Filter optimization for Multi-Way Speakers

Content

Motivation

The frequency range of a loudspeaker is usually divided into several ways. The crossover (passive or active) ensures that specific band-passes are assigned to the drivers. These band-passes are usually realized with minimum-phase filters with limited steepness.

Due to the limited steepness, there are overlapping areas between the band-passes. Minimum-phase filters have the property of distorting the phase response. In the area of the cutoff frequency, the slope of the phase change is greatest. Now, due to the finite steepness of the filters and the narrow frequency ranges of the ways, more than two paths overlap in a frequency range. As a result, the phase values of the band-passes no longer fit together and the superposition does not take place completely constructively.

Equalizing the overall amplitude response has two disadvantages. On the one hand, maximum level is lost due to the destructive interference and on the other hand, the dispersion cannot be corrected.

In the following, an example will be used to show the effect of this superposition on the overall frequency response and the dispersion behavior. Furthermore, possible solutions are shown.

Problem

1. Frequency response

The band-passes for a 4-wayer were simulated. The filters are of the type Linkwitz-Riley 4th order. The crossover frequencies are chosen as follows.

	Woofer	Mid-woofer	Mid-tweeter	Tweeter
High Pass	-	200 Hz	800 Hz	2500 Hz
Low-pass	200 Hz	800 Hz	2500 Hz	-

The complex frequency responses of the band-passes are shown below.

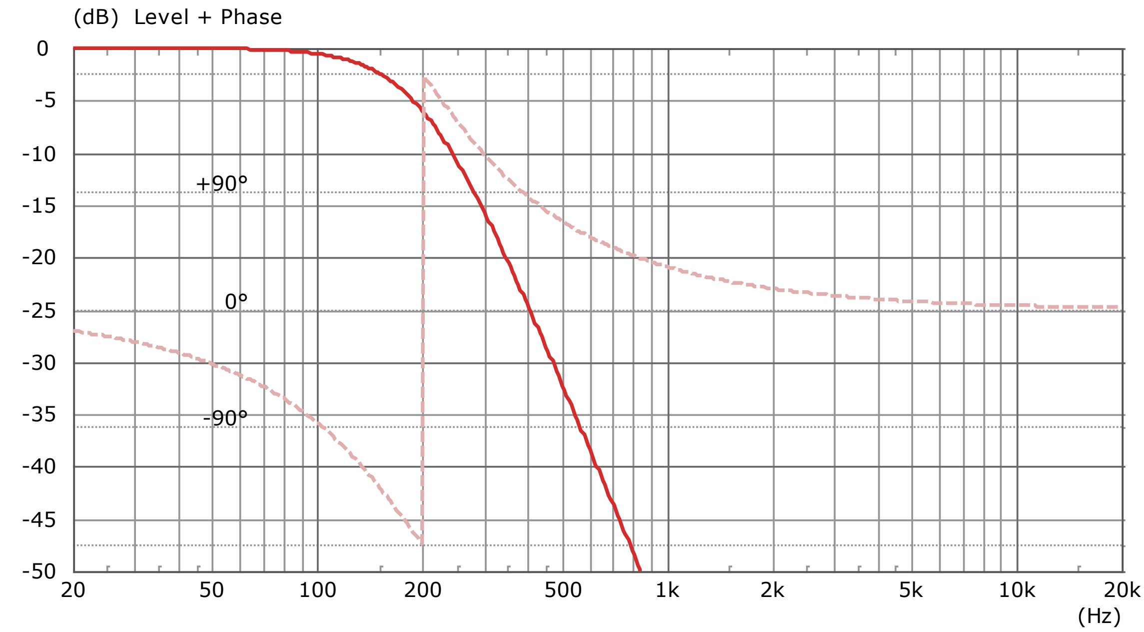

Figure 1: Woofer

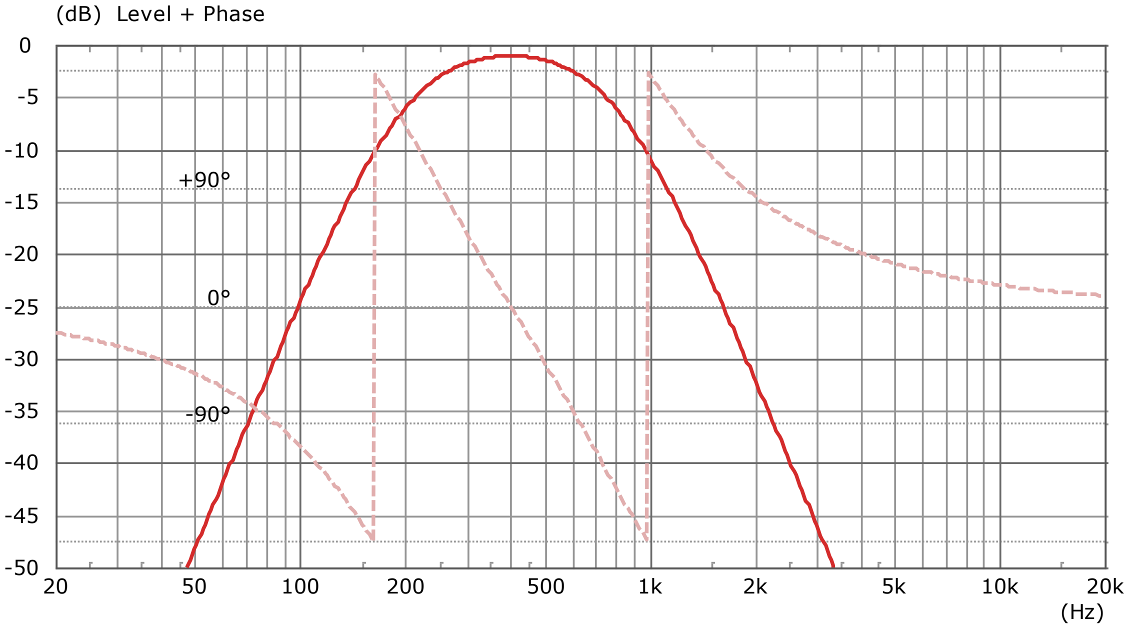

Figure 2: Mid-woofer

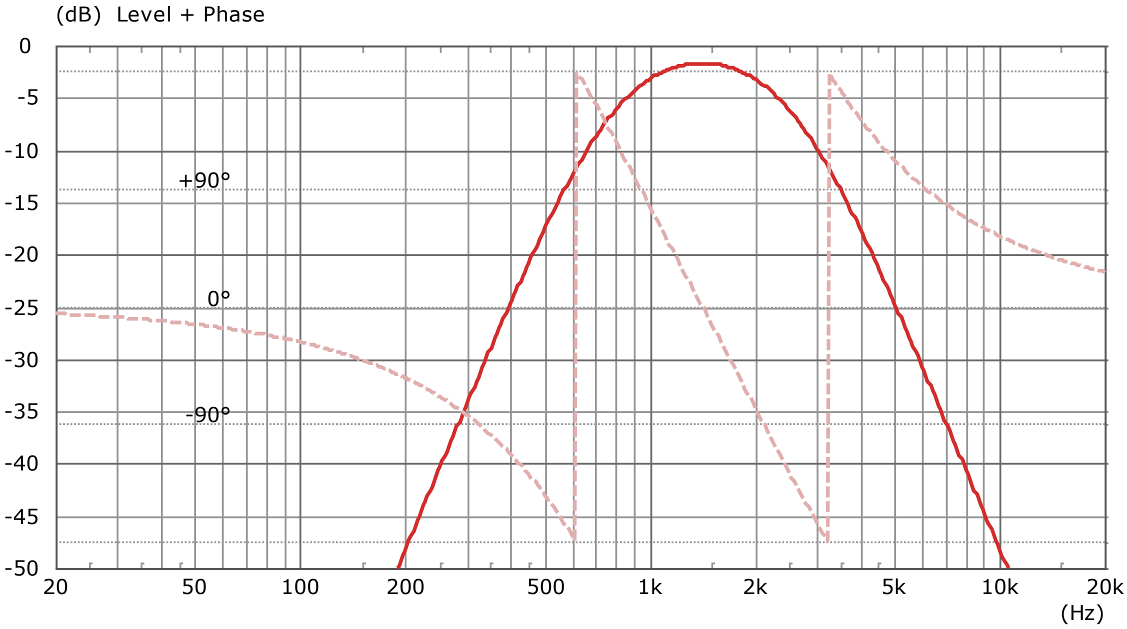

Figure 3: Mid-tweeter

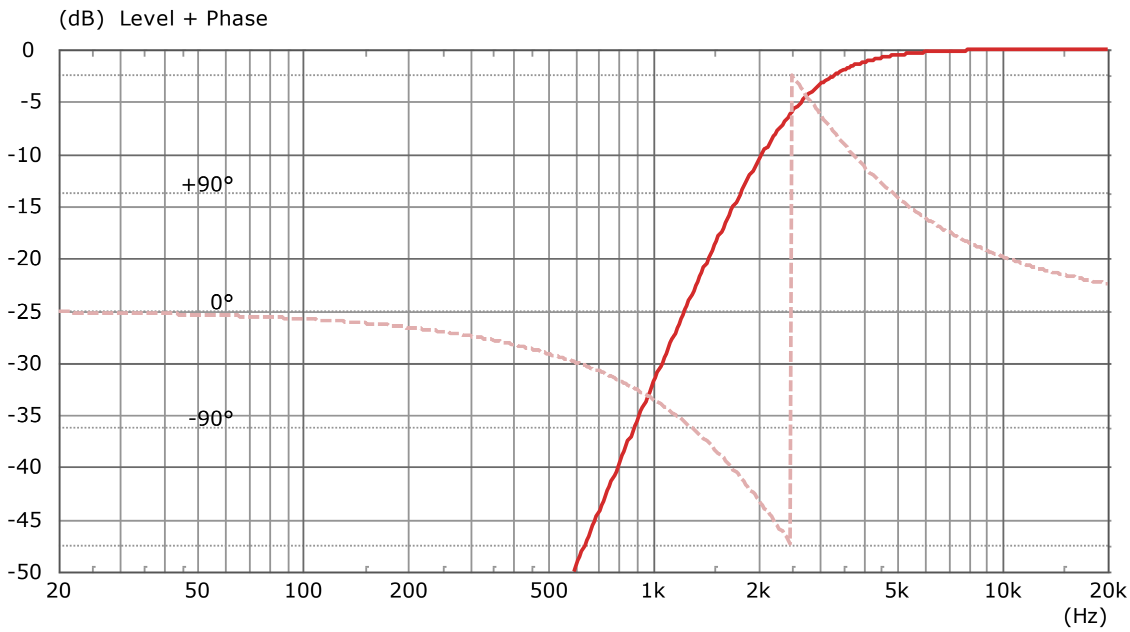

Figure 4: Tweeter

The total frequency response is as follows. As can be seen, the superimposition in the midrange is not purely constructive. There is a broad dip in the frequency range of about 200 – 2500 Hz.

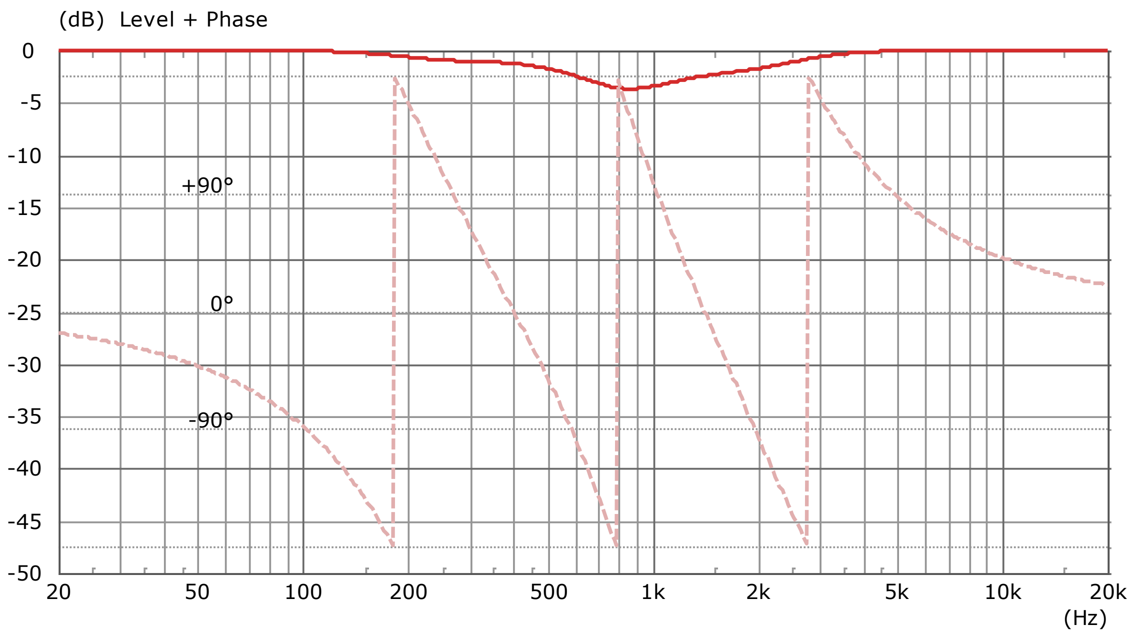

Figure 5: Total frequency response of all ways

2. Dispersion

In the following, the influence of the different phase responses on the vertical dispersion is shown. For this purpose, a system of ideal point sound sources was simulated, which were connected with low and high passes with the above cutoff frequencies.

The system consists of four ways, which are arranged vertically symmetrically around a tweeter as pairs of drivers (starting from the tweeter: mid-tweeter, mid-woofer, woofer). Concerning the tweeter two point sources were simulated, as a line radiator is better suited for the resulting narrow vertical dispersion. The aim is to achieve a vertical dispersion that is as constant as possible. The most outer sound sources (woofers) have a distance of 1.4 m.

Figure 6: Idealized loudspeaker made of ideal point sources

First, linear-phase filters were configured. This means that the phase response has been completely ignored. So, all paths have a constant phase. As you can see, the dispersion is very uniform up to 5 kHz.

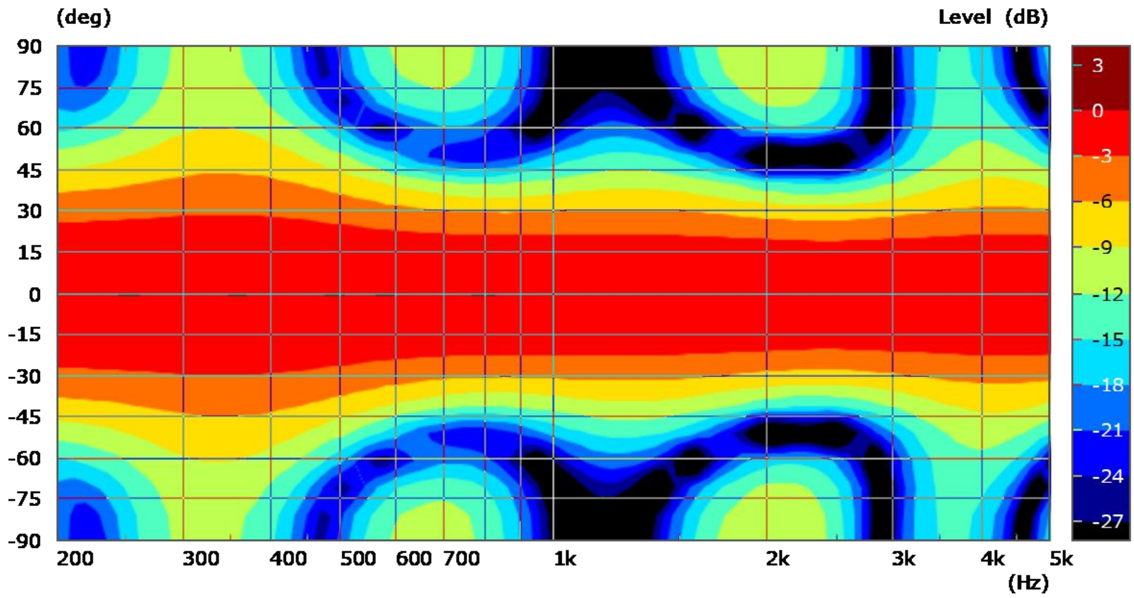

Figure 7: Directivity with linear-phase filters

Next, the minimum-phase filters were configured. Due to the non-purely constructive superposition, strong sidelobes occur. The uniform radiation is thus destroyed. However, the driver dimensions are not simulated here, which may attenuate the sidelobes somewhat.

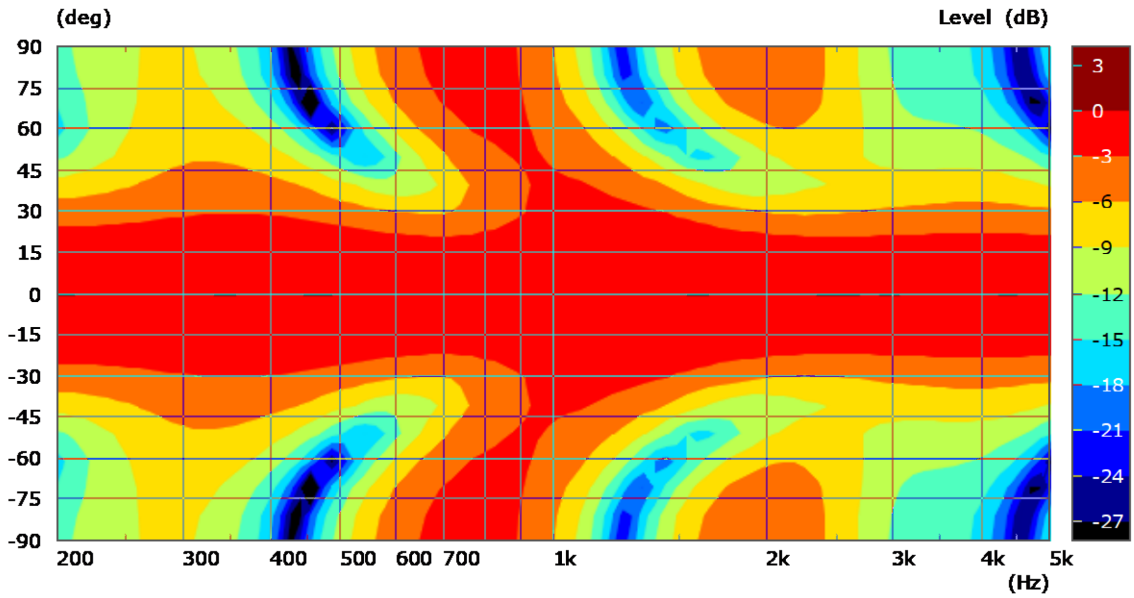

Figure 8: Directivity with minimum-phase filters

Solutions

1. Additional filters to adjust the phase response

The problem of the non-purely constructive superposition can be solved by adding the missing high and low passes of the other ways to each way. Thus, the phase response is equally distorted in all ways, resulting in a purely constructive superposition over the entire spectrum.

This method can be approximated with all-passes instead of high- and low-passes. The amplitude distortion of the additional high- and low-passes is so low that practically only the phase distortion is relevant. However, additional high and low-passes were added in the following.

	Woofer	Mid-woofer	Mid-tweeter	Tweeter
Add. high-pass	-	-	200 Hz	200 Hz
Add. high-pass	-	-	-	800 Hz
Add. low-pass	800 Hz	-	-	-
Add. low-lass	2500 Hz	2500 Hz	-	-

As you can see, there is a perfect overlay now. The amplitude response is constant.

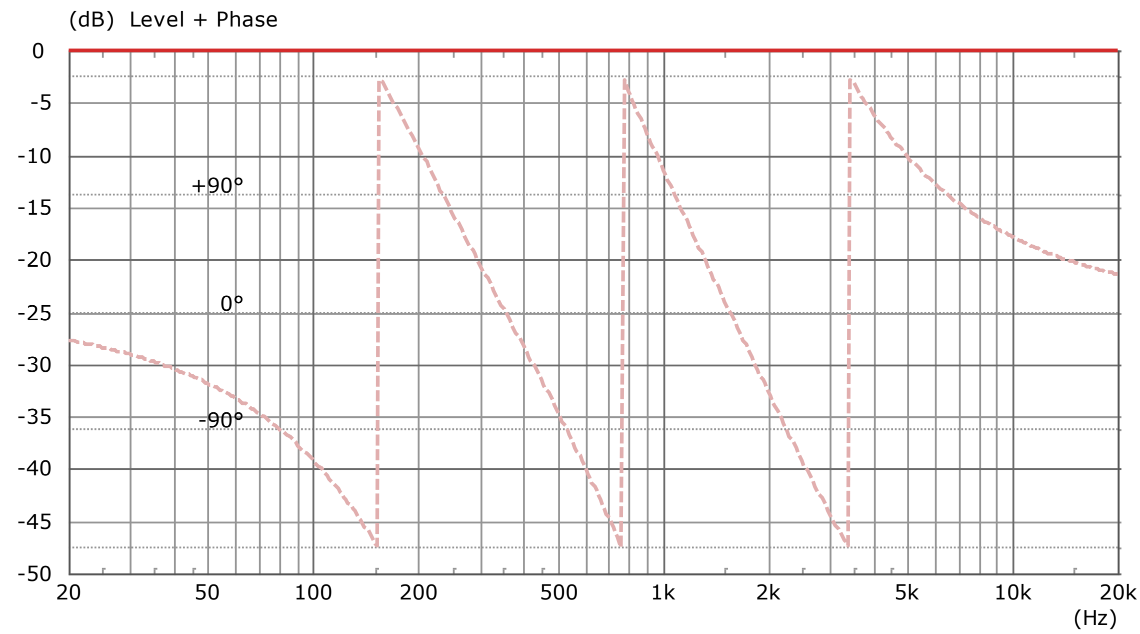

Figure 9: Overall frequency response with additional filters

Due to the additional phase distortion the group delay increases slightly. This is especially true for the lower frequency range.

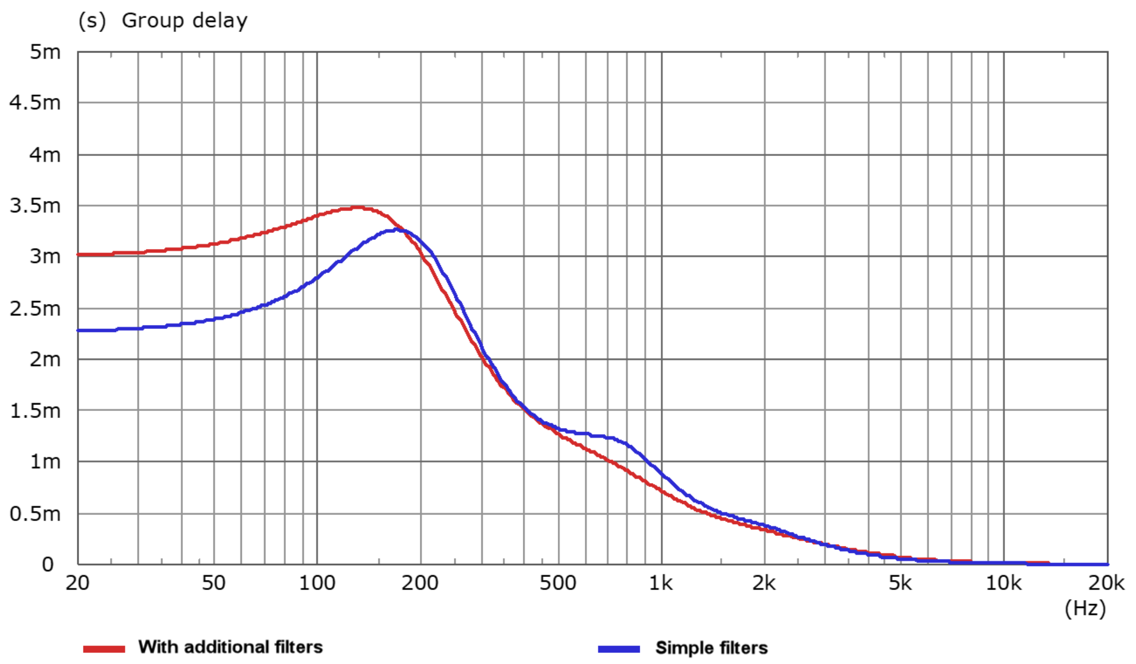

Figure 10: Group delay distortion

The advantage of this solution is that, unlike linear-phase FIR filters, no frequency-neutral delay is added. On the other hand, the group delay is not constant and increases towards low frequencies.

1.1. Additional phase linearization

Since the phase responses of the paths now match each other, the overall phase response can be completely linearized by applying a single FIR filter. However, the constant group delay's price is an additional frequency-neutral delay.

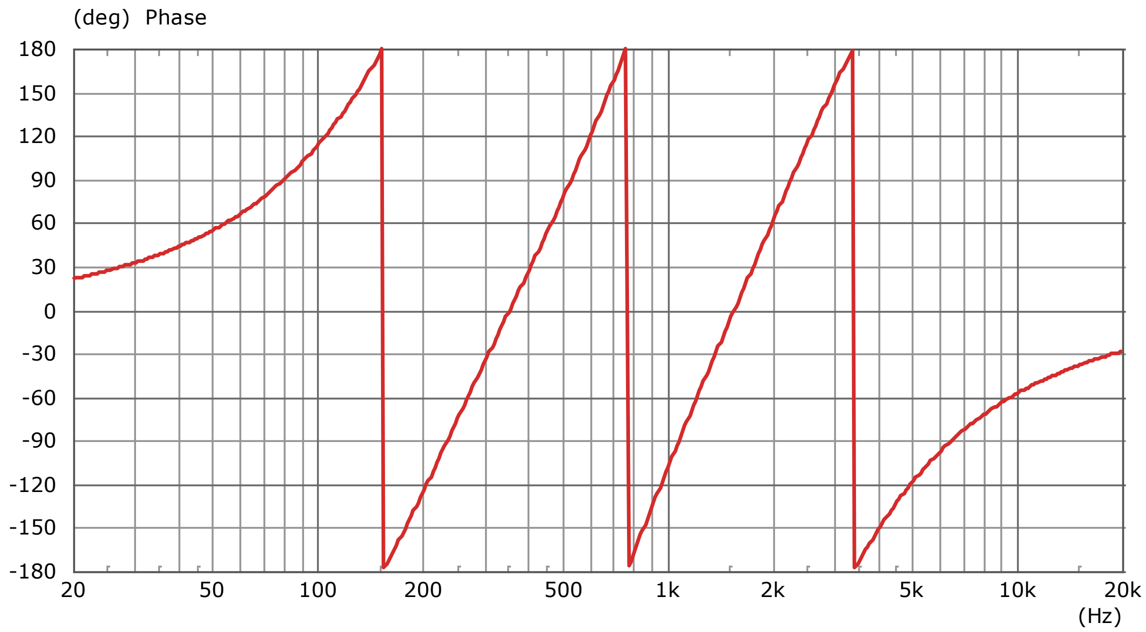

Illustration 11: FIR correction filter for the overall phase response

2. Linear-phase crossover

Another solution is to implement the high- and low-passes as linear-phase FIR filters. The superposition is thus constructive in the entire frequency range and the group delay is constant. However, it introduces frequency-neutral delay, which is unacceptable in certain situations.

The following example shows the mid-woofer driver, where the FIR filter only specifies the amplitude response, but does not affect the phase.

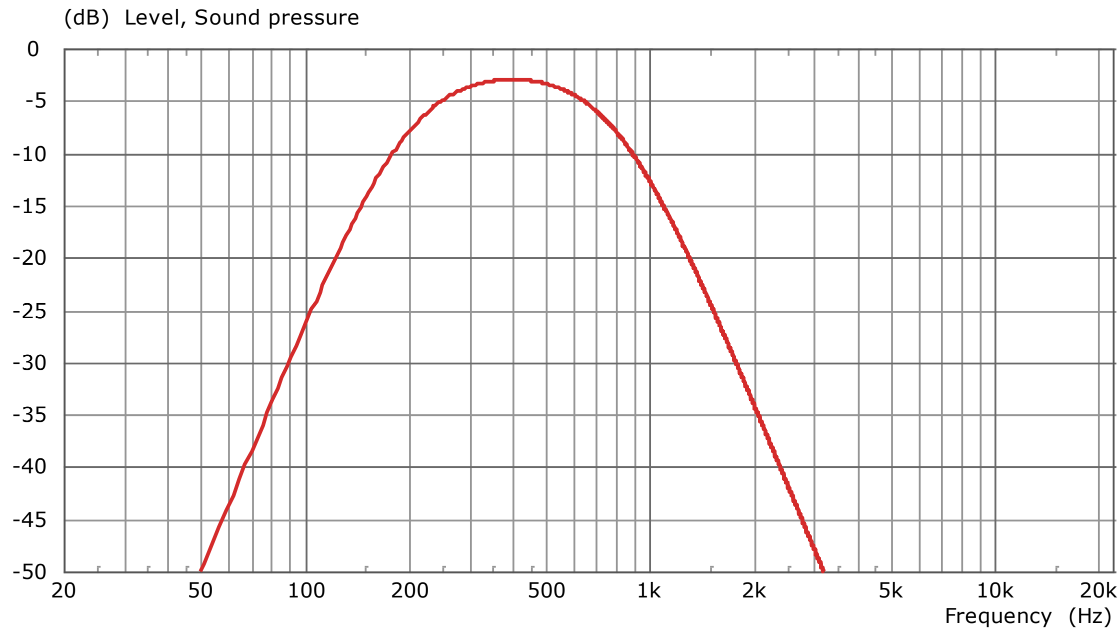

Illustration 12: Linear Phase FIR Filter Example

This option can only be implemented digitally and therefore requires a separate DSP and power amplifier channel for each branch.

3. Compensation of phase distortion

One advantage of FIR filters is the ability to manipulate amplitude and phase response separately. This opens up another possibility:

- Crossover with minimum-phase IIR filters that distort the phase
- Equalization of the phase responses by applying of FIR filters

The order of the filters is not relevant. The only important thing is that the phase response of each way is equalized individually. This means that a separate DSP channel is necessary for each way.

This variant also generates a constant group delay and thus a frequency-neutral delay.

The following example shows the filters on the basis of the mid-woofer driver. First, the amplitude response is brought to the target function via minimum-phase filters. This initially distorts the phase response. After that a FIR filter is applied which only compensates for the phase distortion.

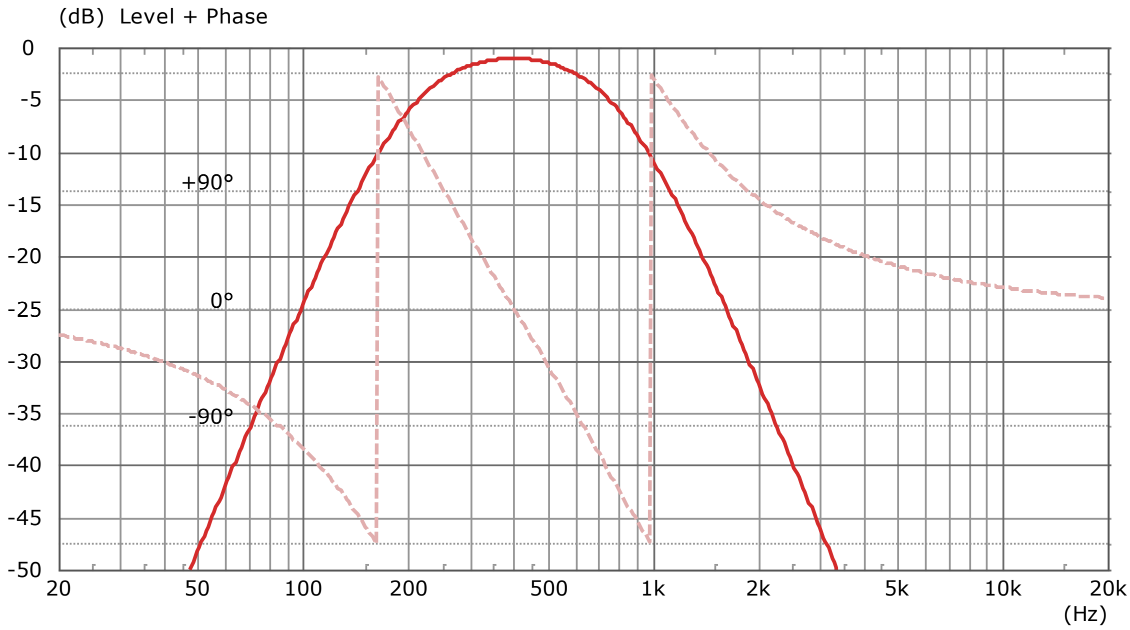

Illustration 13: Minimum-phase IIR filter for the mid-woofer driver

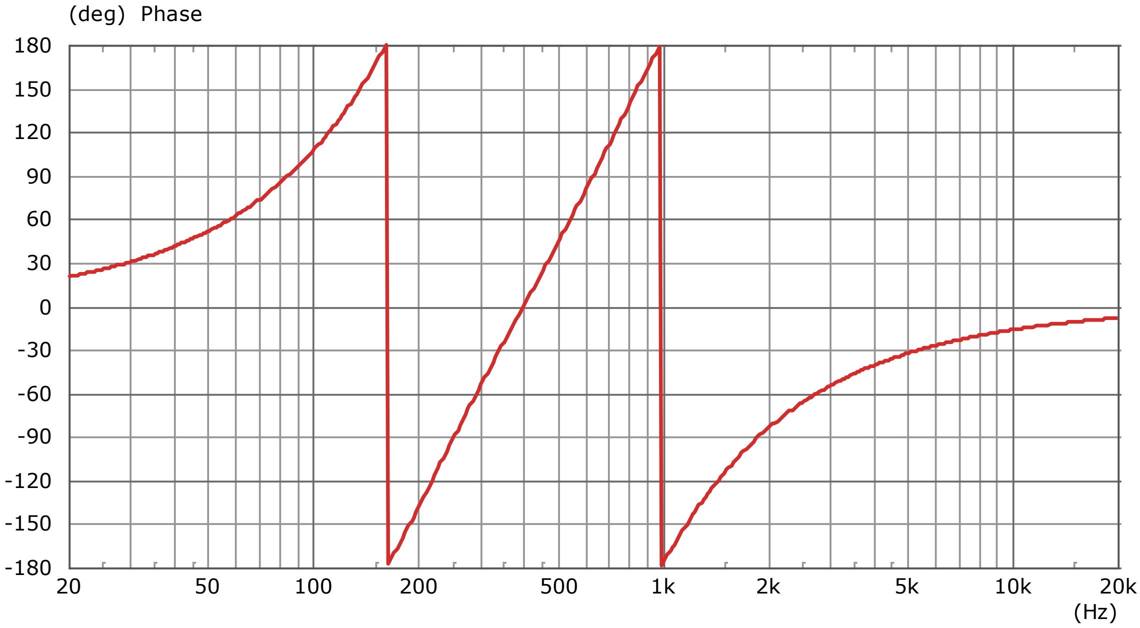

Illustration 14: FIR compensation filter for phase distortion of IIR filter

The advantage of this solution is that the FIR filters can be smaller in memory, as they only equalize the phase. This means that a DSP with less memory or higher sample rates can be used without significantly degrading the filtering function.

Summary

In the following, the characteristics of the different variants are summarized in tabular form.

	Variant 1	Variant 1.1	Variant 2	Variant 3
Group delay	Frequency-dependent	constant	constant	Constant
Channels for convolution	0	1	4	4
Memory requirements in the DSP	very low	low	high	Medium