Coca Alin Petru

Crossover Requirements

· General Requirements and Priorities

The design of any crossover system, whether active or passive, is guided by five principal requirements. These are ranked in order of importance, starting with the adequate flatness of the summed amplitude / frequency response on-axis, followed by sufficiently steep rolloff slopes between bands. The remaining criteria include maintaining an acceptable polar response, an acceptable phase response, and finally, ensuring acceptable group delay behaviour.

· Flatness of Summed Amplitude and Frequency Response

For a crossover to be effective, the output of each filter must be carefully matched in both amplitude and phase over a sufficient range. This ensures that when the signals are combined, the overall response remains flat. It is important to note that a flat amplitude response does not automatically restrict phase shifts; in many cases, significant phase variation will exist across the audio band.

· Standard Crossover Types and Optimizations

Several specific crossover designs are recognized for achieving a completely flat amplitude response. These include the first-order crossover, the second and fourth-order Linkwitz-Riley, the third-order Butterworth, and the newer Neville Thiele Method.

Additionally, other types can be tuned for near-flat performance by adjusting filter cuttoff frequencies. For example, a second-order Bessel crossover can achieve flatness within ± 0,07 dB by applying a frequency offset ratio of 1,45 times. Similarly, a third-order Linkwitz-Riley can be adjusted to within ± 0,33 dB using an offset ratio of 0,87 times.

Coca Alin Petru

• Rolloff Slopes and Polar Response

Crossover slopes must be fast enough to prevent driver damage, particularly to protect tweeters from low-frequency energy. Steep slopes are preffered because they reduce non-linear distortion and prevent the excitation of resonances outside a driver's intended range. While the minimum practical slope is 12 dB/octave (second-order), steeper options like 18 dB (third-order) or 24 dB (fourth-order) are highly desirable for better performance.

• Polar Response and Lobing.

A well-spread polar response is essential to create a wide listening area and avoid floor reflections that cause comb-filtering. However, when two drivers radiate simultaneously in the crossover region, their output interfere, creating a vertical radiation pattern known as lobing. To minimize this effect, designers try to keep the crossover frequency range as narrow as possible.

• Phase and Lobing Error

The direction of sound lobe depends on the phase relationship between drivers. if the outputs are in phase, the lobe points forward; if there is a phase shift (as in first or third-order crossovers), the lobe tilts toward the drive unit that is phase-lagging.

This usually directs energy toward the floor, a frequency-dependent problem known as "lobing error" that is most severe at the crossover frequency.

Coca Alin Petru

* Polar, Phase, and Group Delay

• Optimizing Polar Response

To keep the main sound lobe centered on the axis, it is highly desirable for the lowpass and highpass outputs to be in phase. This property is found in second-order crossovers (with one output inverted) and fourth-order Linkwitz-Riley crossovers. Correct polar response also requires precise time-delay compensation, ensuring sound from each driver reaches the listener at the exact same time. Without this, the sound lobe will tilt toward the driver with the longest air path.

• Acceptable Phase Response.

Most crossovers are not linear-phase; they typically behave like allpass filters where the phase changes by 180° or 360° over the audio brand. For instance, the fourth-order Linkwitz-Riley has a 360° phase change. Despite these shifts, they are generally considered inaudible when listening to music, making this requirement relatively easy to satisfy.

• Acceptable Group Delay Behaviour.

Group delay measures how much a signal is delayed and is mathematically defined as the rate of change of the total phase shift with respect to angular frequency. Because phase change varies across the audio band, group delay also varies and often peaks near the crossover frequency. While extreme variation could cause "time-smearing" of acoustic events, the levels found in standard crossovers are rarely severe enough to be audible.

Coca Alin Petru

- Crossover & Active System Requirements

Rolloff Slopes and Protection. Steep slopes are vital to protect drivers - especially tweeters - from damaging low frequencies. They minimize non-linear distortion and prevent resonances outside a driver's intended range. While 12 dB/octave is the practical minimum, 18 dB or 24 dB/octave slopes are highly preferred for better performace.

- Polar Response and Alignment

To keep the sound lobe centered, lowpass and highpass outputs must be in phase, which is a key benefit of 2nd and 4th-order Linkwitz - Riley crossovers. Accurate time - delay compensation is also required so sound from all drivers arrives at the listener simultaneously.

- Phase and Group Delay

Most crossovers cause phase shifts of 180° to 360°, but these are generally inaudible in music. Group delay often peaks at the crossover frequency. However, typical values are well below the perception thresholds, making "time-smearing" a rare issue.

Active systems must remain transparent to avoid signal degradation. Key requirements include:

- Negligible extra noise.
- No loss of system headroom or reliability.
- Minimal extra distortion and flat frequency response.

Coca Alin Petru

• Noise Performance and Headroom

• Noise in Active vs. Passive Crossovers

While passive crossovers do not add significant noise to a signal, active crossovers process audio at line level, which provides many opportunities for signal-to-noise ratio degradation. Because active crossovers are positioned after the main volume control, poor circuit design can result in audible hiss from the loudspeakers. To combat this, high-quality designs utilize low-impedance circuits, active gain controls, and optimized stage-ordering - such as placing lowpass filters last to filter out upstream noise.

• Techniques for noise reduction

Internal signal levels can be raised to improve the signal-to-noise ratio, provided gain controls are placed correctly. High-quality designs can achieve ratios between 117,5 dB and 127,4 dB, often making the crossover quieter than a power amplifier with balanced inputs. Placing lowpass filters last in the signal path further reduces upstream noise by several decibels.

• System Headroom and Transparency

While elevating internal levels helps noise performance, it must be balanced to avoid clipping and preserve system headroom. The ultimate goal for an active crossover is total transparency, ensuring no degradation in signal quality, frequency response, or reliability occurs when the unit is added to the system.

· Managing System headroom

Coca Alin Petru

To maintain optimal noise performance, active crossovers often run at elevated internal signal levels. However, this requires careful gain control placement to prevent internal clipping. Excessive attenuation between the crossover and power amplifier should be avoided, as it forces the preamp to work harder, risking "crunch" or distortion during signal peaks. In professional sound reinforcement, using compressors or limiters helps ensure these unpredictable input levels do not exceed the crossover's limits.

While loudspeakers and vinyl sources are significant distortion contributors, electronic components like active crossovers must still be designed for maximum linearity. in the electronic domain, the power amplifier is typically the greatest source of distortion. Therefore, an active crossovers ~~must still be~~ built to high standards can achieve lower distortion levels than the power amplifier it feeds, ensuring that the extra signal-processing stage does not degrade the overall sound quality.

An active crossover's primary purpose is to modify the frequency spectrum, but it must only do so in intentional ways. Beyond the planned filter slopes, the unit should maintain a perfectly flat and transparent response. This ensures that the only modifications to the signal are the necessary divisions for the different drive units, with no unwanted "frequency response impairments" introduced by poor circuit design.

Coca Alin Petru

* Reliability, Linear Phase, and minimum phase.

Negligible impairment of reliability

Active crossovers using op-amp circuitry are generally reliable due to low voltage / current levels and internal overload protection. However, designers must avoid specific "landmines" such as undersized regulator heatsinks in hot climates or poor decoupling capacitors that can cause unpredictable power supply failures. Maintaining these components within safe limits ensures the equipment does not fail or stop working prem.

Linear phase crossovers. A linear-phase crossover introduces only a pure time delay, meaning the group delay remains constant. While theoretically desirable for transparency, these filters are difficult to achieve and are not considered strictly necessary for high-quality audio performance on normal music. Common examples include first-order non-inverted crossovers and subtractive crossovers with time delay.

Minimum Phase Characteristics.

Minimum phase is often confused with linear phase, but they are nearly opposites. A minimum-phase system is defined as having the smallest possible phase shift required to achieve its specific amplitude / frequency response. In these systems, the phase response can be directly predicted from the frequency response.

Coca Alin Petru

• Understanding Minimum Phase

A minimum-phase system is one that achieves a specific amplitude and frequency response with the smallest possible amount of phase shift. In these systems, the phase response can be mathematically derived directly from the frequency response and vice-versa. Most standard crossover filters, such as highpass and lowpass types, are inherently minimum phase. A notable exception is the allpass filter used for time-delay correction; because it has a flat amplitude response but varying phase, it is impossible to deduce its phase from its frequency response.

• Summation and Phase characteristics.

The classification of a crossover can change based on how it is configured. For example, a first-order is minimum phase when its outputs are summed normally. However, if one output is inverted, the summed result takes on an allpass phase response (swinging from 0° to -180°), meaning it is no longer minimum phase. Additionally, while linear-phase crossovers ~~at~~ act as pure time delays and are not minimum phase themselves, a system including allpass filters for physical alignment can still be considered minimum phase relative to what the listener hears.

Absolute phase refers to whether a signal's overall polarity is inverted. Research shows that while listeners can detect differences in absolute phase when hearing asymmetrical waveforms - such as unaccompanied human voices or rectified sinewaves - the effect is generally inaudible with complex signals like music.

Coca Alin Petru

- Preserving Phase in audio systems.

Active crossovers must maintain correct phase relationships between all outputs to prevent severe response errors. Modern hi-fi equipment, including ~~an~~ preamplifiers and power amplifiers, is typically designed to preserve absolute phase. Similarly, mixing consoles are engineered to maintain phase consistency to avoid unwanted cancellation effect when signals are combined.

- Phase shift and Group delay Distortion.

Many crossovers exhibit dramatic phase changes near crossover points. if phase-shift is proportional to frequency, group delay remains constant, creating a linear-phase system that acts as a pure time-delay with no audible consequences. However, in most cases, phase-shift is not proportional to frequency, leading to varying group delay across the spectrum. This variation is sometimes reffered to as "group delay distortion", though it describes a linear process rather than non-linear distortion.

- Minimum-phase and exceptions.

While most components in the recording and reproduction chain are minimum-phase, there are two major exceptions: the multi-way loudspeaker and the analogue magnetic tape recorder. Loudspeakers and crossovers often exhibit allpass behavior, meaning their phase cannot be predicted solely from their amplitude response.

Ohm's Acoustic Law states that the ear perceives sound as a set of sinusoidal harmonics. it concludes that a tone's timbre depends on the number and level of these harmonics, not their relative phases.

Coca Alin Petru

• Findings on Phase Audibility

Research on phase non-linearities suggest that while they can be audible using specific test signals - especially when using headphones in an anechoic environment - they are generally not audible with normal music or speech. Studies indicate that high-Q all-pass filters can cause a perceived "ringing" effect in impulse responses, but this is typically only detectable with isolated clicks rather than complex audio. Consequently, while high-Q all-pass filters should be avoided, standard phase distortions are largely considered inaudible.

• Listening Tests and waveform distortion

Listening tests conducted by Siegfried Linkwitz compared first-order and second-order all-pass filters against a direct connection. Although these filters significantly distort square waveforms, the results were found to be inaudible in practice. These findings tend to support Ohm's Acoustic Law, suggesting that the human ear does not perceive this type of waveform distortion during music reproduction.

• Neurophysiology and Phase perception

From a neurophysiological standpoint, auditory nerves do not fire in synchrony with sound waveforms at frequencies above 2kHz. This implies that phase perception above this frequency is likely impossible for the human ear. However, the ear does not function strictly as a simple spectrum analyzer; the phenomenon of "beats" - where two similar tones produce a perceived 5Hz pulsation - demonstrates that the ear processes signals in more complex ways.

Coca Alin Petru

. The Ear and phase perception

While neurophysiology suggest phase perception is impossible above 2kHz, the brain still responds to the peak amplitude "envelope" of combined waveforms. In this way, the ear acts more like an oscilloscope than a spectrum analyzer, yet it is not a phase-sensitive detector. Consequently, crossover phase responses that emulate first or second-order allpass filters are considered entirely acceptable.

Target Functions and Integration

A target function is the desired combined response of the crossover and the driver. Drive unit irregularities should be corrected via equalization, which is easier to document than complex filters modifications. Often, the natural acoustic rolloff of a driver and its enclosure is used as part of the filter itself to reach a higher-order final alignment, such as a fourth-order Linkwitz-Riley.