Improving high-end active speaker performance using digital active crossover filters

Dave Brotton - May 21, 2013

Consumer requirement for fewer wires connecting their home entertainment systems is driving up the demand for wireless active speakers. In order to achieve the best audio quality from high end active speakers, adoption of alternative technologies can improve performance; in this context, digital active crossovers can be shown to make a significant contribution.

Current wireless active speakers consist of four elements in the signal path before the drive unit; receiver, DAC, amplifier and crossover. The receiver may be Bluetooth running a high performance codec. The amplifier could be a conventional analogue input class AB type to ensure a high audio quality with high a performance DAC at its input. The final element in the signal path is a passive crossover network.

Alternatively, utilising high performance Class D amplifiers, efficiency savings can make direct driving woofer and tweeter a reality. If the Class D amplifier features a digital input, the availability of DSP resources can facilitate the implementation of high performance digital crossovers which can offer substantial advantages over their passive counterparts.

Active speaker architecture

Figure 1 represents a conventional wireless active speaker architecture. The receiver is Bluetooth, potentially running a high performance codec such as aptX™ to ensure the optimum audio performance. To facilitate the change from digital to analogue domain, the system requires a high performance DAC before the amplifier input. Pre and power amps operate in the analogue domain, with the single power amplifier driving both woofer and tweeter.
Delivering a high audio quality suggests a Class AB amplifier architecture. However, the significant power savings offered by an analogue input Class D amplifier can be attractive; today’s closed loop analogue input Class D amplifiers can offer good audio performance. This increased efficiency also means smaller power supplies.

With this architecture, passive crossover networks provide high and low pass filtering to split the audio signal into the appropriate frequency bands for the woofer and tweeter drivers.

The availability of very-high-performance digital-input Class D amplifiers makes an alternative architecture attractive; figure 2. Here the audio signal stays in the digital domain right up to the amplifier power stage output; this in itself offers audio performance advantages, eliminating conversion errors between digital and analogue domains by removing the need for a DAC.

To achieve the best audio performance, a closed-loop digital amplifier needs to be selected. In this example CSR Direct Digital Feedback Amplifier (DDFA™) technology is used as the platform.

With this architecture, pre and power amplifier functions are achieved in a single circuit. Although an amplifier channel per driver is required, the power level of each is exactly scaled to match woofer
and tweeter sensitivities.

The available signal processing capability offers major advantages with respect to the crossover. On chip DSP facilitates easy implementation of high performance active filters which can be configured to exactly match driver characteristics, eliminating the need for passive components.

Passive versus active crossovers

Passive versus active crossovers

Figure 3 shows a typical passive crossover implementation; this example is considered in detail later.

![Figure 3: Passive crossover implementation](image)

This design uses a conventional 2nd order filter for each driver with a crossover frequency of approximately 2.2kHz. The woofer impedance is 3.5Ω, the tweeter 3.2Ω.

The circuit is constructed with simple inductors and capacitors which, being in the power path, need to be relatively large. Efficiency losses are likely, resulting in heat dissipation and performance drift. These effects get worse as power levels increase, higher levels of distortion can result.

Although the circuit design appears simple, component interactions are complex making it difficult to fully isolate one driver from another. The response of the filters is also directly influenced by the drivers whose characteristics change with frequency, power and temperature.

The crossover accommodates the different driver sensitivities by adding padding resistors, resulting in further dissipation. It’s important that this is done correctly, an overpowered inductor can saturate and cause distortion at high power or even failure resulting in blown tweeters.

A digital active crossover approach can address these issues resulting in a better performing, simpler product.
The active crossover is placed in the low-level digital signal path of the system, eliminating efficiency losses and thermal effects experienced with the passive design. Here, the filters are isolated from the load and from each other, eliminating performance degradation due to interactions between the two. Digital gain control is simple to implement, accommodating different driver sensitivities without losses and eliminating the need for the padding resistors.

Digital filters are not affected by signal levels so results are far more precise, linear and repeatable with distortion maintained at a constant low level. Elegant control of limiting can be introduced eliminating any overload issues. Delay is also readily available, enabling optimum driver time alignment.

DSP resources in digital amplifiers take up very little overhead allowing significant processing capacity to be made available. This means that higher order, more complex filters can be implemented allowing better performance levels to be achieved at no additional cost.

More complex filter designs can offer far better matching to speaker enclosure and driver characteristics. Furthermore, filter characteristic sets can be developed to allow choices in performance, for example, to compensate for room conditions or music styles.

**DSP filter performance**

With an active crossover implementation, attention must be paid to the filter specification in order to maintain optimum audio performance. For example, resolution errors can produce increased noise levels unless the appropriate architecture is applied.

In digital amplifiers, filters are created by a combination of biquad stages, each providing a 2\textsuperscript{nd} order characteristic, with the type defined by a number of coefficients; in this example, 5 24 bit coefficients configure each stage.

Ensuring the system is capable of resolving and processing all expected input signals, requires consideration of computational resolution as well as coefficient bit width. For example, with an amplifier dynamic range target of 116dB, a computational resolution of 35 bits ensures filtering without compromising noise or distortion with a coefficient resolution greater than 20 bits.

**Digital filter implementation**

**Digital filter implementation**

To illustrate the performance differences between passive and active filter implementations, an existing speaker design is used. The passive crossover, figure 3, is characterised whilst attached to the woofer and tweeter drivers; figure 4.
With a higher efficiency, the inclusion of the padding resistor is the reason for the amplitude reduction of the tweeter channel. With the digital crossover, this difference is easily accommodated with a simple gain adjustment during amplifier and filter configuration. This adjustment also improves tweeter channel SNR; it’s advantageous to keep tweeter noise level low given its higher sensitivity.

The digital implementation for the tweeter is replicated using a single biquad filter stage with coefficients adjusted to match the passive crossover and driver combination; table 1.

<table>
<thead>
<tr>
<th>Filter type</th>
<th>Centre frequency (Hz)</th>
<th>Q</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd order high pass</td>
<td>3660</td>
<td>0.42</td>
<td>-3.2</td>
</tr>
</tbody>
</table>

**Table 1: Tweeter biquad filter setting**

To achieve the less smooth woofer characteristic, four biquad stages are required. A low pass set to 2.2kHz, two peaking filters to achieve the small deviations at 150Hz and 1.7kHz plus a hi-shelf set to 450Hz; table 2.
Table 2: Woofer biquad filter setting

These settings result in the characteristic of figure 5, with a very close match to the passive implementation.

<table>
<thead>
<tr>
<th>Filter type</th>
<th>Centre frequency (Hz)</th>
<th>Q</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; order low pass</td>
<td>2170</td>
<td>1.1</td>
<td>-0.9</td>
</tr>
<tr>
<td>Peaking</td>
<td>150</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Peaking</td>
<td>1692</td>
<td>0.85</td>
<td>-2.8</td>
</tr>
<tr>
<td>Hi shelf</td>
<td>450</td>
<td>0.71</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

**Table 2: Woofer biquad filter setting**

These settings result in the characteristic of figure 5, with a very close match to the passive implementation.

![Passive and active crossover characteristic with attached drivers](image)

**Figure 5: Passive and active crossover characteristic with attached drivers**

**Measurement of key characteristics**

Three key characteristics are measured contrasting the audio performance between a speaker utilising the passive and active crossover filter designs.

An Audio Precision analyser is used to measure total harmonic distortion and noise (THD+N) and intermodulation distortion (IMD). With the intent to reveal the difference in performance attributable to the crossover, the load for each is 4Ω.

Consideration of the two system structures suggest a further performance measurement with the impedance looking back from the load. Damping factor, which is the ratio between these two
impedances, has a significant influence on audio performance.

In each case the same amplifier architecture is used; a 30W, two-channel digital amplifier based on the CSR DDFA CSRA6600/6601 chipset. With the passive crossover, the amplifier filter DSP is bypassed; with the active crossover, the amplifier DSP is configured with the filter architecture previously described.

THD+N
Figure 6 shows the THD+N vs. power characteristic for the passive and active woofer filter at 500Hz.

![THD+N vs. Power into 4Ω](image)

Figure 6: Passive and active woofer THD+N vs. power into 4Ω

It’s clear the passive filter is introducing substantial levels of distortion and noise, a situation which worsens as output power increases.

A plot of THD+N vs. frequency at 22W for the active crossover, figure 7, emphasises the consistently low THD+N performance across the audio band with both woofer and tweeter. THD+N is consistently below 0.005% and never higher than 0.01%.
Figure 7: Active woofer and tweeter THD+N vs. frequency into 4Ω at 22W

IMD

A comparison of intermodulation distortion performance, figure 8, is more revealing. This FFT uses an SMPTE test with frequencies of 60Hz and 7kHz and contrasts the active and passive woofer filter performance at 14W.
Figure 8: Passive and active woofer IMD characteristic into 4Ω at 14W

The passive filter not only exhibits higher level intermodulation distortion products, but also suffers from raised noise at lower frequencies. This noise floor is modulated by the signal amplitude in the passive case, but is constant for the active crossover.

**Damping factor**

A further benefit to performance with the active crossover filter implementation is with damping factor. Damping factor is a measure of the ratio of the driver load impedance to the amplifier system output impedance. A high damping factor ensures better control of the driver voice coil movement, resulting in improved audio performance, particularly in the bass frequency range.

In the passive crossover case, output impedance is determined by the crossover components, in the active case it’s the amplifier output impedance. If the digital amplifier is closed loop, as in this example, then a very low amplifier output impedance results.

Table 3 contrasts the damping factor achieved with the woofer channel with passive and active crossovers for a range of frequencies with an 8Ω load.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Passive crossover</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Woofer filter output impedance (Ω)</td>
<td>Damping factor</td>
<td>Woofer amplifier output impedance (Ω)</td>
<td>Damping factor</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.22</td>
<td>36</td>
<td>0.03</td>
<td>267</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>0.28</td>
<td>28</td>
<td>0.03</td>
<td>267</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.93</td>
<td>8.6</td>
<td>0.03</td>
<td>267</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>28</td>
<td>0.3</td>
<td>0.02</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Contrasting passive and active woofer channel damping factor

The poor measurement with the passive filter at 1500Hz is attributable to the passive components LC resonance at 1752Hz; i.e. not at the crossover frequency. This resonance can be clearly demonstrated with a simple simulation; figure 9. A digital implementation avoids such resonant peaks completely.
Conclusion
From the measurements, it’s clear there is considerable advantage to be gained with an active crossover implementation.

The potential for reduction in THD and IMD is substantial. Damping factor can be increased from values in the tens to many hundreds, with impedance anomalies totally removed. Improvements in these characteristics contribute to better sound quality.

Lower levels of distortion improve clarity, revealing more fine detail and instrument separation. Eliminating noise floor modulation allows dynamics to stand out, with a low noise floor allowing very low level detail to be resolved. A high damping factor allows superior woofer control ensuring the delivery of fast and precise bass and transients.

In addition to these characteristics, use of a digital input Class D amplifier per driver enables power levels to be scaled exactly to match woofer and tweeter sensitivities. This, combined with no dissipation in the active crossover, ensures optimum efficiency.

A digital filter implementation is very repeatable, eliminating effects from variable tolerances of passive components. Thermal effects are minimised giving a more consistent performance from active speaker systems.

With DSP facilities provided almost for free, more complex filter architectures are easily created allowing more precise filter characteristics to be developed – a capability beyond practical implementation with passive networks. Additional features such as driver time alignment and limiting can help provide the best performance.

The benefits of using active crossovers in high performance wireless active speakers are compelling.
More about Dave Brotton