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Chapter 4 – Crossover Types

Overview

Crossover networks are essential components in loudspeaker design, responsible for dividing the audio frequency spectrum into separate bands that are sent to appropriate driver units (e.g., tweeters, midrange, woofers). This chapter presents a thorough classification and analysis of various crossover types, focusing on their characteristics, advantages, limitations, and practical considerations. The discussion spans from simple first-order crossovers to more complex higher-order designs, including notable filter types like Butterworth, Bessel, Linkwitz-Riley, and Chebyshev, among others.

1. *Introduction to Crossover Types*

Crossover networks divide the audio spectrum into frequency bands that are routed to different loudspeaker drivers (e.g., woofer, midrange, tweeter).
This chapter classifies crossovers by their acoustic summation behavior, rather than by circuit topology. The focus is on how filtered outputs combine in amplitude, phase, and power.

Electrical correctness does not guarantee acoustic correctness; summation behavior is the decisive factor.

The primary goal of a crossover is not just to separate frequencies electrically, but to achieve smooth summation acoustically in a seamless manner. Acoustic summation (interaction in air) is more critical than electrical theory in terms of phase and amplitude in the air, rather than the theoretical perfection of the electrical circuit alone.

2. Fundamental Concepts

2.1 *Poles and Zeros*

Poles and Zeros: The chapter begins by explaining poles and zeros in the context of filter transfer functions. Poles cause the frequency respons to decrease at 6 dB/octave; zeros cause an increase at 6 dB/octave but are not equivalent to simple highpass filters. Poles and zeros can appear in conjugate pairs, producing resonances or notches.

All-Pole Crossovers: Composed entirely of all-pole filters such as Butterworth, Bessel, and Linkwitz-Riley types, which have monotonic rolloff (response only goes down after cutoff).

Non-All-Pole Crossovers: Include inverse-Chebyshev and elliptical (Cauer) filters that incorporate zeros and poles, resulting in non-monotonic rolloffs with stopband notches.

Notch-Type Crossovers: Use inverse-Chebyshev or notch filters (e.g., Bainter filter).

All-pole filters dominate crossover design because predictable summation is more important than steepness.

Crossover filters are built using "poles" (which create the downward slope) and "zeros" (which create notches). All-pole filters are the industry standard for crossovers because they provide a smooth, predictable slide into silence (monotonic rolloff), whereas non-all-pole filters introduce erratic ripples that make acoustic summation difficult.

*3. **Crossover Classifications***

3.1 All-Pole and Non-All-Pole Crossovers comparison.

- All-pole crossovers
  Composed entirely of all-pole filters; smooth slopes.
- Non-all-pole crossovers
  Include zeros, producing ripples or notches.

3.2 ***Symmetry and Subtractive Crossovers***

Symmetric Crossovers: Filters with identical slopes at the crossover point, e.g., 12 dB/octave on both HF (high-frequency) and LF (lowfrequency) filters.

Asymmetric Crossovers: Differing slopes at the crossover point, such as 18 dB/octave on HF and 12 dB/octave on LF, which don’t generally sum to flat unless driver responses compensate.

Subtractive Crossovers: A form of asymmetric crossover where subtraction produces an output always with a 6 dB/octave slope. Time delays 14 can equalize slopes but require precise alignment (covered in Chapter 6)

The subtractive approach is theoretically elegant but practically limited.

Crossovers are categorized by how they treat signal energy. APC designs (like Linkwitz-Riley) prioritize flat amplitude on-axis, making them ideal for listening accuracy. CPC designs prioritize total power output but may sound uneven at the sweet spot. Subtractive designs offer perfect phase timing but are rarely used because they fail to protect tweeters adequately due to shallow slopes.

3.3 ***All-Pass Crossovers*** (APC):

Filter outputs sum acoustically to produce a flat sound pressure level (SPL) on-axis. Summation is vector addition including phase, and filters typically produce all-pass phase responses. Examples include first-order inverted, second-order Linkwitz-Riley, and third-order Butterworth crossovers.

Constant-Power Crossovers (CPC): Outputs sum to produce a flat power response (total acoustic power radiated), using RMS addition ignoring phase. Not widely used due to lack of flat on-axis response but sometimes advantageous in reverberant rooms.

APCs are preferred for flat on-axis response; CPCs are less common.

3.4 ***Constant-Voltage (Subtractive) crossovers***

• Definition: Differ from APCs; one output is generated by subtracting a filter output from the unfiltered input, resulting in linear-phase outputs capable of perfect waveform reconstruction.

• Advantages: Linear phase and waveform reconstruction; outputs sum to recreate the input waveform.

• Disadvantages: The subtracted output always has a shallow 6 dB/octave slope, which is often inadequate for driver protection.

4. Crossovers by Order

4.1 ***First-Order Crossovers***

• Characteristics: Only slope of 6 dB/octave; unique among all-pole crossovers in producing linear-phase and minimum-phase responses, allowing waveform reconstruction when summing outputs.

• Advantages: Simplest filter, lowest component count, lowest power loss.

• Disadvantages: Gentle slopes provide poor driver protection, risk tweeter damage from low frequencies, and require drivers well-behaved over wide frequency ranges.

• Phase Behavior: Without phase inversion, summed response is flat with zero phase shift; inverting one output yields an all-pass phase response shifting 180° over the audio band.

• Lobing Error: Due to broad overlap, the vertical radiation pattern tilts by 15°, upward or downward depending on output phase inversion; time 15 alignment and baffle spacing critically affect this.

• Group Delay: Normal connection shows flat group delay; inverted connection shows a flat section (~318 µs) rolling off across crossover region.

• Waveform Reconstruction: Only first-order allows perfect reconstruction of input waveforms (e.g., square wave).

• Solen Split First-Order Crossover: Variation that offsets cutoff frequencies (579 Hz lowpass, 1.726 kHz highpass) to reduce crossover overlap, causing a 6 dB dip in summed response unless one output is phase-inverted,

which reduces the dip to 1.2 dB .

• 3-Way First-Order Crossovers: Difficult due to shallow slopes and wide driver overlap; generally impractical.

First-order crossovers require drivers designed explicitly for this use.

4.2 ***Second-Order Crossovers*** (12 dB/octave)

Advantages Over First-Order: Steeper 12 dB/octave slopes reduce lobing and time-alignment sensitivity; widely used in passive crossovers for balance of complexity and performance.

• Phase Shift: Second-order filters have a 180° phase difference between outputs, causing a cancellation notch at crossover frequency if outputs

summed in phase.

• Polarity Inversion: Reversing one output eliminates the notch but introduces a +3 dB hump (Butterworth), or flat response (Linkwitz-Riley).

• Frequency Offsets: Adjusting cutoff frequencies of highpass and lowpass filters can reduce amplitude ripple and improve flatness.

• Driver Time Alignment: Less critical than first-order; 1-inch misalignment causes minimal amplitude errors (~fractions of dB).

• Second-Order Butterworth Crossover: Without phase inversion, produces deep notch; with inversion, +3 dB hump at crossover. Frequency offset of 1.30 reduces hump to ±0.45 dB ripples. Power response is flat without frequency offset but dips by 8 dB with offset, indicating trade-offs.

• Phase and Group Delay: Sum phase resembles first-order allpass; group delay lower than first-order crossover.

• Waveform Reconstruction: Fails completely due to phase shifts.

• Second-Order Linkwitz-Riley Crossover: Achieved by setting Q to 0.5, identical cutoff frequencies, outputs -6 dB at crossover. With one output inverted, summed amplitude response is perfectly flat. Power response has a -3 dB dip at crossover. Phase and group delay similar to Butterworth.

• Second-Order Bessel Crossover: Provides slower rolloff but maximally flat group delay.

4.3 ***Third-Order Crossovers*** (18 dB/octave)

- Reduced overlap and lower sensitivity to misalignment.

Butterworth:

- Flat summed amplitude and power.
- Phase difference 270° (90° with inversion).
- Prone to vertical tilting and coverage tilt.

Linkwitz-Riley:

- −3 dB dip in summed response.
- Offset ≈ 0.872 reduces ripple to ±0.33 dB.

Bessel:

- Dips and humps in summed response.
- Offset ≈ 1.22 improves flatness.

Chebyshev:

- Large peaks and dips.
- Offset provides limited improvement.

4.4 ***Fourth-Order Crossovers*** (24 dB/octave)

Provide excellent driver separation and low sensitivity to alignment errors.

Butterworth

- +3 dB hump in-phase.
- Offset ≈ 1.128 reduces ripple to ±0.47 dB.
- Flat power response (CPC).

Linkwitz-Riley

- Flat summed amplitude response (APC).
- −3 dB power dip.
- Outputs effectively in-phase (360°).
- Moderate group-delay peak.

Bessel

- Dips and humps in summed response.
- Offset ≈ 1.229 reduces deviation.

Linear-Phase

- Cannot achieve better than ±0.66 dB flatness.

Gaussian

- Slow rolloff.
- Offset ≈ 0.8045 reduces dip to −1.05 dB.

Legendre

- Faster rolloff than Butterworth.
- Offset ≈ 1.029 reduces ripple to ±0.39 dB.
- Significant group-delay peak.

Key notes/information

• **Phase Relationships:**

– Odd-order Butterworth crossovers have outputs 270° apart, which can cause lobing and coverage tilt.

– Even-order Linkwitz-Riley crossovers have outputs 360° apart; effectively in-phase, avoiding lobing.

– Reversing the phase of one output often improves summed response and phase behavior.

• **Frequency Offset Technique:**

– Adjusting crossover frequencies of lowpass and highpass filters (offset ratio) can reduce summation ripples (humps or dips).

– Works well for Bessel, Butterworth, and Linkwitz-Riley crossovers but less effective or impractical for Chebyshev filters.

• **Power Response vs Amplitude Response:**

– Amplitude response flatness is usually prioritized.

– Power dips or humps at crossover (e.g., -3 dB or +3 dB) are often minor concerns in typical listening environments.

• **Group Delay:**

– Lower-order filters tend to have less group delay and smaller peaks.

– Higher-order filters have steeper slopes but may cause more significant group delay peaking near crossover.

– Group delay impacts timing and phase coherence, influencing sound quality.

• **Filter Selection:**

– Butterworth and Linkwitz-Riley are the most commonly used crossover alignments.

– Bessel filters offer flat group delay but require frequency offset for flat amplitude summation.

– Chebyshev filters generally not recommended due to passband ripple and poor summation behavior.

• **Implementation Considerations:**

– Higher-order passive crossovers require more components (inductors, capacitors), increasing cost and losses.

– Trade-off between crossover slope steepness, phase behavior, and component complexity must be considered.

4.*5 Higher-Order Crossovers*

- Orders five through eight (up to 48 dB/octave).
- Narrow crossover region and strong driver protection.
- Increased group delay and component sensitivity.
- Typically implemented using DSP.

As crossover "order" increases, the slope becomes steeper.

1st Order: Perfect sound purity but dangerous for drivers and physically impractical.

2nd Order: Offers a balance of slope steepness, though polarity must be flipped for summation.

4th Order (specifically Linkwitz-Riley): The professional standard. It offers excellent driver protection and flat frequency response, and the drivers move in sync (in-phase), though it sacrifices some time-domain accuracy compared to 1st order.

5. *Frequency Offset Determination*

Frequency offsets adjust highpass and lowpass cutoff frequencies to flatten the summed amplitude response.

Procedures:

1. Simulate filters at equal cutoff frequencies.
2. Sum outputs and observe deviation.
3. Increase spacing for peaks; reduce spacing for dips.
4. Split offset evenly using the square root of the ratio.

Practical approach avoids complex algebra and uses modeling and component value tuning.

Note: This method is practical and avoids complex analytical solutions.

Ideal textbook formulas rarely work perfectly in the real world. Frequency offsetting is a "tuning" technique where the crossover points of the woofer and tweeter are deliberately misaligned (spread apart or pushed together) to smooth out bumps or dips in the final frequency response.

6. ***Specialized Crossover Concepts***

6.1 ***Filler-Driver Crossover***

• Adds an extra driver ("filler-driver") with a bandpass filter centered at crossover frequency to provide missing terms for linear-phase response.

• Used with second-order Butterworth crossover in-phase (normally reversed phase is used).

• Filler driver's bandpass filter has a low Q (~0.6667) and 6 dB/octave slopes.

• Implementation complexities:

– Requires extra driver, amplifier, filters.

– Increased cost and enclosure complexity.

• Filler-driver concept rarely used due to these drawbacks.

6.2 ***Duelund Crossover***

- Extension using two cascaded bandpass sections.
- Provides 12 dB/octave slopes.
- Retains high complexity and driver demands.
- Similar to filler-driver, but uses two cascaded bandpass filters for the filler output.
- Demands on filler driver remain high.

These are esoteric designs intended to solve the non-standard filter equations of standard crossovers. They introduce extra drivers or complex cascading circuits to achieve perfect phase and amplitude simultaneously, but their high cost and complexity make them rare in commercial products.

7. ***Multi-Way Crossover Topology***

- In-line topology
  Cascaded sections; phase accumulation causes summation errors.

- Branching topology
  Equal filter paths before summation.
  Minimizes phase-related errors.

8. Simple three-way crossovers made by cascading two two-way crossovers (e.g., 400 Hz and 3 kHz).

• ***Two common topologies***:

– In-line topology: Filters follow one after another.

– Branching topology: Filters branch off from a common point.

• ***Issue with In-line Topology*:**

– Summed outputs are not perfectly flat.

– For close crossover frequencies (e.g., 50 Hz and 200 Hz), in-line topology causes phase shift issues resulting in dips (~ -0.74 dB) in summed response due to uneven filtering paths.

– Example: MID to LF summation distorted because LF passes through a lowpass filter that MID does not.

• ***Branching Topology*:**

– All signals going to a specific crossover frequency pass through the same prior filters.

– Eliminates phase mismatch and flattens summed response.

– Still, when summing all three outputs, one output will pass through fewer filters, causing minor phase and amplitude errors.

– For well-spaced crossovers (e.g., 400 Hz and 3 kHz), error is small (~ -0.20 dB dip).

– Frequency offset can further minimize this dip, converting it into a small ripple (+0.11 dB), which is generally acceptable.

Note: Branching topology is preferred, especially when crossover frequencies are close.

When designing speakers with more than two drivers (e.g., 3-way), how you wire the filters matters. **Branching topology** is superior because it treats each driver independently, preventing phase errors in the bass section from messing up the midrange or treble

9. ***Final conclusions***

- First-order crossovers offer unmatched phase behavior but are impractical for most systems.
- Second-order Linkwitz-Riley provides flat summation with moderate slopes.
- Third-order Butterworth sums flat but introduces directivity issues.
- Fourth-order Linkwitz-Riley offers the best overall compromise.
- Linear-phase and filler-driver concepts are theoretically sound but rarely practical.
- Multi-way systems require careful topology and phase management.

***Essential notes/information*:**

Fourth-Order Linkwitz-Riley is the standard “best” crossover for flat summation and minimal phase issues.

Frequency offsets are critical to achieve maximal flatness in summed response; offset ratios vary by filter type and order.

Filler-driver crossovers provide linear-phase response but are complex and rarely used.

Duelund crossover is an advanced filler-driver variant with steeper slopes but similar drawbacks.

In multi-way crossovers, topology greatly affects summation quality; branching topologies reduce phase-related summation errors.

Frequency offsets can also be used in multi-way crossovers to smooth out residual dips caused by phase mismatches.

Group delay generally increases with filter order; higher delay can be audible and is a trade-off in higher-order designs.

Simulation and iterative adjustment of cutoff frequencies are practical methods to optimize crossover performance without heavy algebra.

There is no "perfect" crossover, only the best compromise for the application. While 1st-order filters are the theoretical ideal for phase/time response (timing), they usually result in blown tweeters. For high-fidelity and professional audio, the **4th-Order Linkwitz-Riley** is the industry standardt because it solves the most audible problems (amplitude flatness and power handling) while keeping the drivers working in unison.