Understanding output filters for Class-D amplifiers

John Widder and Yun Tao Zhao, STMicroelectronics - January 09, 2008

Class D amplifiers generally use a low-pass filter to attenuate the switching noise in the output waveform while passing the audio signal to the loudspeaker, but many engineers are not familiar with the functions performed by the various components in a Class-D amplifier filter or how to calculate the proper values. This article explains the purpose of the filter components and how to calculate their values.

The heart of a Class-D amplifier filter is a L-C low-pass filter. The corner frequency of the filter is chosen so that the filter will have minimal effect on the desired output frequency range while attenuating the switching noise as much as possible.

![Figure 1: A low pass filter for a Class-D amplifier](image)

**Low-Pass Filter**

The optimum value for the filter inductor is

\[ L = \frac{R_L}{2\pi f_C} \]

where \( f_C \) is the desired corner frequency of the filter and \( R_L \) is the load (speaker) resistance. Note that the inductor value is dependent on both the desired corner frequency and the speaker impedance so the inductor value will change if the speaker impedance changes.

Practical designs require the use of standard component values so small adjustments usually have to be made to the ideal inductor and capacitor values. Rather than calculating the inductor and
capacitor values independently and then adjusting their values, it's better to calculate the inductor value, select the closest standard inductance value, and then calculate the required capacitance using the selected inductor.

\[ C = \frac{1}{(2\pi f_C)^2 \cdot L} \]

The quality factor (Q) of a filter is the ratio of the center frequency to the filter bandwidth.

\[ Q = \frac{R_L}{\sqrt{C/2L}} \]

A high Q produces an underdamped curve and a low Q produces an overdamped curve. The Q of the filter should be in the range 0.6 > Q > 0.8 to avoid underdamped or overdamped behavior. If you use the equations above the filter should have a Q of about 0.7, which provides good performance and allows for impedance variation in the speakers. Note that the Q of the filter will change if the speaker impedance is changed without adjusting the filter component values, which can result in an underdamped or overdamped response.

**Component Selection**

Not only is it important to choose the correct L-C filter values, it is also important to choose the correct types of components for the class-D amplifier in order to avoid losses and minimize harmonic distortion.

The DC current rating of filter inductors must be greater than or equal to the maximum current that it will see. The change in inductance versus load current should not be more than 10%. The core material can affect the amplifier's harmonic distortion and should have very low hysteresis losses.

The capacitor should be a multilayer polyester, polypropylene or polycarbonate film capacitor. Avoid using ceramic capacitors in the low-pass filter. Ceramic capacitors experience large changes in capacitance as the voltage across them changes, which can result in distortion.

**Single-Ended Outputs**

Single-ended amplifiers also have a few disadvantages compared to amplifiers with bridge-tied load (BTL) outputs. First, single-ended amplifiers require either split positive and negative power supplies or DC blocking capacitors. If DC blocking caps are used, they need to be large in order to prevent them from affecting the low-frequency performance of the amplifier. For example, an amplifier with an 8Ω speaker needs a 1000µf cap in order to achieve a -3dB point of 20Hz.

DC blocking caps can also cause audible pops as they charge up to Vcc/2 when the amplifier is
turned on. A resistor divider from Vcc to ground can be used to charge the capacitor up to Vcc/2 at a relatively slow rate when the power is turned on, minimizing or eliminating the pop.

If the amplifier does not have feedback then PSRR might be a problem. Two DC blocking capacitors can be used to create a low-impedance AC voltage divider to improve the PSRR. If two DC blocking capacitors are used then each cap only needs to have ½ of the capacitance because the circuit sees the parallel impedance of the two capacitors.

![Figure 2a: Single-ended amplifier with a DC blocking capacitor](image1)

![Figure 2b: Single-ended amplifier with a resistor divider to minimize pop at turn on](image2)
BTL Outputs
Amplifiers with BTL outputs are popular because they do not require DC blocking caps even when operating with a single positive power supply. DC blocking caps limit the low-frequency response of the amplifier and can be quite large.

BTL amplifiers have another advantage over amplifiers with single-ended outputs - the maximum peak-to-peak voltage that a amplifier with BTL outputs can apply to the speaker is twice the power supply voltage, which in turn means that up to four times as much output power can be delivered to the load compared to a single-ended amplifier. This can be a big advantage in applications where the power supply voltage is limited, especially in portable applications where the amplifier is operating off of a battery.

Common-Mode Filters

Common-mode filters are L-C filters with one side of the capacitor grounded. The inductor is placed in series with the amplifier output(s) and the capacitor is connected from the speaker terminal to ground. Since single-ended amplifier filters already have one side of the capacitor grounded the low-pass filter is a common-mode filter.

When used with an amplifier with BTL outputs, the filter shown in figure 1 would be a differential filter since it filters the signal between the two outputs. Common-mode filters for amplifiers with BTL outputs are different than the differential low-pass filter. The filter inductance for BTL amplifier outputs is normally split into two separate inductors, with one inductor is placed in series with each of the amplifier outputs. Each inductor has half of the total inductance required for the low-pass filter.

Because the capacitance across the load is now the series combination of the two capacitors for BTL outputs, each capacitor needs to be twice the value calculated for the low-pass filter so that the total
capacitance will be correct. Note that because the inductance for each BTL output is cut in half but the capacitance to ground is twice the normal value, the resonant frequency of the common-mode filter is the same as the resonant frequency of the differential filter.

\[ f_c = \frac{1}{(2\pi\sqrt{LTC_T})} = \frac{1}{(2\pi\sqrt{\frac{1}{2}L_T \cdot 2C_T})} \]

The simplest common-mode L-C filter is just an inductor and a capacitor to ground (figure 3). This produces excellent attenuation at high frequencies but this filter has an underdamped common-mode response that can cause unwanted ringing on the speaker leads. It can also cause very high ripple current through the inductor and capacitor. The impedances of the inductor and capacitor cancel at the resonant frequency so the current at the resonant frequency is only limited by the stray resistance in the circuit (primarily the output impedance of the amplifier and the DC resistance of the inductor).

Figure 3: A simple common-mode filter and its response

In order to damp the common-mode response of the filter it is necessary to add some resistance to the filter. Normally a resistor is added between the capacitor and ground.

However, adding a resistor between the capacitor and ground creates a zero in the filter response which can greatly reduce the filter's effectiveness at higher frequencies. The effects of adding a
A resistor in series with the capacitor can be seen in the following plot. Note that the amplitude of the resonant peak is greatly reduced but the attenuation at high frequencies is also reduced.

For this reason a second capacitor is usually placed across the resistor to create a pole above the filter's resonant frequency. This pole cancels the effect of the zero created by the resistor at higher frequencies while allowing the resistor to provide damping at the L-C resonant frequency. Figure 5 shows the response of a filter with a capacitor in parallel with the damping resistor. Note that the resonant peak of the filter is still much lower than without a damping resistor but the attenuation at high frequencies is much better than without the second capacitor.
Calculating the component values for a common-mode filter is easy. The total inductance and capacitance in the filter remains the same as for a differential-mode filter:

\[
L_T = R_i/(2\pi f_C) \quad \text{and} \quad C_T = 1/((2\pi f_C)^2 \cdot (L_T))
\]

Because the inductance for BTL outputs is divided between two inductors in series, however, the value of each inductor is equal to \( \frac{1}{2} \) of the total inductance

\[
L_1 = L_2 = \frac{1}{2}L_T = R_i/(4\pi f_C)
\]

Similarly, the capacitance for each filter is divided between two capacitors in series, so the value of each capacitor is equal to twice the total capacitance

\[
C_1 = C_2 = C_3 = C_4 = 2/((2\pi f_C)^2 \cdot L_T) = 1/((2\pi f_C)^2 \cdot L_1)
\]

The value of the common mode resistors should be

\[
R_1 = R_2 = 1/(\sqrt{2} \cdot 2\pi f_C \cdot C_1)
\]

This resistor value will insure that the zero is below the L-C resonant frequency and the pole is above the LC resonant frequency, allowing the resistor to damp the filter response at the resonant frequency.

Using a common-mode filter has another beneficial effect. The response of a differential-mode filter is normally damped by load (the speaker). However, if the amplifier is operated without a speaker connected the response of the filter will be very underdamped, similar to the response shown in figure 3. The use of a common-mode filter with damping resistors will ensure that the filter response is always well behaved, even without a speaker attached.
Hybrid Filters

Hybrid Filters
Metal film capacitors are relatively expensive so increasing the number of capacitors in the filter from one to four can have a significant impact on the total cost of the amplifier. It is possible to keep the filter cost close to what a simple L-C differential filter would cost while providing some of the benefits of a common-mode filter by using a hybrid filter that combines elements of both common-mode and differential filters.

![Figure 6: A hybrid output filter. C1 is a metal film capacitor and the other capacitors are X7R multilayer ceramic capacitors.](image)

A hybrid filter has split inductors and R-C networks between the speaker terminals and ground like a common-mode filter, plus a capacitor across the speaker terminals like a differential low-pass filter. At first this would seem to be counterproductive since it adds a fifth capacitor to the design. The total cost can be reduced by making the value of the differential capacitor significantly larger than the common-mode capacitors and only using a metal film capacitor for the differential cap.

The other four capacitors can then be less expensive X7R multilayer ceramic capacitors. This makes the cost of the hybrid filter only slightly more expensive than the cost of a differential L-C filter while still providing some common-mode attenuation and some damping under no-load conditions. The drawbacks of the hybrid filter are:

1.) The differential attenuation is the same as for a normal common-mode filter but the common-mode attenuation is not as good. Because the common-mode capacitors in a hybrid filter are smaller than they would be in a pure common-mode filter, the center frequency for common-mode filters is higher and therefore the attenuation at the switching frequency and its harmonics is lower.
2.) The differential-mode damping of a hybrid filter under no-load conditions is not as good as a pure common-mode filter because most of the high-frequency current flows through the larger capacitor across the speaker terminals. Normally this isn’t a problem because the speaker provides the differential-mode damping, but if the amplifier is operated without the speaker connected then the damping will not be as good. Care needs to be taken to insure that the damping of a hybrid filter is good enough to protect the amplifier under no-load conditions.

3.) The harmonic distortion with a hybrid filter will be slightly higher than with a common-mode filter because ceramic capacitors provide some of the filter capacitance, while a pure common-mode or differential low-pass filter would normally only use metal film capacitors with much better characteristics.

Despite these drawbacks, hybrid filters can provide some of the benefits of a common-mode filter while keeping the cost close to that of a differential-mode filter.

As might be expected, calculating the component values for a hybrid filter are somewhat more complex because choosing the component values involves making performance trade-offs. In order
to prevent harmonic distortion from being a problem, the value of the ceramic common-mode capacitors should be smaller than the value of the film differential capacitor.

However, making the ceramic capacitors too small will hurt the common-mode EMI attenuation and the no-load damping. Amplifier manufacturers will normally recommend hybrid filter component values for common speaker impedances that provide good filter performance.

**Hybrid Filters for Single-Ended Outputs**

Hybrid filters for amplifiers with single-ended outputs are slightly different than hybrid filters for amplifiers with BTL outputs. At high frequencies the impedance of C1 is much less than the series combination of C2 and C3 so capacitor C3 is not needed.

![Figure 9: A hybrid filter for a single-ended amplifier](image)

**Snubbers**

When the output of a Class-D amplifier switches there normally is a "dead" time between the time when one transistor is turned off and the other transistor is turned on. The dead time is necessary to insure that both transistors are never conducting at the same time, which would cause large currents to flow from the power supply to ground through the transistors. However, the dead time causes a problem because it interrupts the current flowing through the inductors. Snubbers are normally used on the amplifier outputs to provide another path for the inductor current during the dead time.

There are two types of snubbers. Amplifiers with BTL outputs can use a differential snubber, with a single resistor and capacitor in series in between the two outputs. Common-mode snubbers have a resistor and capacitor in series from the output to ground and can be used with either single-ended or BTL outputs.

Common-mode snubbers for amplifiers with BTL outputs use twice as many parts as a differential snubber but they may reduce harmonic distortion. The type of snubber to use will depend on the application. The amplifier manufacturer will normally recommend values for the snubber components.

**Filterless Amplifiers**

No discussion of Class-D output filters would be complete without talking about filterless Class-D amplifiers. The primary purpose of the output filters is to reduce EMI. However, it is possible to operate a Class-D amplifier without any filters on the outputs. Although there is a large amount of high-frequency switching noise on the amplifier outputs, this noise is far outside of the response
range of most speakers so filters are not necessary for good audio quality. Filterless Class-D amplifiers are less efficient because the high-frequency energy that is normally absorbed by the filter is dissipated as heat and EMI.

Filterless Class-D amplifiers should have controlled rise and fall times to limit the high-frequency content in their output spectrum. Filterless Class-D amplifiers also require very careful attention to circuit board layout to prevent EMI problems. In particular, the distance between the speaker and the amplifier must be kept as short as possible, and loop area between the amplifier output and its return path (either another output or ground) must be as small as possible.

The wires from the circuit board to the speaker should be twisted together in order to keep the distance between them as small as possible. Of course, these measures are good practice for Class-D amplifiers with filters also.

The second article in this series offers some pc-board layout guidelines designed to help optimize the performance and reliability of Class-D amplifiers.

About the authors:

**John Widder** is a Market Development Manager at [STMicroelectronics](https://www.st.com). During his eight years at ST, John has focused on design and development support for printers and audio products. Before joining ST, John spent 20 years working in printer design and development. John has a BSEE from the University of Portland and a Master's degree in Engineering Management from Washington State University.

**Yun-tao Zhao** is a Senior Application Engineer at [STMicroelectronics](https://www.st.com) where he focuses on design and support for audio products. Prior to joining ST, Yun-tao spent four years in consumer audio video electronics product design and development. Yun-tao has a BSEE from Xi'an Jiao tong University.

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