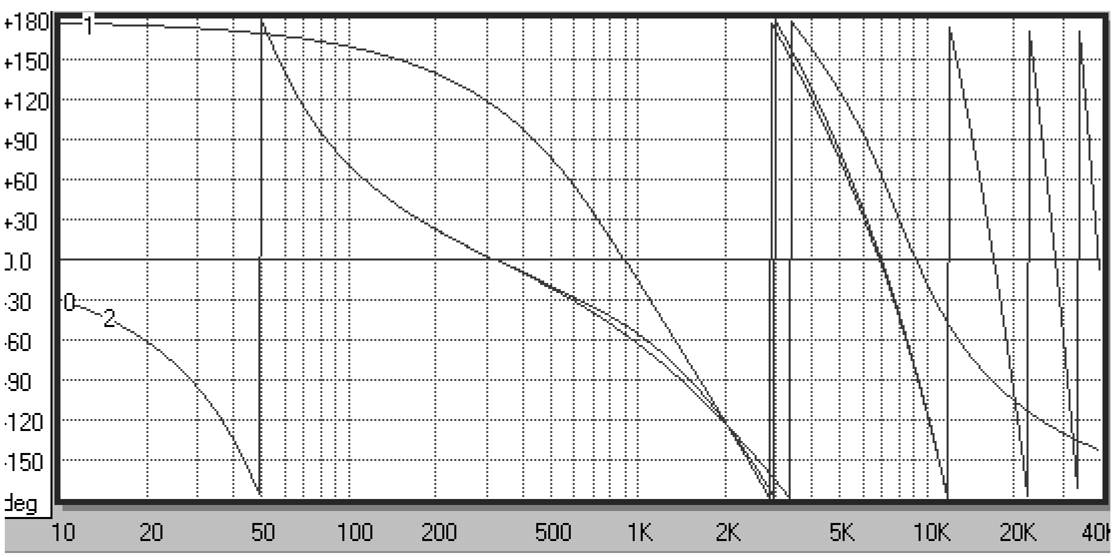

Figure 15. Phase response of woofer, 0, tweeter, 1, and system, 2, for 2nd order L-R crossover with tweeter offset 28mm and connected with reversed polarity.

Higher-order Crossovers

The 4th-order L-R Crossover

Looking briefly at the 4th-order L-R crossover, we can guess at the result. The steeper rolloff rates and more rapid phase shifts associated with the higher-order crossover will result is an even narrower region of influence between the HP and HP sections. As with the lower-order crossovers, the tweeter will need to be offset to match the phase at the crossover point. We should note that this offset has remained constant regardless of crossover order simply because we are only compensating to the mismatch in the driver phase at the chosen crossover point. The system amplitude response for a 4th-order L-R crossover with the tweeter offset 28 mm is shown in Figure 16. As can be seen the response is perfectly flat throughout the crossover region. The system phase response is shown in Figure 17. The phase response shows again that below the crossover point the system phase tracks the woofer phase and above it, it tracks the tweeter phase. Also note that at the crossover point the woofer and tweeter phase follow each other closely from about 1600 Hz to 2500 Hz. At the point where the woofer or tweeter is at the –12db level the error in the phase tracking results in less than a 0.1db error in the amplitude response. It should be noted that the small reduction in the tweeter level that can just be seen in the figure results for the 28 mm offset, and is not due to a significant error in the summed response.

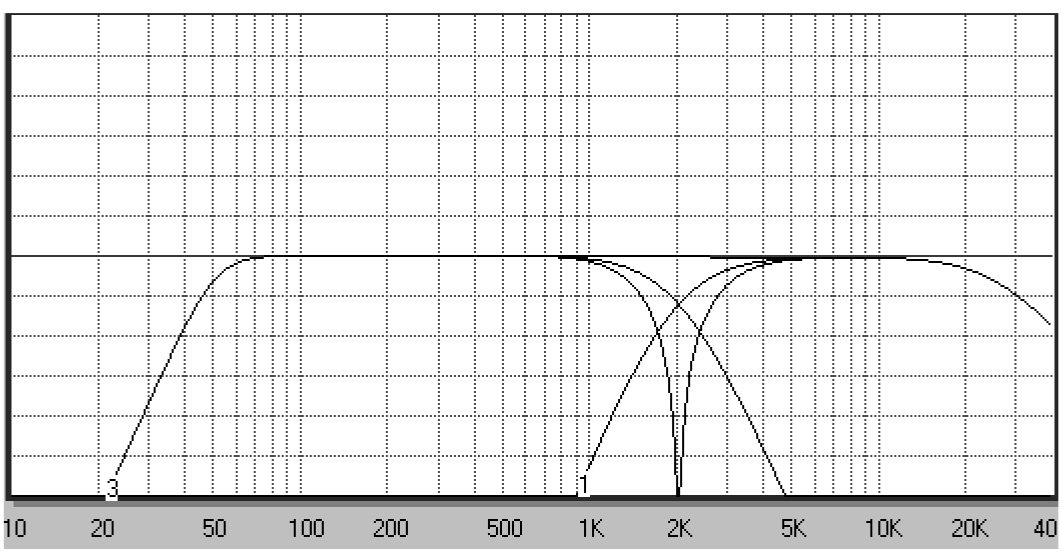

Figure 16. Amplitude response for 4th order L-R crossover with tweeter offset 28 mm.

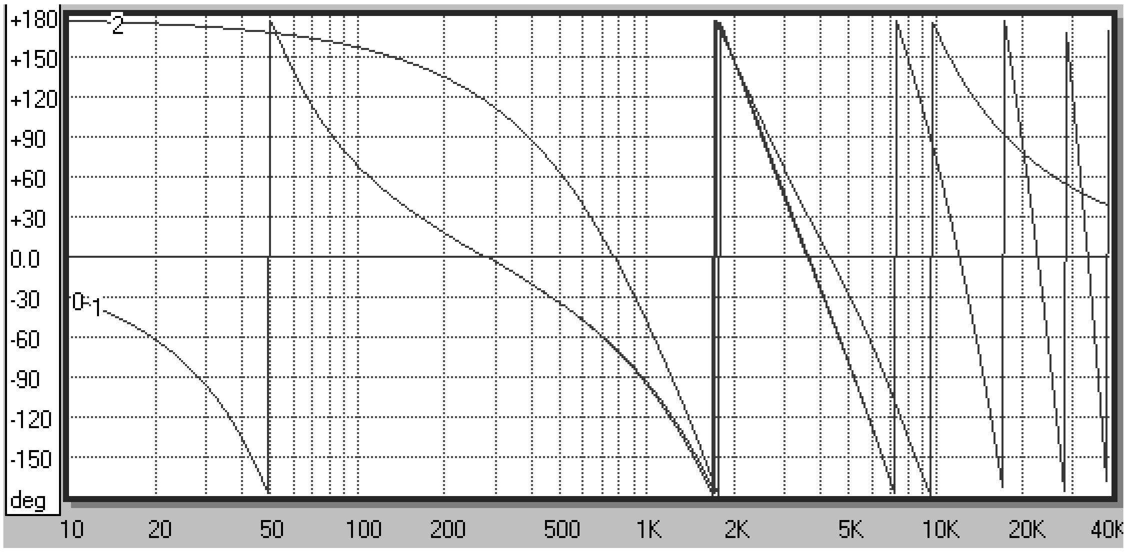

Figure 17. Phase response for 4th order L-R system with tweeter offset 28 mm. 0 - woofer, 1- system, 2 - tweeter.

The 4th-order Butterworth Crossover

The 4th-order, or any even-order Butterworth crossover, is not popular today because it is believed to be inferior to the L-R crossover since when the phase is aligned at the crossover point the summed response exhibits a +3db bump. However, in certain applications it may actually be preferable to the L-R crossover. In all the examples given so far the tweeter offset has been set to yield the correct inter-driver phase relationship at the crossover point. However, there is no particular reason that this must be done. As was shown for the 1st- and 2nd-order crossovers considered so far, correct phase alignment at the crossover point did not result in the correct, theoretically flat response due to the additional phase shift introduced by the drivers' rolloff. For higher-order crossovers, where the overlap region of the woofer and tweeter is narrow, we can exploit the phase mismatch to achieve favorable results with other crossover characteristics. For example, we know that for crossovers for which the –3db amplitude occurs at the crossover point, the response will sum flat at the crossover point if the inter-driver phase shift is 90 degrees. The question is then, "How much error is introduced in the amplitude response to each side of the crossover point?" This is shown in Figure 18 for a 4th-order Butterworth crossover. In this case to increase the phase difference between the drivers to 90 at the crossover point, the *woofer is recessed* by 15 mm. The resulting amplitude response is shown in Figure 18. As can be seen, there is very little error in the summed amplitude

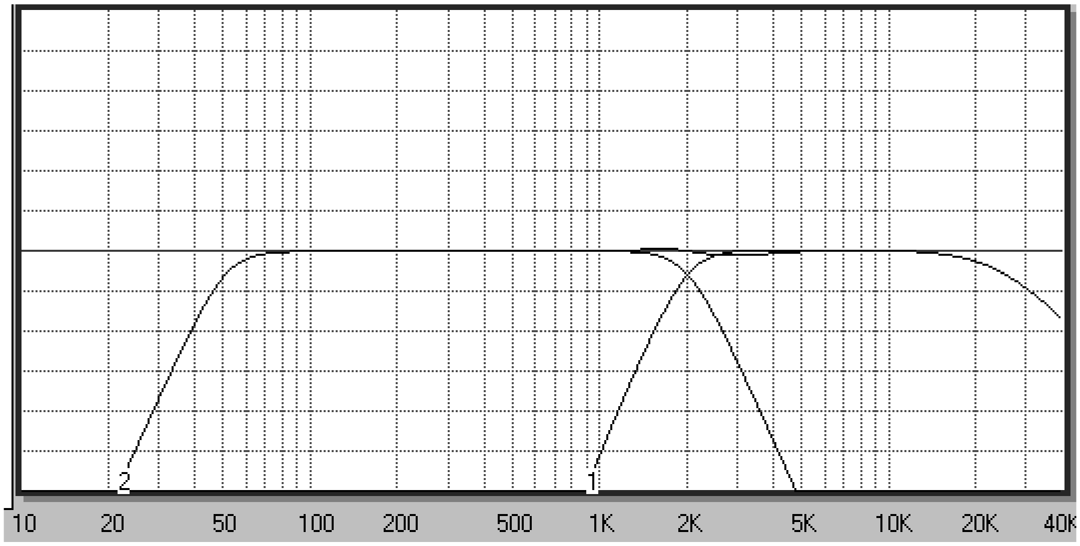

Figure 18. System amplitude response for 4th order Butterworth crossover with woofer offset 15mm.

response. This result is with the tweeter connected with normal polarity. Reversing the tweeter polarity yield a small dip below the crossover point, and a rise above it. That is, the opposite of the result shown in Figure 18. Thus we see that good use can be made of the 4th-order Butterworth crossover as it is usually easier to increase the woofer offset than the tweeter offset without having to worry about diffraction caused by stepped baffles. In fact, in one highly regarded speaker that I am aware of the woofer is mounted behind the baffle for this reason. I have also used this approach in a successful design. The approach can also be used with 2nd-order Butterworth filters, but the results are less impressive owing to greater response errors to each side of the crossover point. Finally, I would like to note that this same approach can be used with mixed-order L-R crossovers. For example, if the phase difference between the woofer and tweeter is 90 degrees at the desired crossover point, using a 4th-order L-R HP section on the woofer and a 6th-order HP section on the tweeter yields a summed response that has very little amplitude error. An example of a system using this approach, as well the 4th-order Butterworth approach (as an option) is the MTM system using Focal 5NV4211 woofers and the Morel MDT30 tweeter which may be found on my web page.

A Word about Offsets

Throughout this discussion I have talked about offsetting the woofer or the tweeter to align the phase between the woofer and the tweeter at the crossover point. We often hear discussion of the need to offset the drivers to align the acoustic centers if summed amplitude response is to agree with the theoretical results. However, as I have shown here, this is not entirely correct. In fact, as I noted in the section under limited bandwidth drivers, the modeled drivers do have aligned acoustic centers when there is no relative offset. The offset introduced to align the driver phase at the crossover point is due solely to the finite band width effects of the model drivers and is in *addition* to any offset that may be required to align the acoustic centers of real drivers. Also, the alignment of the minimum-phase acoustic centers is not necessarily the correct alignment for time-aligned systems. Systems that are time-aligned with regard to having the most coherent rise to a step response (a typical definition of time-alignment) depend on the rise time of the individual drivers in the system. The rise time is then governed by the highest frequency passed by the driver/filter combination and the phase at that frequency. This usually implies that the tweeter phase in the area of 15k to 20k Hz should be the same as the woofer phase at the crossover point. While this usually produces a system with excellent step response, the phase relationship between the woofer and tweeter at the crossover point can be rather arbitrary. Achieving flat response through the crossover region requires careful selection of the crossover point.

At this juncture I would like to spend a minute discussing the measurement of the minimum phase acoustic center of a driver. I use the Liberty Instruments IMP with MLS option as a measuring system. To find the acoustic center of a driver, I flush mount the driver on a large baffle and carefully measure the distance from the baffle surface to the microphone. I then collect a sample using an MLS. I then carefully place the left-hand marker in the time window to eliminate the propagation delay and perform the FFt to obtain the frequency response. At this point I examine the phase and amplitude response and then perform a Hilbert transformation on the amplitude data. If the marker in the time window was correctly located, the phase response from the Hilbert transformation will almost exactly match the measured phase response. If the match is not good, I relocate the time window marker and repeat the process until satisfactory agreement is obtained. From the final position of the marker, I can determine the total propagation delay, thus the propagation distance. Subtracting the distance from the baffle surface to the mic from this result yields the minimum phase offset for the driver. For consistency, I always make sure that the distance from the baffle to the mic is the same in every test I make. The result is very consistent data for the minimum phase acoustic center for all the drivers I measure. This offset can then be input to my CAD program. With Sound Easy, my primary CAD program, additional driver offsets can be added in the system module (referred to as the Sum-plot module in Sound Easy jargon) to place the driver acoustic centers in the same plane, or to position them to correct the relative phase of the HP and HP crossover sections, as discussed above.

Is this for real?

You bet it is! Let me show you some results for a high quality driver, the Dynaudio 15W75. Figure 19 shows the amplitude response and (minimum) phase response for this driver when mounted in a vented box. The amplitude scale is 10db per division.

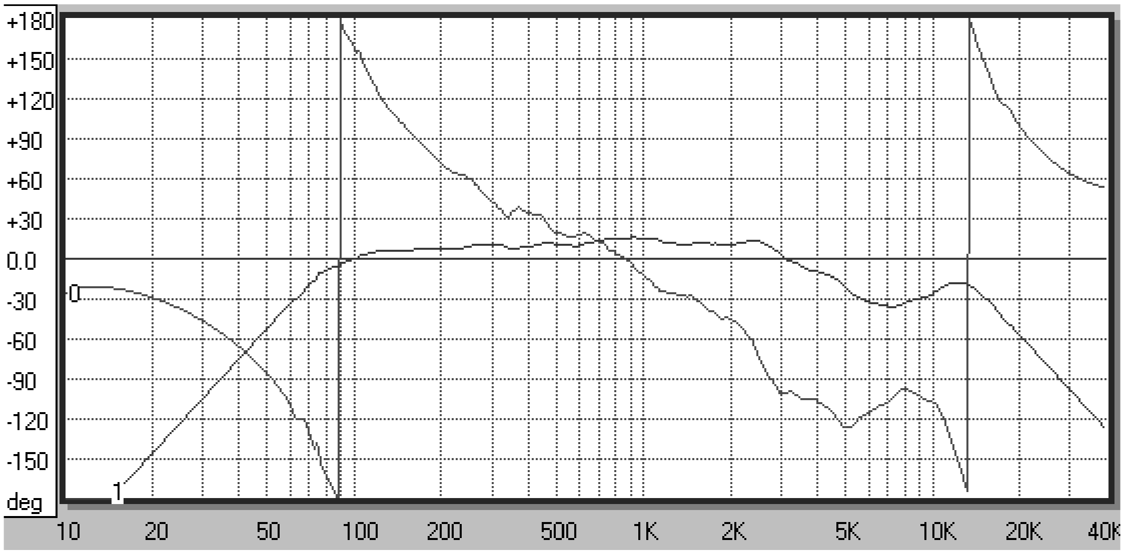

Figure 19. Amplitude and minimum phase response for Dynaudio 15W75 mounted in a vented box.

Note that the phase response reflects the irregularities in the amplitude response, particularly above 2500 Hz where the SPL rolls off into a valley, then rises again before the final rolloff above 12000 Hz. This driver is well suited for a crossover point of around 2k Hz. In my application for this driver, I chose a 2nd-order L-R crossover at 2k Hz. Figure 20 shows a straight forward second-order crossover consisting of a series inductor, a shunt RC element, and an addition RLC shunt that was added to smooth the final response in the area of 2.5k Hz where there was a small, but significant bump. The crossover was optimized for a 2nd-order, 2k Hz L-R acoustic amplitude response. The result is compared to a target function, which includes the low frequency rolloff of the system. As we can see, the SPL amplitude response follows the target very accurately up to 7k Hz, almost 2 octaves above the desired crossover point. At the low frequency range of the plot we see that the phase of the system and the target are in very good agreement. However we can also see that the phase response begins to diverge from the smooth target phase curve at about 1500 Hz. At the crossover point the divergence in phase is about 15 degrees, and it continues to worsen as the frequency rises. This is all a result of the poor match in the amplitude response above 7k Hz. (Please recognize that the multiple vertical lines around the 5k Hz point are due to the fact the phase varies slightly around -180 degrees there and wraps and unwraps quickly until the phase finally exceeds –180 degrees for good. At that point, just over 6k Hz, the phase wraps for the last time.)

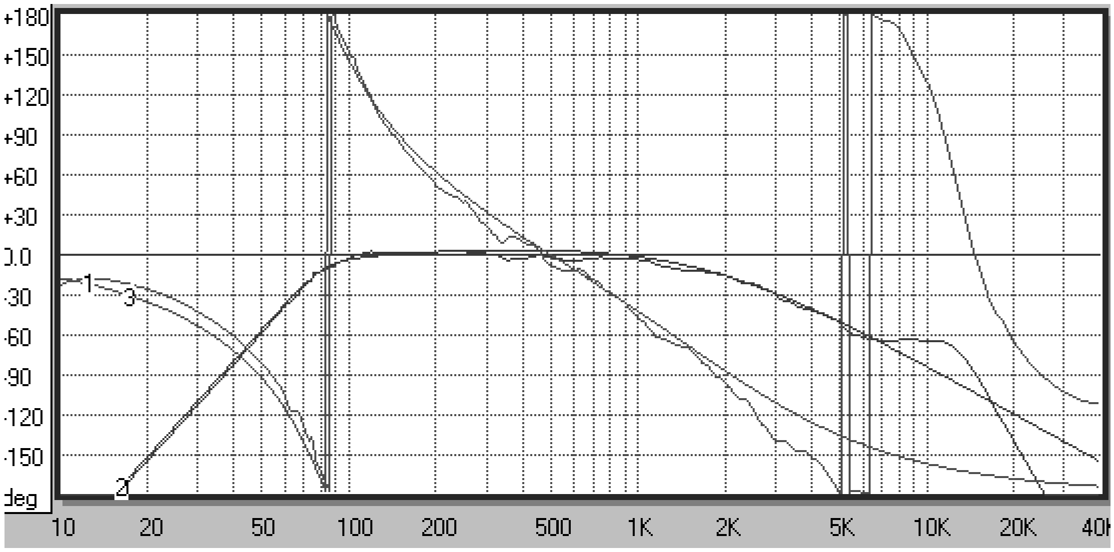

Figure 20. Optimized (simple) 2nd order L-R 2k Hz crossover amplitude and phase response with comparison to the target function response.

While this level of agreement may be satisfactory for a typical loudspeaker, I found it to be unacceptable for a high quality mini-monitor. To improve upon this crossover, the RC shunt was removed and replaced with a second RLC shunt. A resistor was also added

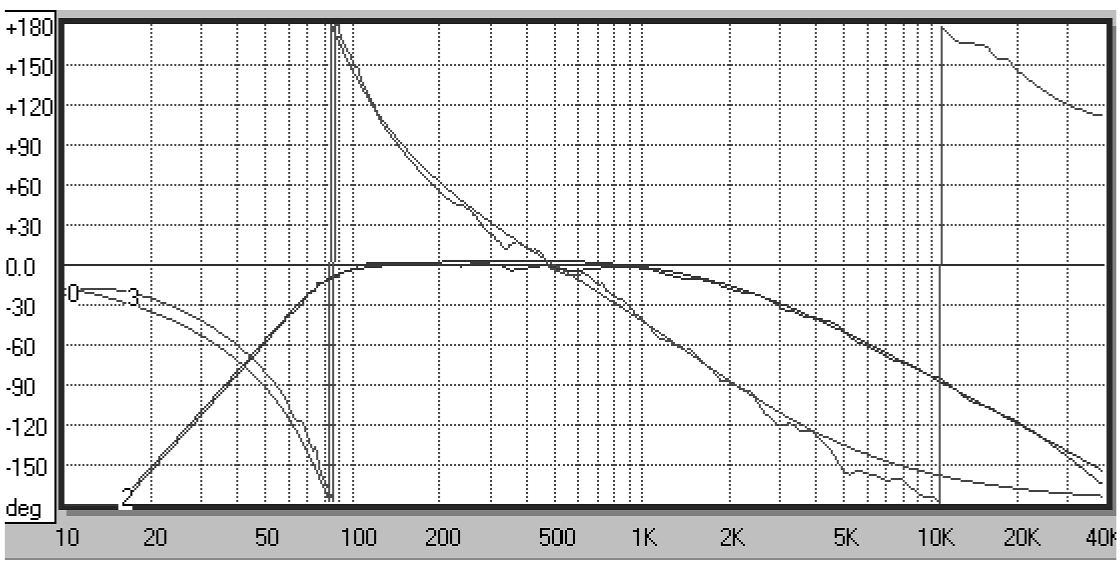

Figure 21. Modified 2nd order L-R crossover with comparison to target response.

parallel to the series inductor. The optimized result for this modified crossover is shown in Figure 21. We can see that the amplitude response now follows the target curve to above 25k Hz before it begins to drop below the target level slightly. Even so, the phase begins to diverge form the target curve around 4k Hz. But up until that point the agreement is excellent.

The extra wrap in the driver/crossover phase response, which is due to the slight divergence in the amplitude response above 25k Hz, indicates that the driver/crossover combination has an asymptotic rolloff greater than 12 db/octave. To demonstrate this, I modified the circuit used to generate the target function by adding a small inductance between the filter and the driver. In effect, the topology of the low-pass section of the target function circuit was changed from 2nd-order to 3rd-order. However, the values of the first inductor and the shunt capacitor were held at their 2nd-order values. The extra inductor was tuned only to roll off the response above 25k Hz so as to match the actual driver/crossover amplitude response. This comparison is shown in Figure 22. As we can

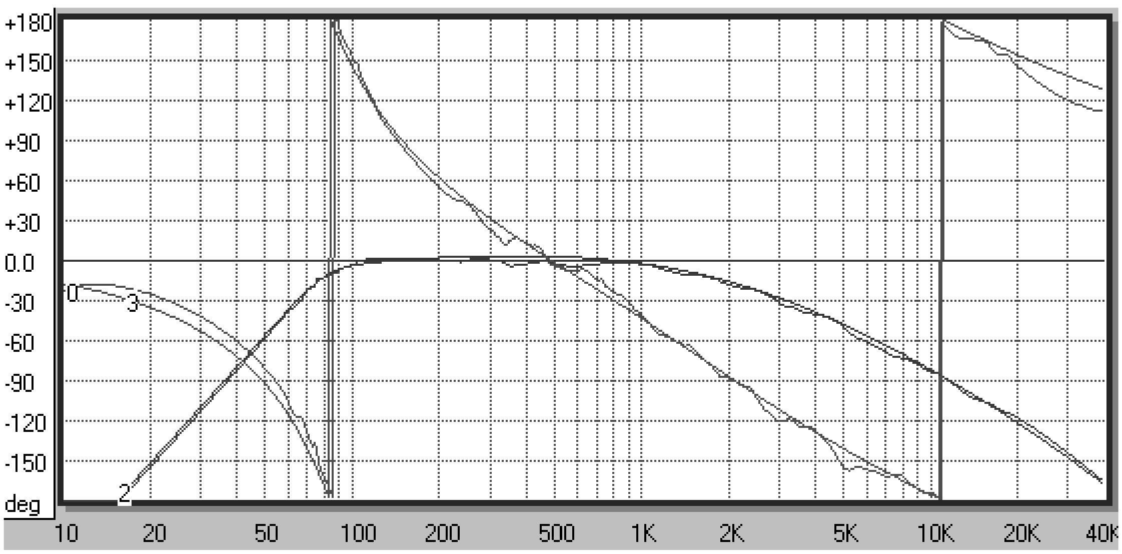

Figure 22. Comparison of driver/crossover amplitude and phase response with modified target function.

see, both the modified target function and the actual driver/crossover amplitude response are in very close agreement beyond the scale of the figure, and the phase response matches closely all the way to 20k Hz. WOW!

As a point of interest I have included the response of the crossover without the driver in Figure 23. This is probably not what comes to mind when one think of a filter for a 2nd L-R crossover, but then again that's part of the art of speaker building. The point here is that this rather complex and convoluted crossover topology and response is what is required to achieve an accurate 2nd-order L-R acoustic characteristic in the final design. It clearly shows the importance of considering the driver response well outside the intended pass band when designing the crossover and the effect this out of band response has on the pass band phase response. Ultimately, this will significantly affect the way the woofer and tweeter response sum and blend into a smooth, full range response.

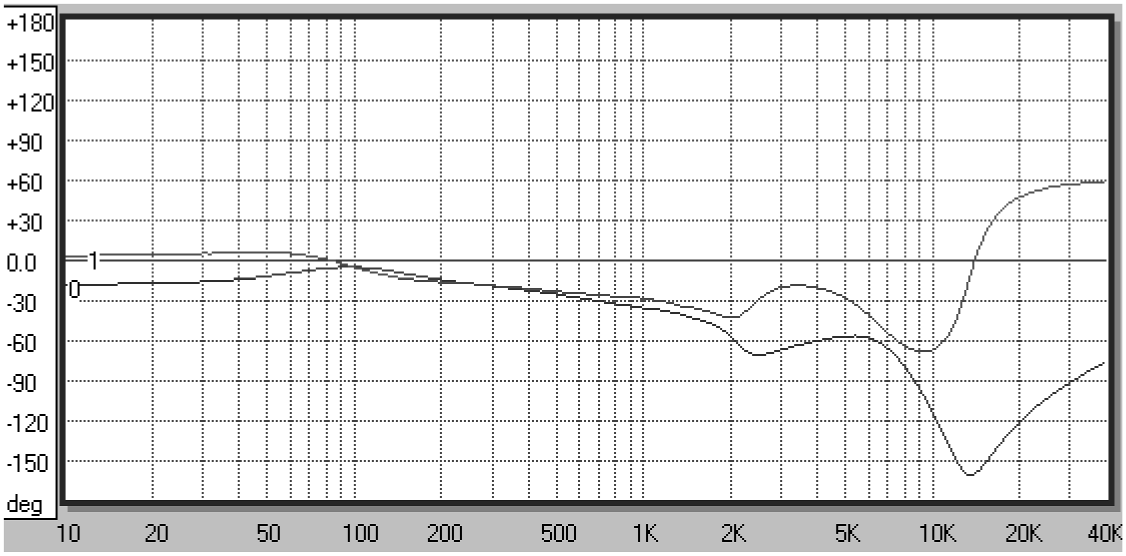

Figure 23. Amplitude (lower curve) and phase response of electrical filter which yields a 2nd order L-R acoustic crossover when used with the Dynaudio 15W75 in my vented box.

Closing Remarks

What I have attempted to show in this discussion is simply that when designing a crossover it is extremely important to consider the phase response of the driver as well as the amplitude response. It is also important to recognize that the flat frequency response in the desired bandpass region of the driver is not particularly the most important property when selecting a driver for a given application. Provided the driver does not have any abrupt changes in it's raw amplitude data across the desired pass band, the driver rolloff at the frequency extremes will likely play a more significant role in how well a target acoustic response, both amplitude and phase, will be achieved.

I have briefly addressed the full range driver and have shown that even though such drivers may eliminate the need for a crossover in the sensitive upper midrange, the idea that they will provide perfect transient response is simply not true. The ability of any system to achieve true phase coherence is limited by the system bandwidth and the rolloff rate at the system limits. The low frequency rolloff is of particular importance in this regard.

I have also addressed the interaction of standard crossovers with finite bandwidth drivers and shown just how the bandwidth limits of the driver affect the acoustic phase response in the crossover region even though the amplitude response may appear to be a good match to the target response. I touched upon the need to offset the drivers to compensate for the driver induced additional phase at the crossover point, and how such offsets can

be manipulated for uses with different crossovers. I also tried to show that these effects have a less damaging result when higher-order crossovers are implemented.
Finally, I showed that these theoretical effects are indeed real by examining the amplitude and phase response for a high quality driver and low-pass filter section. It was demonstrated that without highly accurate matching of the amplitude response with the target function to beyond 20k Hz, phase errors propagated well in to the crossover region.

While the treatment here is certainly not comprehensive, I hope that the information presented is helpful in developing an understanding of the importance of the driver's phase response to the successful development of high quality crossover. While I am not recommending one crossover topology over another, the difficulties of achieving the desired result with lower-order crossovers should be apparent. Additionally, the discussion has really only addressed the on axis response of a system. When making a crossover choice the designer should also bring into the picture those other aspects of the design that he believes important. Lastly, with the CAD programs available today, it is possible for the designer to ignore these phase-related problems and allow the CAD program to determine the optimum HP and HP filter characteristics that yield a flat response. While such an approach may well yield suitable results for "midfi" type speaker systems, I do not believe such an approach is adequate for a high quality, state of the art speaker system that strives to achieve the utmost in fidelity.

Reference:

1. See, for example, R.C Heyser, *Loudspeaker Phase Characteristics and time Delay Distortion: Part 1,* J. Audio Eng Society, Jan 1969, V 17, No. 1.

