RaneNote 107

LINKWITZ-RILEY CROSSOVERS

- ZERO LOBING ERROR
- 24 dB/OCTAVE SLOPES
- STATE VARIABLE SOLUTION
- TIME CORRECTION

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The assumption is made that the reader is familiar with active crossovers and how they are used in professional sound systems. For those who are not and want to review the basics, one of the best references will be found in an article entitled. “Crossover Basics”. by Richard Chinn, in the September 1986 issue of STEREO REVIEW.

INTRODUCTION

What’s a Linkwitz-Riley, and why do I care? First off, its not “what’s”, but “who”: Siegfried Linkwitz and Russ Riley are two Hewlett-Packard R&D engineers who wrote a paper[1] in 1976 describing a better mousetrap in crossover design. Largely ignored (or unread) for the past several years, it is now receiving the attention it deserved in 1976. Typical of most truly useful technical papers, it is very straight-forward and unassuming. A product of careful analytical attention to details, with a wonderfully simple solution.

The, “why do I care?”, part is easily answered by stating that a Linkwitz-Riley crossover will give you a clearer and more accurate sound system. Period. It will automatically clean up the messiness that mars most systems at their crucial crossover points. (It is at the crossover points that most systems lose it.)

It is seldom whether to cross over, but rather, how to cross over. Active crossovers have proliferated over the past few years at a rate equal to the proverbial lucky charm. The potential crossover buyer must choose from among a dozen different manufacturers and designs. Some are adequate; some are even good; but none seem to offer just the right mix of features, technology and cost. Until now.

An attempt will be made within this Note to present the essence of a Linkwitz-Riley design, and to introduce Rane’s answer to a truly affordable crossover that features the very best technology, with exactly the right features.

A 4th-order state variable active filter[2] has been developed by Rane Corporation to implement the Linkwitz-Riley alignment for crossover coefficients. In addition to the active crossover, the unit features a variable time delay circuit so the user may effectively “move” the drivers into front-to-back alignment. With both these tools, the professional sound person now has the means to smooth out and perfect the crucial crossover region, resulting in a sound system that exhibits unsurpassed clarity and accuracy.

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A PERFECT CROSSOVER

Mother nature gets the blame. Another universe, another system of physics, and the quest for a perfect crossover might not be so difficult. But we exist here and must make the best of what we have. And what we have is the physics of sound, and of electromagnetic transformation systems that obey these physics.

A perfect crossover, in essence, is no crossover at all. It would be one driver that could reproduce all frequencies equally well. Since we cannot have that, then second best would be multiple speakers, along the same axis, with sound being emitted from the same point, i.e., a coaxial speaker that has no time shift between drivers. This gets closer to being possible, but still is elusive. Third best, and this is where we really begin, is multiple drivers mounted one above the other with no time shift, i.e., non-coincident drivers adjusted front-to-rear to compensate for their different points of sound propagation. Each driver would be fed only the frequencies it is capable of reproducing. The frequency dividing network would be, in reality, a frequency gate. It would have no phase shift or time delay. It's amplitude response would be absolutely flat and its roll-off characteristics would be the proverbial brick wall. (Brings a tear to your eye, doesn't it?)

Using digital technology, such a crossover is possible, but not at a price that is acceptable to most working musicians. What is possible at an affordable price is a very good compromise known as the Linkwitz-Riley crossover.

LINKWITZ-RILEY CROSSOVER

What distinguishes the Linkwitz-Riley crossover design from others is its perfect combined radiation pattern of the two drivers at the crossover point. Stanley P. Lipshitz[3] has coined the term "lobing error" to describe this crossover characteristic. It's a good term and should spread through the industry as the standard. It derives from the examination of the acoustic output plots (at crossover) of the combined radiation pattern of the two drivers (see Figures 1 & 2). If it is not perfect. the pattern forms a lobe that exhibits an off-axis frequency dependent tilt with severe amplitude peaking.

Interpretation of Figure 1 is not particularly obvious. Let's back up a minute and add some more details. For simplicity, only a two way system is being modeled. The two drivers are mounted along the vertical center of the enclosure (there is no side-to-side displacement, i.e., one driver is mounted on top of the other.) Any front-to-back time delay between drivers has been corrected. The figure shown is a polar plot of the side-view, i.e., the angles are vertical angles.

It is only the vertical displacement sound field that is at issue here. All of the popular crossover types (constant voltage[4], Butterworth all-pass[5], etc.) are well behaved along the horizontal on-axis plane. To illustrate the geometry involved here, imagine attaching a string to the speaker at the mid-point between the drivers. Position the speaker such that the mid-point is exactly at ear level. Now pull the string taut and hold it up to your nose (go on, no one's looking). The string should be parallel to the floor. Holding the string tight, move to the left and right. This is the horizontal on-axis plane. Along this listening plane, all of the classic crossover designs exhibit no problems. It is when you lower or raise your head below or above this plane that the problems arise. This is the crux of Siegfried Linkwitz's contribution to crossover design. After all these years and as hard as it is to believe, he was the first person to publish an analysis of what happens off-axis with non-coincident drivers (not-coaxial). (Others may have done it before, but it was never made public record.)

Figure 1A represents a side view of the combined acoustic radiation pattern of the two drivers emitting the same single frequency. That is, a plot of what is going on at the single crossover frequency all along the vertical plane. The pattern shown is for the popular 18 dB/octave Butterworth all-pass design with a crossover frequency of 1700 Hz and drivers mounted 7 inches apart[1].

What is seen is a series of peaking and cancellation nodes. Back to the string. Holding it taut again and parallel to the floor puts you on-axis. Figure 1A tells us that the magnitude of the emitted 1700 Hz tone will be 0 dB (a nominal reference point). As you lower your head, the tone will increase in loudness until a 3 dB peak is reached at 15 degrees below parallel. Raising your head above the on-axis line will cause a reduction in magnitude until 15 degrees is reached where there will be a complete cancellation of the tone. There is another cancellation axis located 49 degrees below the on-axis. Figure 1B depicts the frequency response of the three axes for reference.

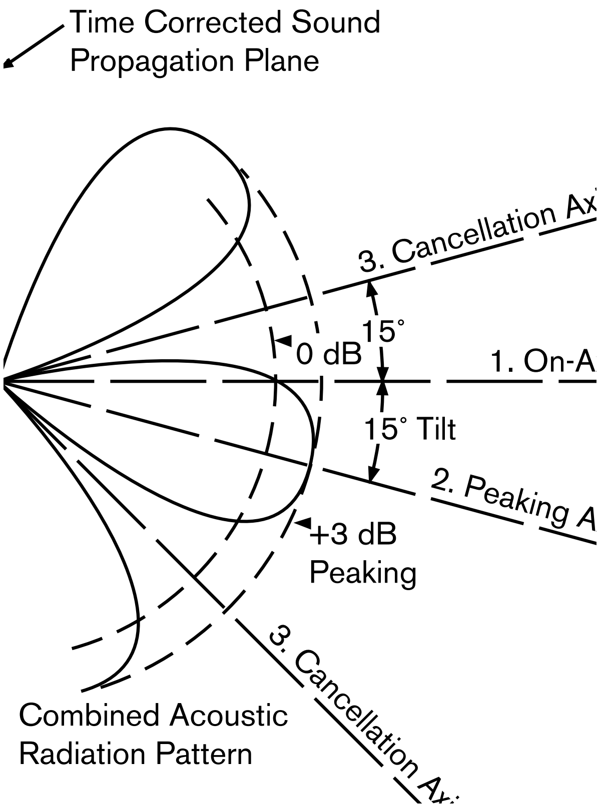

Figure 1A.

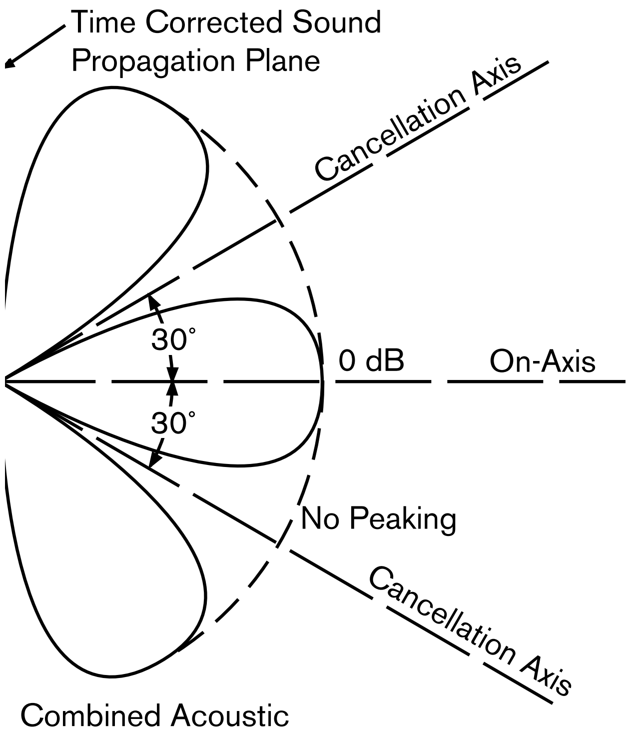

Figure 2. Linkwitz-Riley Radiation Response at Crossover

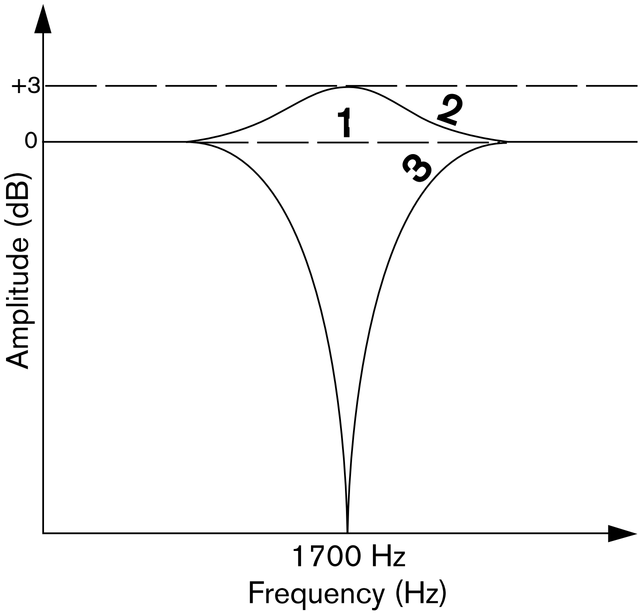

Figure 1B.

For a constant voltage design, the response looks worse, having a 6 dB peaking axis located at -20 degrees and the cancellation axes at +10 and -56 degrees, respectively. The peaking axis tilts toward the lagging driver in both cases, due to phase shift between the two crossover outputs.

The cancellation nodes are not due to the crossover design, they are due to the vertically displaced drivers. (The crossover design controls *where* cancellation nodes occur, not *that* they occur.) The fact that the drivers are not coaxial means that any vertical deviation from the on-axis line will result in a slight, but very significant differences in path lengths to the listener. This difference in distance traveled is effectively a phase shift between drivers. And this causes cancellation nodes — the greater the distance between drivers, the more nodes.

In distinct contrast to these examples is Figure 2, where the combined response of a Linkwitz-Riley crossover design is shown. There is no tilt and no peaking. Just a perfect response whose only limitation is the dispersion characteristics of the drivers used. The main contributor to this ideal response is the in-phase relationship between the crossover outputs.

Two of the cancellation nodes are still present but are well defined and always symmetrical about the on-axis plane. Their location changes with crossover frequency and driver mounting geometry (distance between drivers). With the other designs, the peaking and cancellation axes change with frequency and driver spacing.

Figure 1. Butterworth All-Pass Design Radiation Pattern at Crossover.

Let's drop the string and move out into the audience to see how these cancellation and peaking nodes affect things. Figure 3 shows a terribly simplified, but not too inaccurate stage-audience relationship with the characteristics of Figure 1 added.

The band is cooking and then comes to a musical break. All eyes are on the flautist, who immediately goes into her world-famous 1700 Hz solo. So what happens? The people in the middle hear it sweet, while those up front are blown out of their seats, and those in the back are wondering what the hell's all the fuss!

Figure 4 shows the identical situation but with the Linkwitz-Riley characteristics of Figure 2 added. Now the people in the middle still hear everything sweet, but those up front are not blown away, and those in the back understand the fuss!

I think you get the point.

Now let's get real. I mean really real. The system isn't two way, it's four way. There isn't one enclosure, there are sixteen. No way are the drivers 7 inches apart — try 27. And time corrected? Forget it.

Can you even begin to imagine what the vertical off-axis response will look like with classic crossover designs? The further apart the drivers are, the greater the number of peaks and cancellations, resulting in a multi-lobe radiation pattern. Each crossover frequency will have its own set of patterns, complicated by each enclosure contributing even more patterns. And so on.

(For large driver spacing the Linkwitz-Riley design will have as many lobes as other designs, except that the peaks are always 0 dB, and the main lobe is always on-axis.)

Note that all this is dealing with the direct sound field, no multiple secondary arrivals or room interference or reverberation times are being considered. Is it any wonder that when you move your realtime analyzer microphone 3 feet you get a totally different response?

Now let me state clearly that using a Linkwitz-Riley crossover will not solve all these problems. But it will go a long, long way toward that goal.

The other outstanding characteristic of the Linkwitz-Riley alignment is the rolloff rate of 24 dB/octave (Figure 5). With such a sharp drop-off, drivers can be operated closer to their theoretical crossover points without the induced distortion normally caused by frequencies lying outside their capabilities. Frequencies just one octave away from the crossover point are already attenuated by 24 dB (a factor or about 1/16). The importance of sharp cutoff rate and in-phase frequency response of the crossover circuitry cannot be over-stressed in contributing to smooth overall system response.

A summary of the characteristics of a Linkwitz-Riley crossover reads:

1. Absolutely flat amplitude response through out the passband with a steep 24 dB/octave rolloff rate after the crossover point.
2. The acoustic sum of the two driver responses is unity at crossover. (Amplitude response of each is -6 dB at crossover, i.e., there is no peaking in the summed acoustic output)
3. Zero phase difference between drivers at crossover. (Lobing error equals zero, i.e., no tilt to the polar radiation pattern.) In addition, the phase difference of zero degrees through crossover places the lobe of the summed acoustic output on axis at all frequencies.
4. The low pass and high pass outputs are everywhere in phase. (This guarantees symmetry of the polar response about the crossover point)
5. All drivers are always wired the same (in phase).

A casual reading of the above list may suggest that this is, indeed, the perfect crossover. But such is not so. The wrinkle involves what is known as "linear phase". A Linkwitz-Riley crossover alignment is not linear phase: meaning that the amount of phase shift is a function of frequency. Or, put into time domain terms, the amount of time delay through the filter is not constant for all frequencies. Which means that some frequencies are delayed more than others. (In technical terms, the network has a frequency-dependent group delay. but with a very gradually changing characteristic.)

Is this a problem? Specifically, is this an audible "problem"? In a word, no.

Much research has been done on this question[6-9], with approximately the same conclusions: given a slowly changing non-linear phase system, the audible results are so minimal as to be non-existent; especially in the face of all of the other system non-linearities. And with real-world music sources (remember music?), it is not audible at all.

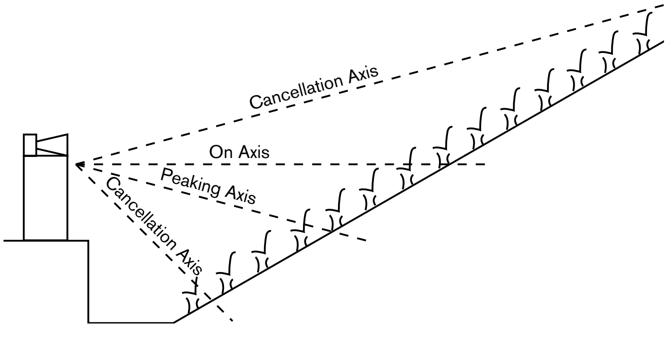

Figure 3. Butterworth All-Pass Crossover Stage-Audience Relationship

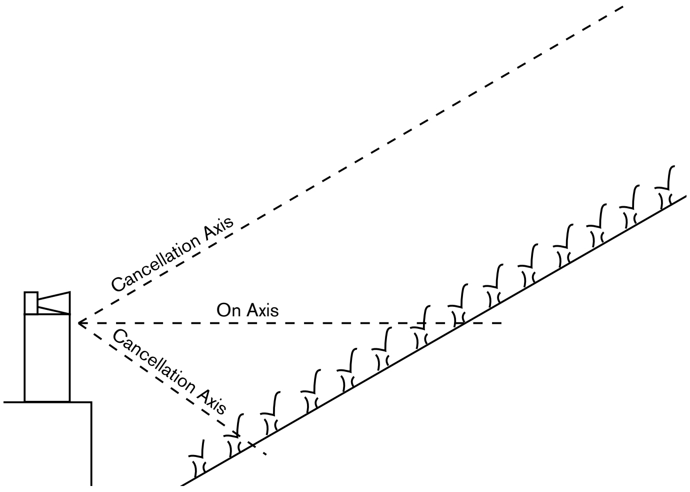

Figure 4. Linkwitz-Riley Crossover Stage Audience Relationship

STATE VARIABLE SOLUTION

One of the many attractions of the Linkwitz-Riley design is its utter simplicity, requiring only two standard 2nd-order Butterworth filters in series. The complexities occur when adjustable crossover frequencies are required.

After examining and rejecting all of the standard approaches to accomplish this task, Rane developed a 4th-order state-variable filter specifically for implementing the Linkwitz-Riley crossover. The state-variable topology was chosen over other designs mainly for the following reasons:

1. It provides simultaneous high-pass and low-pass outputs that are always at exactly the same frequency.
2. Changing frequencies can be done simultaneously on the high-pass and low-pass outputs without any changes in amplitude or Q (quality factor).
3. The sensitivities of the filter are very low. (Sensitivity is a measure of the effects of non-ideal components on an otherwise, ideal response.)
4. It offers the most cost-effective way to implement two 4th-order responses with continuously variable crossover frequencies.

TIME OR PHASE CORRECTION

Implicit in the development of the theory of a Linkwitz-Riley crossover design is the key assumption that the sound from each driver radiates from the some exact vertical plane, i.e., that the drivers have no time delay with respect to each other. The crossover then prohibits any lobing errors as the sound advances forward simultaneously from the two drivers. Figure 6 illustrates such a front-to-back displacement, which causes the lobing error shown in Figure 7a.

A Linkwitz-Riley crossover applied to drivers that are not time-corrected loses most of its magic. The lobing error is no longer zero; it exhibits a frequency dependent tilt with magnitude errors as shown in Figure 7b.

This being the case, Rane incorporates either adjustable time delay or phase shift circuits into its Linkwitz-Riley crossovers.

(See also Rane Note 119 entitled Linkwitz-Riley Active Crossovers Up To 8th-Order: An Overview, for additional information.)

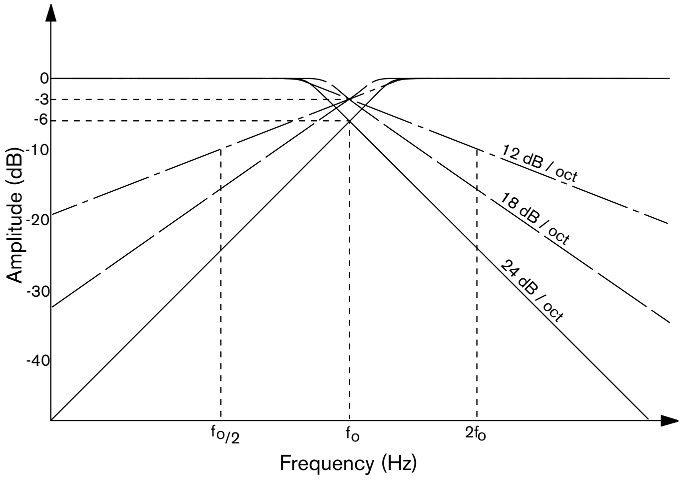

Figure 5. Frequency Response of 4th Order Linkwitz-Riley Active Crossover

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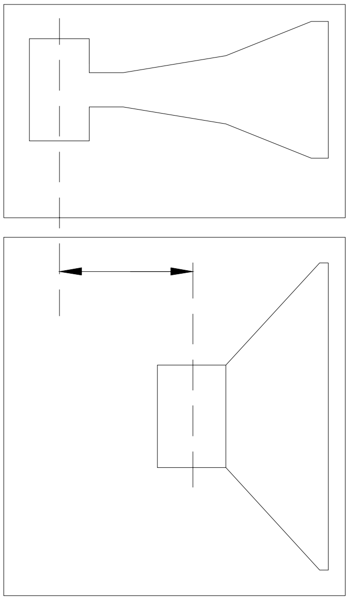

Figure 6. Driver Displacement

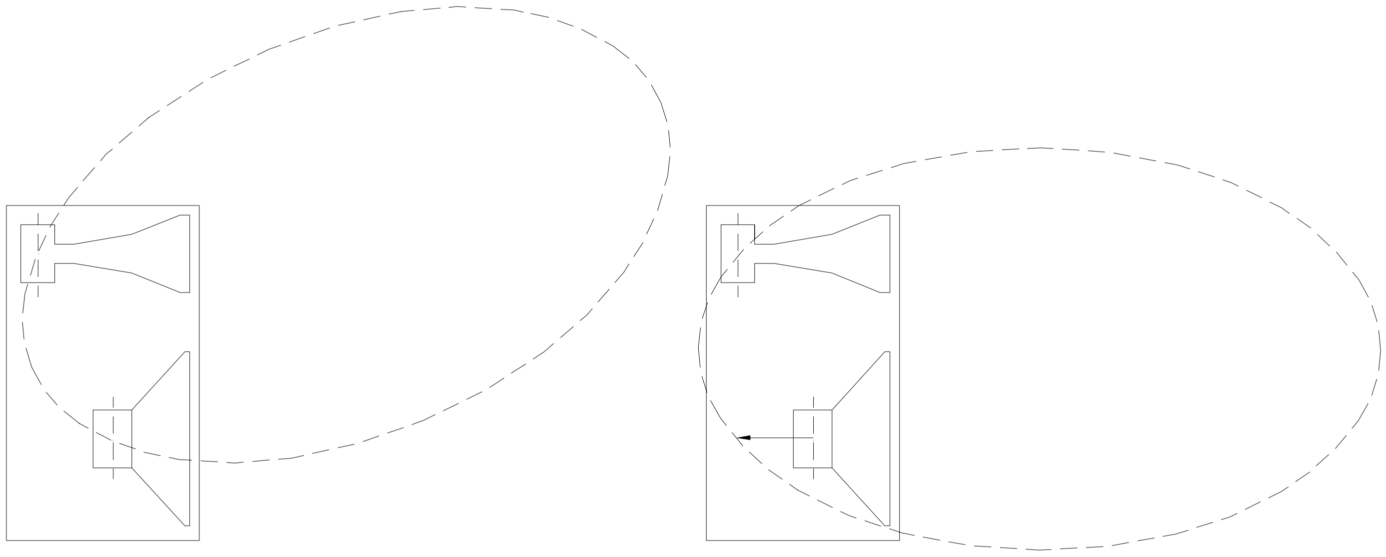

Figure 7a Without Time Alignment.

Figure 7b. With Time Alignment.

Figure 7. Adding Delay to the Forward Driver Time-Aligns the Phase of Both Drivers, Reducing Lobing Error.