 By G.R. Koonce

Passive Crossover Linear Phase Speakers, Part 1

Extensive study of linear-phase passive crossover designs.

The focus here is on a speaker system that when fed an electrical square wave will output an acoustic square wave. Unfortunately, such systems are referred to by a variety of names. It is a system that is "transient perfect," one that produces no "delay dispersion" and no "phase distortion." Articles on any of these topics are of interest to anyone involved in linear-phase systems.

This article discusses ways to implement such systems with conventional cone drivers. The scope is limited to systems using passive crossovers (COs) with passing references to active CO approaches. I also discuss the effect of linear phase on the sound of a multi-way multi-driver system that I built last summer. Finally, I discuss what I learned during that work that may be advantageous to the design and construction of any speaker system.

WHAT IS A LINEAR-PHASE SYSTEM?

The subjects of time delay, group delay, and phase shift can become a bit confusing. Waslo[1] covered this topic very well, and I highly recommend his article. In defining a linear-phase speaker, I will talk only about phase shift and time delay, terms with which I believe the reader is comfortable.

My definition of a linear-phase speaker is one whose system phase shift can be plotted as a straight line at 0°. If it plots at ±180° the input terminals are reversed. How did I arrive at this definition?

To maintain the wave shape from electrical input to acoustic output, the speaker must be a pure time delay. This means it delays all frequencies the same amount of time. On a linear-phase-shift versus linear-frequency grid, a time delay plots as a straight line descending from the origin, 0° at DC. This straight line can be rotated to 0° by subtracting a fixed amount of time.

Once plotted at 0°, it makes no difference whether the frequency axis is linear or logarithmic. No real speaker system goes to DC or infinity, thus you are looking for speaker systems whose phase shift plots at 0° over a major portion of the audio band. The wave shape of signals whose fundamental and vital harmonics are contained within this portion of the band will be preserved.

IMPLEMENTATION POSSIBILITIES

If you had a single driver that covered the full audio frequency range with a stable acoustic origin[2] position, it could produce a linear-phase system. There are systems using a single driver, usually with the back of the cone horn loaded to limit displacement (minimizing Doppler distortion) and boosting the bass response. From what I read, most of these systems suffer from some frequency anomalies possibly because they generally have auxiliary cones (whizzers) that cause movement of the acoustic origin or other problems. They are of no interest to this article.

A good approximation to a linear-phase system can be implemented by a subwoofer-satellite system if the CO frequency is sufficiently low. Small drivers that cover the range from about 100Hz up are now available, and if they have a flat response with stable acoustic origin, they could yield a linear-phase system over a major portion of the band, but with limited power capability. These systems are also outside the scope of this article.

There are numerous linear-phase CO designs that can only be implemented in an active format. If the digital domain is used, then time delay can be included to correct for differences in the driver's acoustic origins. While this is probably the best approach to building a linear-phase speaker, it is not the topic of this article. This article is restricted to fully passive COs; i.e., the speaker system can be driven by a single amplifier channel with the entire CO function after the amplifier.

When you build with multiple drivers and passive COs, the positioning of the drivers is critical. The best case involves using a coaxial woofer-tweeter that has its acoustic origins properly aligned. With independent drivers, the spacing between them introduces additional problems. A multiple driver system shows linear phase over only a small region of the possible listening area. Keeping the drivers vertically aligned yields a wide area in the horizontal plane, but a rather limited area in the vertical plane. All systems studied in this article use vertically aligned drivers, so you need to study only the effects of vertical angle.

PASSIVE CROSSOVER CANDIDATES

The CO that most people know can produce linear phase is the first-order with all drivers connected with the same polarity. You can, indeed, build a linear phase system with this CO, but it is not easy. The first-order crossover requires that the drivers have a wide region where both drivers have a useful response, optimally two octaves each way from the CO frequency. The slow attenuation slopes of the first-order CO also make it susceptible to trouble from impedance anomalies such as the tweeter's resonance. Also, as demonstrated by Carlsson[3], the first-order CO is very sensitive to offsets in the driver's acoustic origins. This article will investigate this CO configuration.

It is well known that when you use a two-way second-order CO with both drivers the same polarity, a notch develops at the CO frequency. It turns out that you can add a third driver to "fill" in this notch, and this configuration can be phase linear. This was first discussed by Baekgaard[4] and expanded on by Stokes[5], who shows two different second-order and one third-order passive configurations. Stokes gives design equations to implement these with passive components. It was reported that someone commented, "If you have three drivers, why not do a three-way system?" I can only conclude this person had never tried to build a phase-linear system. I will look at this passive approach. Active implementations are discussed by Conniff[6] and Koonce[7].

Sandrik[8] offers an interesting approach to curing the problems of the gradual slopes of the first-order CO. He starts with a first-order CO and then increases the attenuation slopes some distance from the CO frequency. He does not claim to produce zero phase shift, only a minimum phase shift. Sandrik gives recommendations but does not show a general approach to circuit implementation. I will cover this approach showing one method of implementation.

Kreskovsky[9] offers a technique for building a phase-linear CO by overlapping the high-pass (HP) and low-pass (LP) responses and then adding an equalization network ahead of the CO to correct the magnitude and phase. For fully passive COs, the equalization must be done at the amplifier output. With this requirement, his approach shows something like a 4dB loss in system sensitivity, which I consider unacceptable and thus will not cover. If you are willing to put the equalization circuit between the preamp and amplifier or use Kreskovsky's[10] full active implementation, this approach looks much better.

THE IDEAL DRIVER

I start the investigation with those drivers you would love to have—but can't buy—the ideal driver. Throughout the audio band these drivers radiate a constant level (which is adjustable) with 0° phase shift and exhibit an input impedance of 8Ω at 0° phase. In addition, the acoustic origin is at the front of the mounting face so if they are flush mounted in a baffle the acoustic origins are in line. They are also point sources, thus radiating equally in all directions.

The only real-world consideration I will give to these drivers is they must be mounted in a vertical array rather than located at the same point in space. I assume a 6½″ woofer and a 4″ tweeter in overall diameter, thus requiring about

6″ center-to-center (CTC) spacing between drivers.

THE SPECIAL PLOTS PRESENTED

There are several items I choose to investigate about each approach. To plot each item independently would greatly increase the length of the article, and I have found that approach confusing when I read such articles. **Figure 1** shows the combination plot developed for this work. The plots are small with limited readability, so you will not be able to read "to the nearest dB." They do, however, show you how the system behaves in one figure. **Figure 1** shows modeled performance for an actual two-way system that I constructed.

The top left shows the response of the CO sections. The plot may be the electrical responses of the CO alone or, as in **Fig. 1**, the on-axis acoustic response of each driver driven by its CO section. The acoustic CO frequency is clearly just above 2kHz.

The second magnitude versus frequency plot is the system response at some point in space. While you don't listen there, the summation point normally used is infinity. If any other distance is being used, that will be noted in the text.

For **Fig. 1** it is the response on the tweeter's axis, the 0° reference, and back 10′ from the speaker's front panel. The lower left plot is the system phase shift at this same spot in space minus the phase shift caused by the sound traveling to that point. The two-way system in **Fig. 1** clearly is not minimum phase.

The top-right polar plot shows how the system magnitude response varies with vertical listening angle relative to the tweeter's axis. You can move the curves on this plot to place the main response at 0dB, so the level shown may not agree with the level shown in the system magnitude versus frequency plot. **Figure 1** shows polar plot curves at six frequencies, which are about 500, 1000, 2000, 3000, 5000, and 10,000Hz. You can't tell the curves apart in B&W printing; it is how the various curves interact that is of interest, not the individual curves. In **Fig. 1** it is clear the system performs best in magnitude at a listening angle between 0 and +10°, +5° being a good choice.

The bottom polar plot shows the system phase shift variation with vertical listening angle for the same frequencies. It is clear the system in **Fig. 1** is not linear phase at any listening angle. Keep in mind there is always an ambiguity when talking about phase shift.

On this polar plot –360° is the same as 0°, which is the same as +360°. When the phase shift was about to go off the plot, it was jumped up or down as needed by 720°. These long jumps have been blanked for clarity on the plot. Shorter jumps of 180° represent where the system has gone through a phase reversal at that frequency. You will see these points correspond in angle with nulls in the magnitude response.

The one item not covered in the figures is the system power response. Refer to the various references for discussion on this topic.

THE TWO-WAY FIRST-ORDER CROSSOVER

Figure 2 shows the performance of a two-way system using ideal drivers and a first-order CO. The drivers are spaced vertically at 6″ CTC and the CO frequency is 2kHz. The plot of electrical CO section outputs is identical to the acoustic driver responses due to the ideal drivers. The 0° reference is the tweeter and the listener is back 10′. The system frequency magnitude is an ideal 0dB and the system phase shift 0° at all frequencies, just as desired. The lower

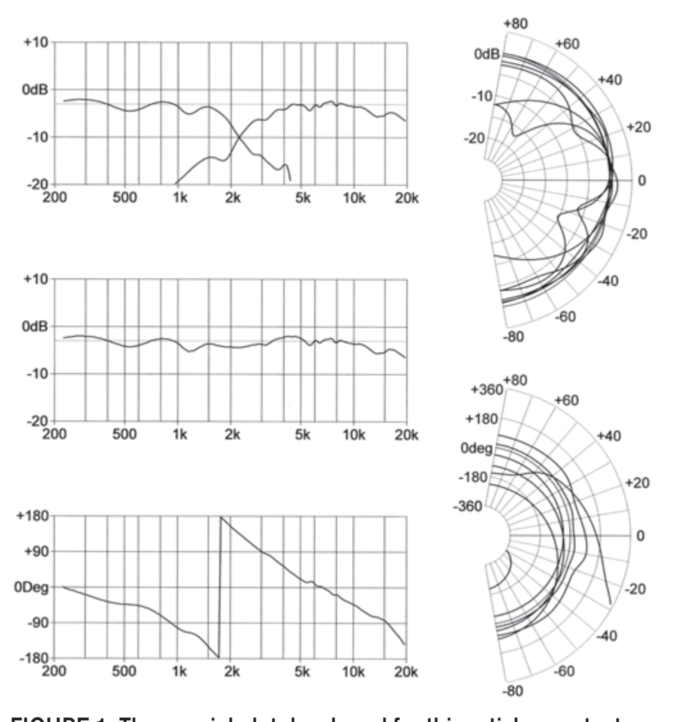

FIGURE 1: The special plot developed for this article, see text.

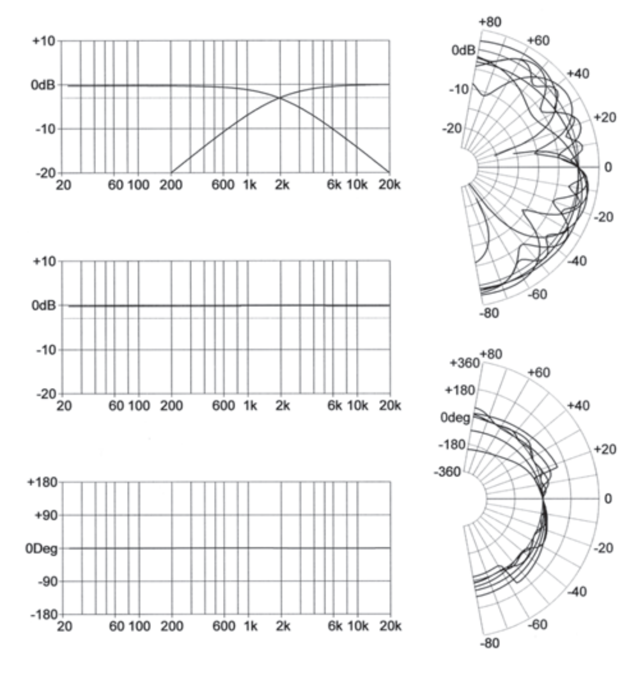

FIGURE 2: Performance of two-way system with ideal drivers and first-order crossover.

polar plot shows the system at 0° is phase linear and varies from linear fairly slowly with vertical angle.

It is the upper polar plot that indicates trouble. Yes, the 0° response is 0dB; however, at numerous other angles certain frequencies show a magnitude of +3dB. These give floor, ceiling, and other echo producers a level advantage over the on-axis response. Note also that at angles slightly above the listening axis certain frequencies show deep magnitude nulls, making performance for a standing listener questionable. These effects are referred to as lobing problems and can result in systems whose sound varies considerably with the location of the speaker and the listener and also the local environment.

To get the system to go phase linear at the listening point, you must move the ideal tweeter 0.12″ behind the ideal woofer. Thus, even with ideal drivers the first-order CO has some problems in a two-way system. A slight step is required in the front panel to focus the response to a fixed listening distance, and the response has mild lobing problems.

When you use real drivers the situation becomes worse. **Figure 3** shows the responses for the two drivers used in the two-driver systems in this article. They show considerable overlap about the 2kHz CO frequency. Real drivers always have zobels to flatten their high-frequency impedance to an approximate resistance.

Both drivers are flush-mounted in a flat front panel. Any change in one driver's acoustic origin position requires a step in the front panel. Also, real drivers have directivity that causes their off-axis magnitude response to roll off at the upper end of their frequency response band.

Figure 4 shows the performance of the two-way system with real drivers flush-mounted on a flat front panel and using a first-order CO. The top-left plot shows the electrical outputs of the two CO sections and a problem is clearly evident. The tweeter's impedance rise at its resonance overrides the slow rolloff of the first-order HP, causing the tweeter input to rise to 0dB. This also causes the notch in the system magnitude response and wiggle in the phase response.

You may also have the real-world problem of possible

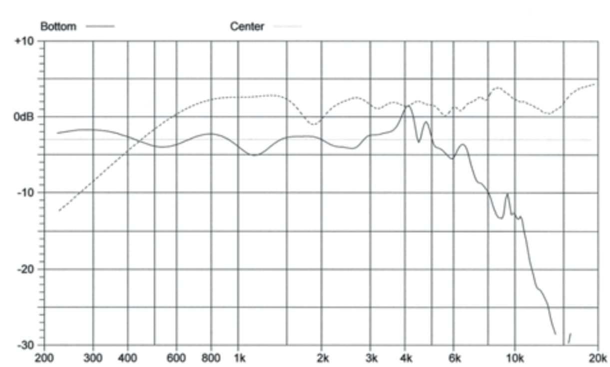

FIGURE 3: Responses of woofer and tweeter used in two-driver systems.

Doppler distortion or destruction of the tweeter. Note also that the point of linear phase is several degrees below the tweeter axis. The magnitude and phase shift versus frequency plots are at a vertical angle of –12°, which you can possibly correct by putting a step in the front panel. The magnitude polar plot is also a mess and does not show an optimum response at the angle of best phase performance.

The cure for the peak in the HP response at the tweeter's resonance is to place a series R-L-C network across the tweeter in an effort to cancel the impedance rise. **Figure 5** shows the same system with this network added and a step in the front panel to move the nearly linear phase point to 0°. The response plots are now on the tweeter's axis with summation at infinity. The system still has lobing problems where the response at 0° is not the largest response relative to other angles.

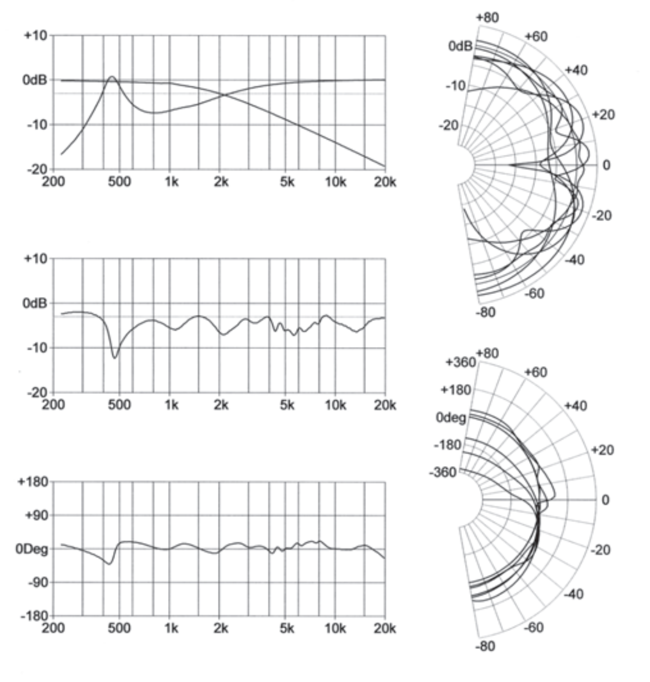

FIGURE 4: Performance of two-way system with real drivers and first-order crossover.

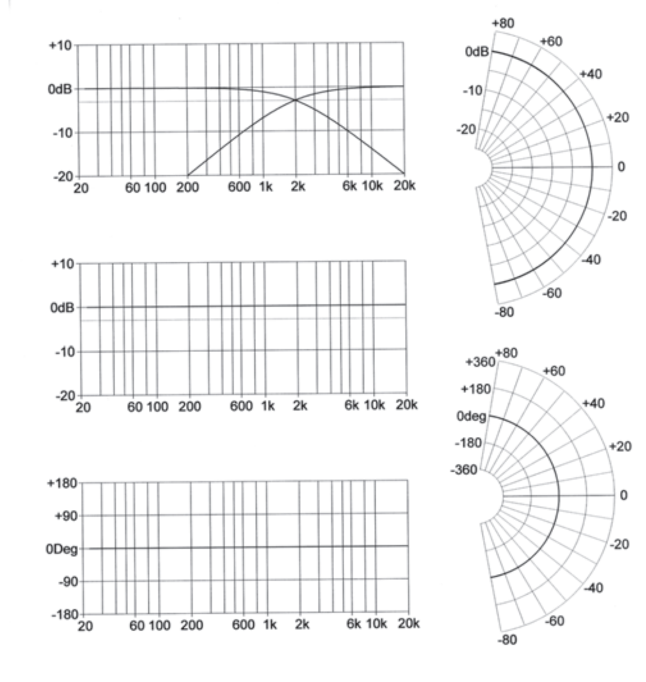

FIGURE 6: Performance of ideal coaxial driver with first-order crossover.

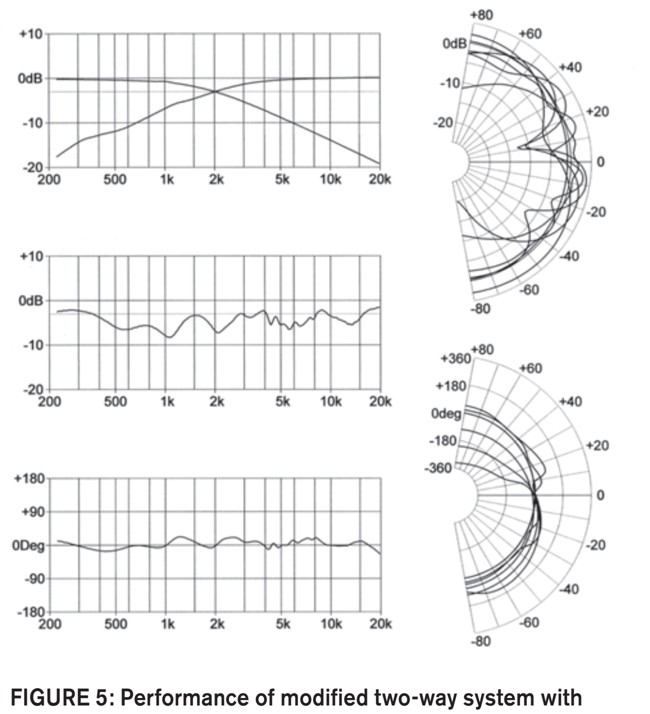

FIGURE 5: Performance of modified two-way system with real drivers and first-order crossover.

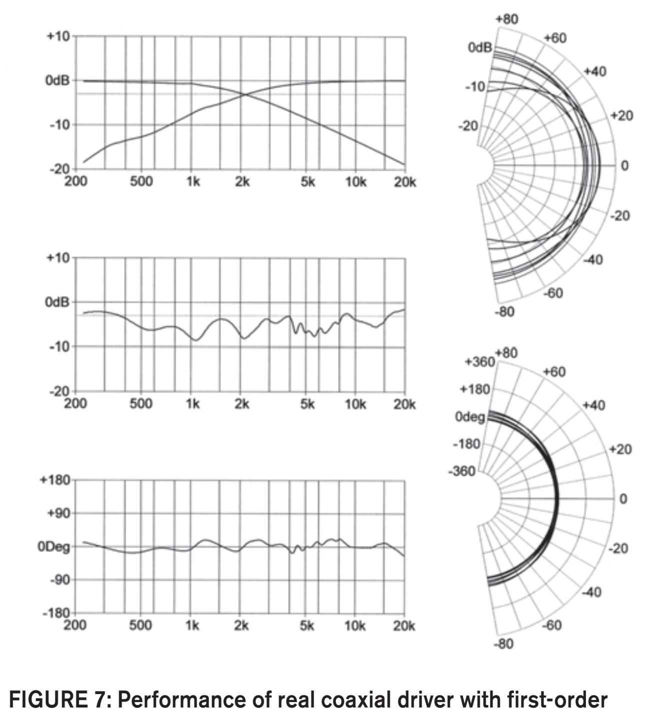

FIGURE 7: Performance of real coaxial driver with first-order crossover.

In summary, the first-order CO with two drivers is not a great approach to building a linear-phase system. Is there any cure? As noted earlier, the coaxial driver has a major advantage, and **Fig. 6** shows the response of an ideal coaxial driver with first-order CO. This looks beautiful. It is phase linear at all angles and has no lobes to cause trouble.

When a real coaxial driver is modeled (the same two drivers located at the same location), the performance is still quite good (**Fig. 7**). Note this still requires the network to cancel the tweeter-resonance-impedance rise and that the manufacturer has properly offset the two acoustic origins. Clearly you have a better shot at building a two-way phase-linear system with a good coaxial driver.

Another helpful consideration is to build with a symmetrical (D'Appolito) configuration of woofer over tweeter over woofer (WTW). Note that this requires a tweeter with 6dB higher voltage sensitivity than the woofers. **Figure 8** shows the performance of a WTW system with ideal drivers all flush-mounted in a flat front panel with 6″ CTC spac-

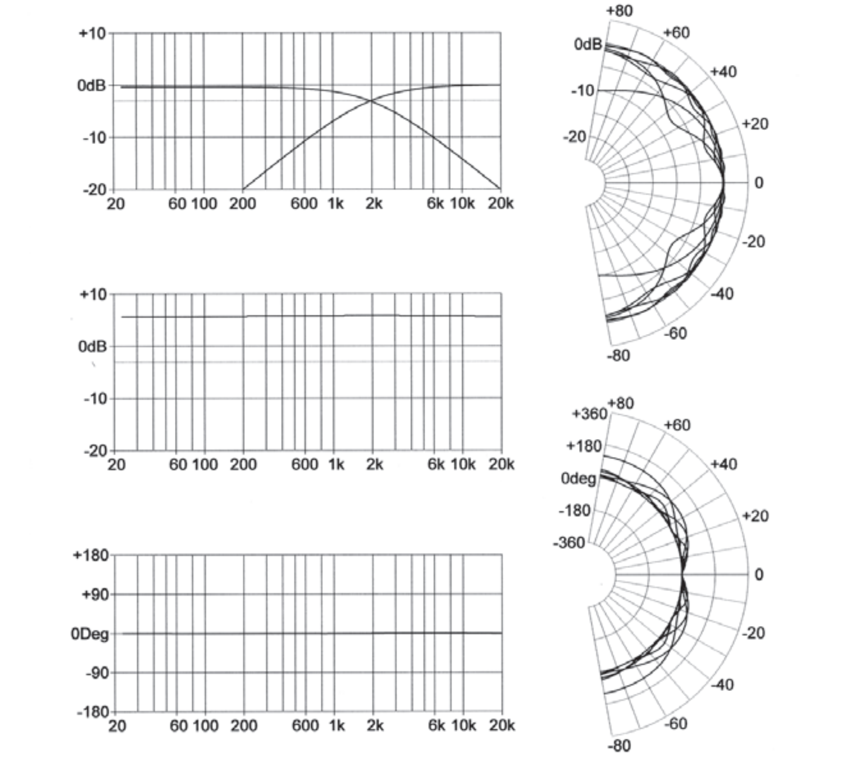

FIGURE 8: Performance of WTW symmetrical system with ideal drivers and first-order crossover.

ing between drivers. The system is linear phase at 0° relative to the tweeter axis and goes bad slowly with vertical angle change. The magnitude response is best at 0° and no lobes exceed the on-axis response. This is a good-looking system if only you could build it.

Figure 9 shows the performance of the WTW system with first-order CO when I install the real drivers. Note this system requires the network to remove the tweeter resonance impedance rise and a stepped front panel (tweeter set back slightly) to achieve the indicated performance. This approach has linear phase at 0° relative to the tweeter axis, which goes bad slowly. It also has less severe magnitude peaks than the non-symmetrical approach; i.e., reduced lobing problems.

If you plan to build a two-way linear-phase system with a first-order CO, you must look for a good coaxial driver or use the symmetrical WTW approach.

THE VARIOUS "FILL DRIVER" CROSSOVERS

The article by Stokes shows three passive implementations of the "fill driver" approach. There are second-order designs by both Yamanaka and Baekgaard and a third-order design by Baekgaard. I will investigate all these approaches, which require three drivers. **Figure 10** shows responses of the drivers that will be used in all real driver investigations requiring three drivers.

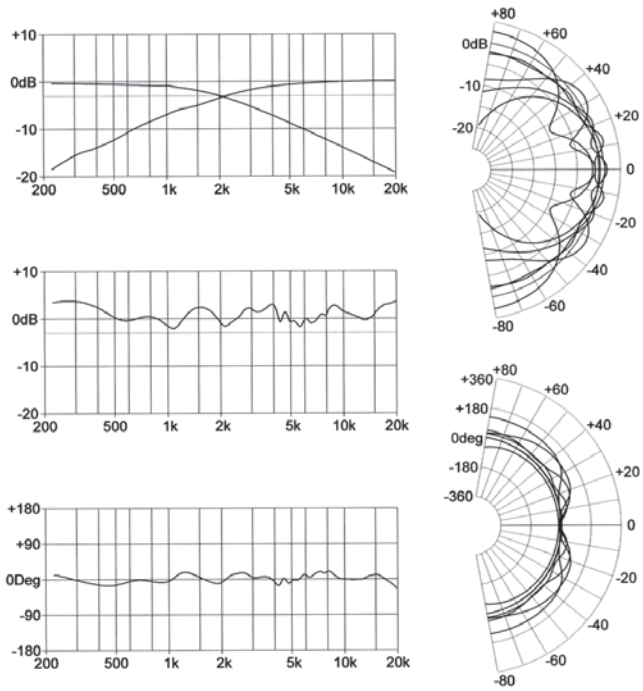

FIGURE 9: Performance of WTW symmetrical system with real drivers and first-order crossover.

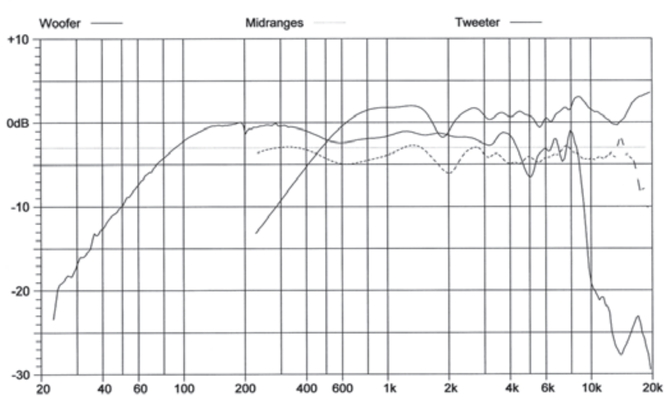

FIGURE 10: Responses of three drivers used in three-driver investigations.

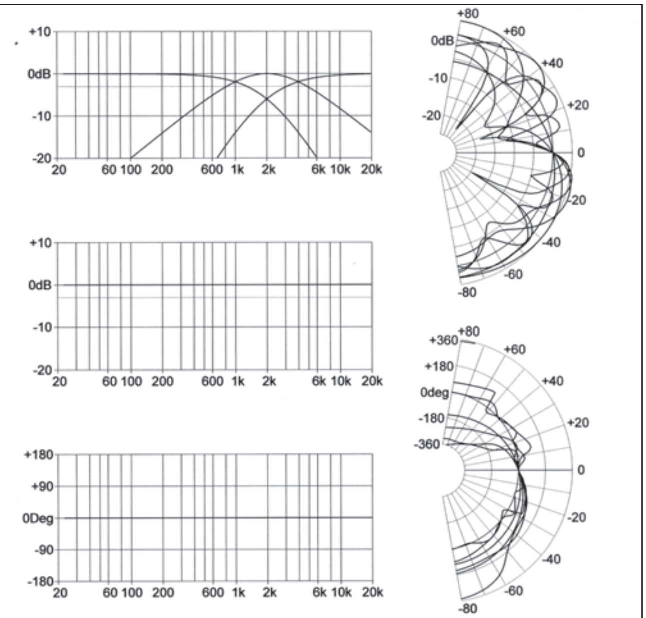

FIGURE 11: Performance of Yamanaka second-order crossover with ideal drivers.

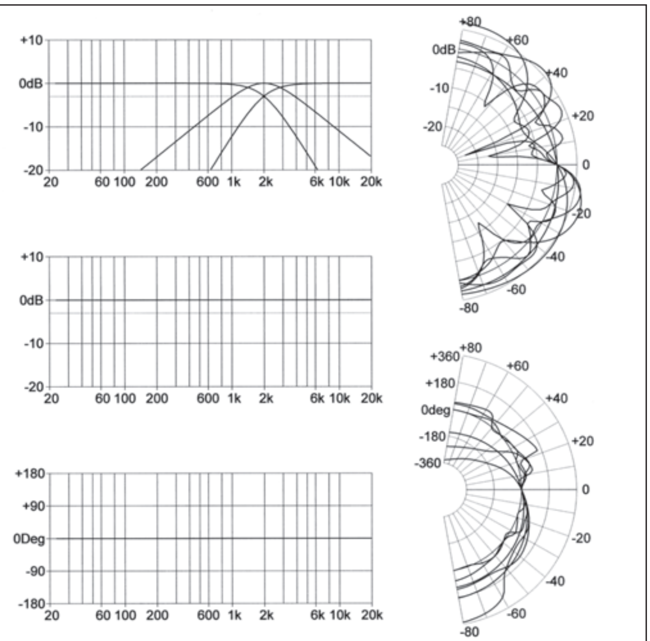

FIGURE 12: Performance of Baekgaard second-order crossover with ideal drivers.

Wideband drivers are identified in **Table 1**. I obtained these drivers from Madisound Speaker Components, who advised me some of them are of limited availability. Note that this tweeter seems very sensitive to its physical environment. Measured in the test baffle, it is very flat, while the curve in **Fig. 10** shows its response mounted in an enclosure with other drivers and grille cloth.

For the fill speaker study, the 6½″ woofer is physically at the bottom, while the 4″ midrange used as the fill speaker is located between the woofer and tweeter. The vertical CTC woofer to midrange spacing is 6″, and the vertical CTC midrange to tweeter spacing is 4.25″. I will use the same spacing when considering ideal drivers.

Figure 11 shows the performance of the second-order Yamanaka CO with ideal drivers. It sums at infinity to 0dB magnitude and 0° phase shift as predicted. The phase shift polar plot shows that it leaves linear phase slowly. However, the magnitude polar plot indicates very bad lobing problems with +5dB lobes off the listening axis.

Figure 12 illustrates the performance for the ideal-driver second-order Baekgaard CO with even worse lobing problems than the Yamanaka approach. **Figure 13** shows the performance with the ideal-driver third-order Baekgaard approach. Note that the fill speaker must have a 6dB higher voltage sensitivity than the other drivers. The lobing problem is even worse, with lobes of about +10dB relative to the 0° listening axis. The performance of these three-driver approaches was so poor that I did not study real drivers.

To give you an idea of what the lobing looks like on a typical speaker design, **Fig. 14** displays the performance of a two-way system with third-order Butterworth CO and ideal drivers. A couple of frequencies near the CO frequency have lobes slightly above the listening axis response, but nothing like what is shown for the fill speaker approaches. In **Fig. 14** both drivers have the same polarity. This CO also works with the tweeter inverted (**Fig. 15**). While neither approach is linear phase, the inverted tweeter has far less total phase shift over the audio band.

I can't recommend any of the fill driver approaches because of their severe lobing problems. Perhaps whoever said if you have three drivers you should build a three-way system was wise after all. You will later see whether a symmetrical array helps with these COs, noting that five drivers are required.

SANDRIK'S MINIMUM-PHASE CROSSOVER

Sandrik's approach is to design a normal first-order CO and then add additional components to increase the rolloff slope at some distance from the actual CO frequency. **Table 2** shows his recommendation of where to place the slope increase based on how much you increase the slope. He recommends that you end up with a final slope of -12dB/octave for the woofer LP, meaning you add an additional first-order CO ahead of the original first-order but designed for twice the CO frequency. For the tweeter HP he recommends a final 24dB/octave slope, meaning you add a third-order CO ahead of the original first-order CO but designed at one-fourth the CO frequency. Sandrik did not show a basic implementation.

I have developed the approach shown in **Figure 16**. For the HP you zobel the tweeter to a resistance and then add the capacitor (C1) for the first-order CO. You then add a series Rt-L1 to "zobel" the capacitor and driver. This results in a resistive load on the pre-CO equal to that of the driver and its zobel. The approach is the same for the woofer LP except you need a series Rw-C2 to compensate for the driver, its zobel, and the first-order CO inductor (L2).

I investigated several versions of Sandrik's approach. Here the ideal woofer and tweeter are located 6″ CTC in a vertical array. **Figure 17** illustrates the performance with both first-order pre-

TABLE 1: DRIVERS USED IN THREE-DRIVER SYSTEMS			
Driver	**Size**	**Make and Model***	**Notes**
Woofer	6½″	Vifa P17WJ00-08	Poly cone mid/bass
Midrange	4″	Vifa MG10SD09-08	Shielded, fiberglass cone
Tweeter	1″	Vifa XT25TG30-04	Dual concentric ring radiator

*The Vifa line is now known as the Peerless V-Line

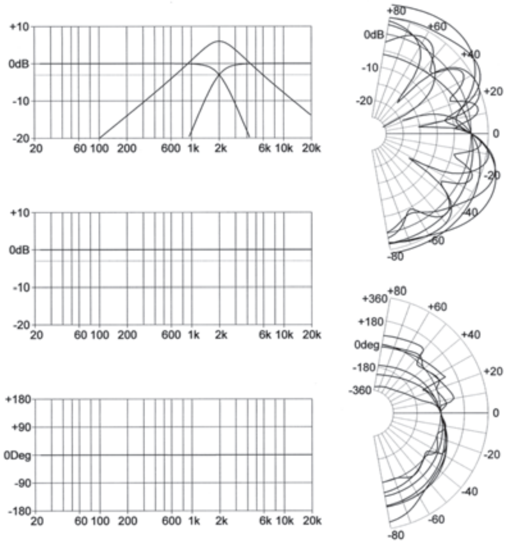

FIGURE 13: Performance of Baekgaard third-order crossover with ideal drivers.

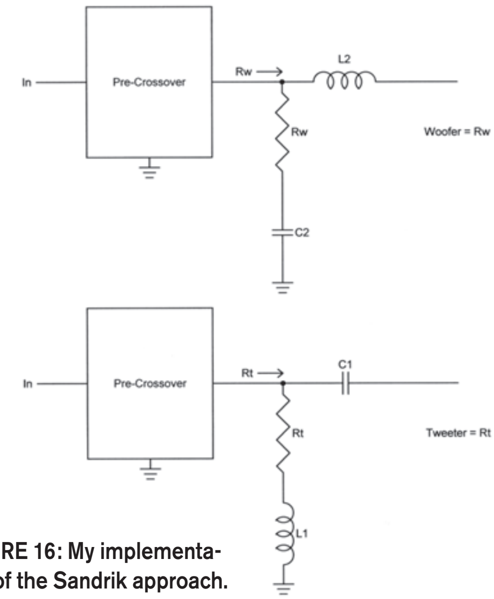

FIGURE 16: My implementation of the Sandrik approach.

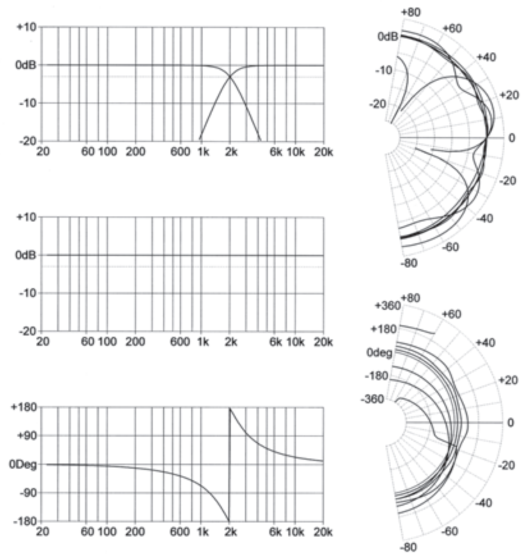

FIGURE 14: Performance of Butterworth third-order crossover with ideal drivers wired with the same polarity.

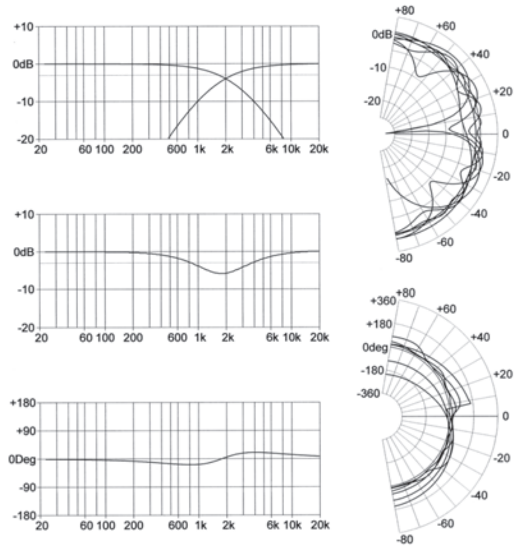

FIGURE 17: Performance of Sandrik approach with both first-order pre-crossover sections and ideal drivers.

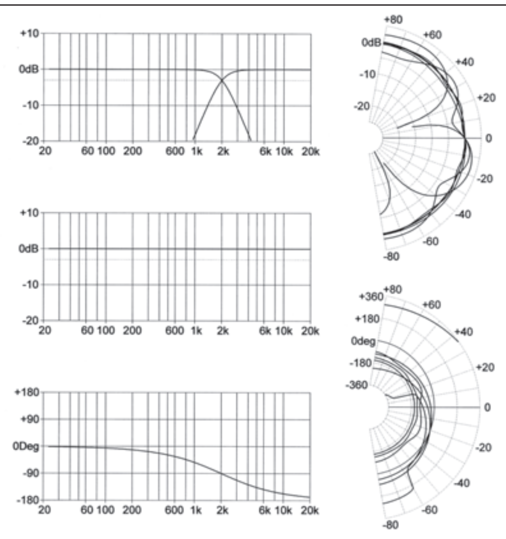

FIGURE 15: Performance of Butterworth third-order crossover with ideal drivers wired with inverted tweeter polarity.

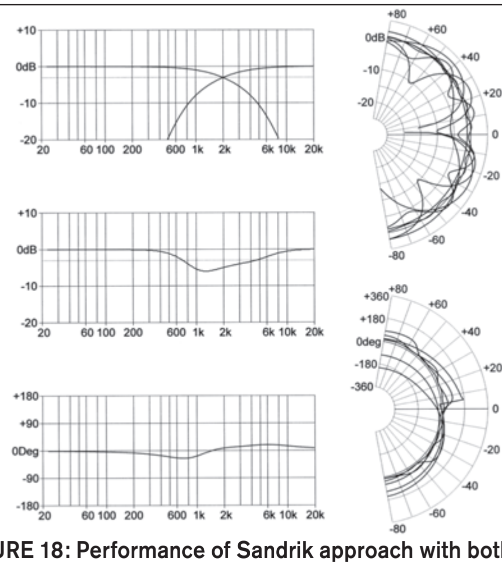

FIGURE 18: Performance of Sandrik approach with both second-order pre-crossover sections and ideal drivers.

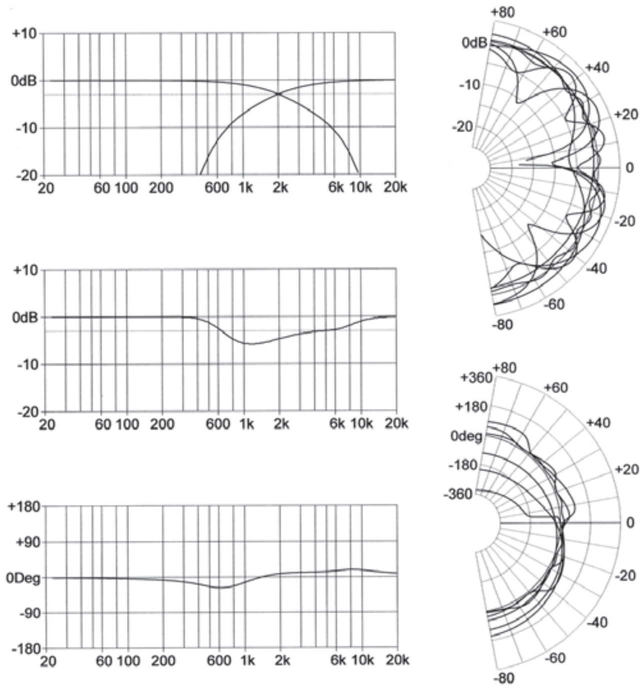

FIGURE 19: Performance of Sandrik approach with both third-order pre-crossover sections and ideal drivers.

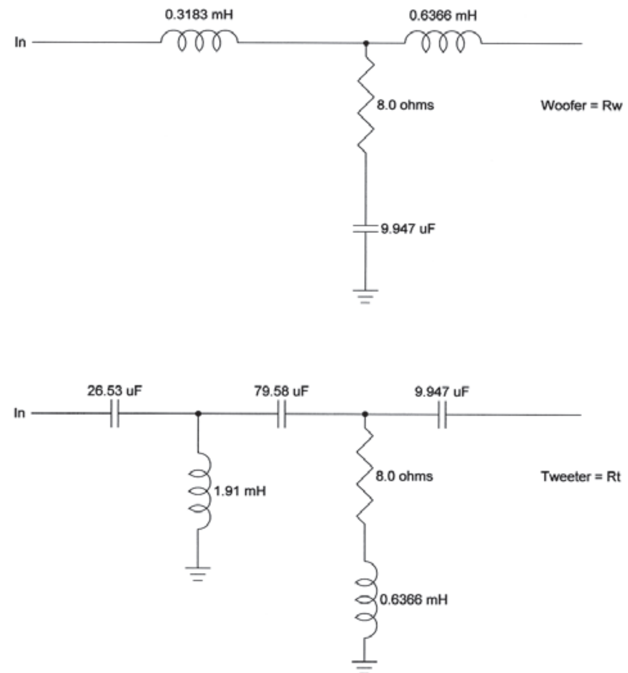

FIGURE 20: Schematic for my implementation of the Sandrik approach with first-order LP pre-crossover, third-order HP pre-crossover, and ideal drivers.

CO sections. The approach is minimum phase, but has a magnitude dip of about 6dB near the CO frequency. The magnitude polar plot shows that just above 0° one frequency nulls badly. **Figure 18** displays both second-order pre-CO sections with about the same result. The same performance is shown in **Fig. 19** for both pre-CO sections third-order.

Figure 20 is the schematic for my approach to Sandrik's recommendation of 12dB/octave final LP slope and +24dB/octave initial HP slope. The component count is becoming rather high. **Figure 21** shows the performance of this configuration with, again, good control of the phase, but still with the magnitude dip and null just above 0°.

Perhaps I do not understand Sandrik's approach, or my implementation is poor. Sandrik states you need to experiment, so I tried playing with acoustic origin

TABLE 2: Sandrik's Recommendations of Where to Add Slope Increase

Final Slope	Frequency for LP Slope Increase	Frequency for HP Slope Increase
±12dB/octave	2 · fco	fco/2
±18 dB/octave	2.828 · fco	fco/2.828
±24 dB/octave	4 · fco	fco/4

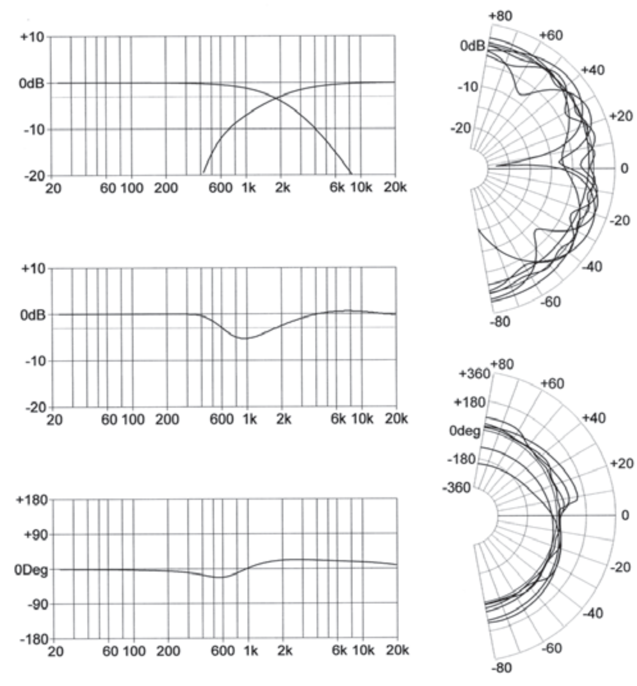

FIGURE 21: Performance of Sandrik approach with first-order LP pre-crossover, third-order HP pre-crossover, and ideal drivers.

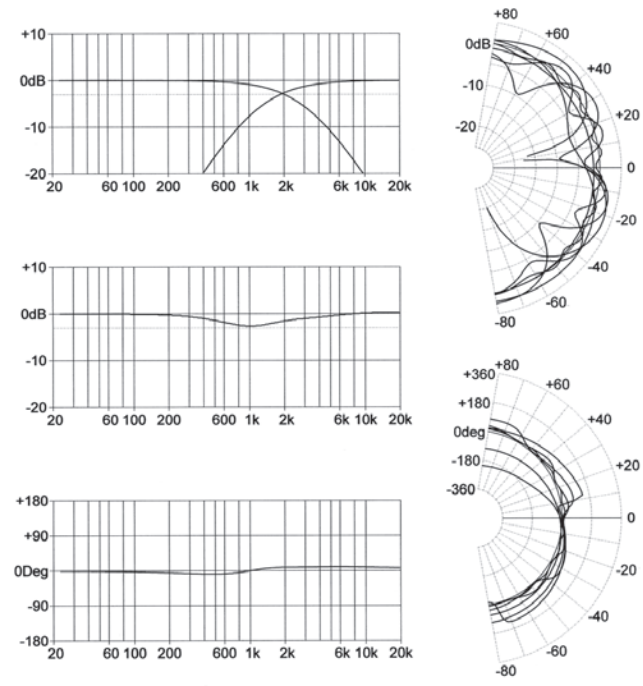

FIGURE 22: Performance of Sandrik approach with both first-order pre-crossover sections, ideal drivers, and 30% overlap.

locations, CO component values, and so on, with not much improvement. What seemed to help was putting some overlap in the original first-order CO sections, but not changing the pre-CO sections. Using 30% overlap (LP designed at 2600Hz, HP at 1400Hz) reduced the dip with both first-order pre-CO sections to under 3dB (**Fig. 22**). Note the lobing performance is not great. Finally, I tried the recommended first-order LP pre-CO and third-order HP pre-CO with the 30% overlap (**Fig. 23**). The magnitude dip is still excessive, and the null just above 0° remains.

I did not have much luck with the Sandrik approach, so I did not bother modeling real drivers. Perhaps if you have drivers that tend to peak near 2kHz (or whatever CO frequency you use), this approach has merit, but be ready to experiment.

Next month the author continues his study of passive CO approaches for building linear-phase systems—Eds. *aX*

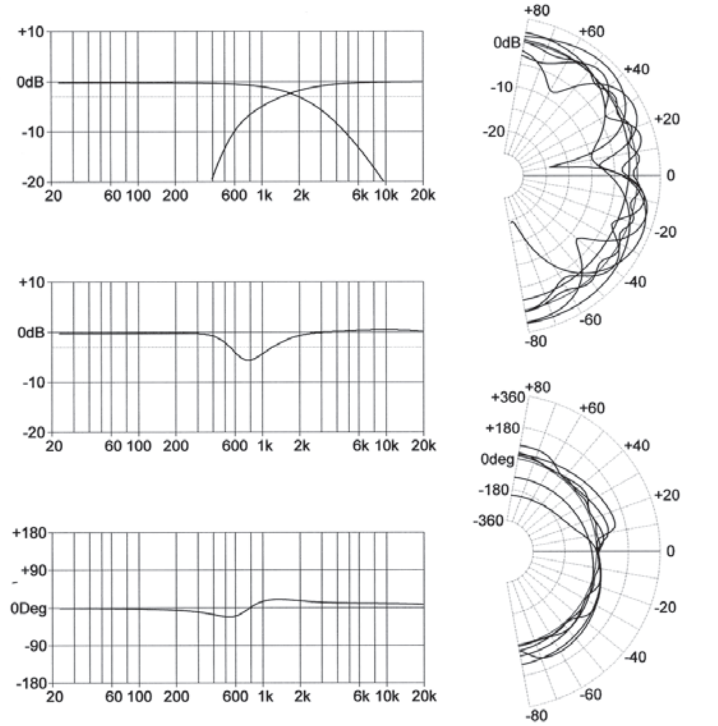

FIGURE 23: Performance of Sandrik approach with first-order LP pre-crossover, third-order HP pre-crossover, ideal drivers, and 30% overlap.

REFERENCES

1. Bill Waslo, "Time, Frequency, Phase, and Delay," *SB* 7/96, p. 12.

2. Many of the references will call the point where the sound appears to radiate from a driver the acoustic center. The currently preferred term is the acoustic origin. For this article you may consider the two terms interchangeable.

3. Bruno Carlsson, "Driver-Offset-Related Phase Shifts in Crossover Design," *SB* 1/95, p. 26, and 2/95, p. 26.

4. E. Baekgaard, "A Novel Approach to Linear Phase Loudspeakers using Passive Crossover Networks," *J*AES (May 1977), pp. 284-294.

5. Steve Stokes, "A Unique Crossover Design with Waveform Fidelity," *aX* 1/07, p. 42.

6. J. F. Conniff, "Baekgaard Revisited," *SB* 2/96, p. 30.

7. G. R. Koonce, "The Baekgaard Crossover Technique," *SB* 2/95, p. 20.

8. T. E. Sandrik, "Minimum Phase, High-Order Filtering," *SB* 4/98, p. 16.

9. John Kreskovsky, "A Transient-Perfect Second-Order Passive Crossover," *aX* 5/01, p. 22.

10. John Kreskovsky, "Designing an Active Transient-Perfect Second-Order Crossover," *aX* 12/02, p. 36.