Output-Filter Optimization for Class-D Audio Amplifiers

The MAX4295 and MAX4297 are switch-mode (or class-D) audio power amplifiers that are capable of operation from a single +2.7V to +5.5V supply. These devices can drive a bridge-tied 4-ohm load with up to 2W of continuous power at efficiencies over 85%. This makes them attractive as speaker drivers for portable equipment where maximizing battery life is a concern.

This article examines the output filtering often necessary with such devices. Not only is output filtering often required to maintain efficiency but also to control any radio frequency (RF) interference produced by the fast transitions on the outputs. Output filtering can be optimized for any given application as long as the designer is aware of the trade-offs involved.

Figure 1 shows some typical output waveforms from a class-D amplifier. Note how the duty cycle of the out+ terminal varies but the pulse period is constant (the time "ticks" between the two waveforms are equal time periods). If the pulses are averaged, the net effect over the sequence shown would be a slowly rising voltage (dashed line). The out- terminal is the inverse of the out+ terminal; thus, it would have a slowly falling voltage. In speaker-driver applications, where the load is connected between the + and - terminals, the "slow-moving" component ends up as the audible output—the high-frequency content is not reproduced.

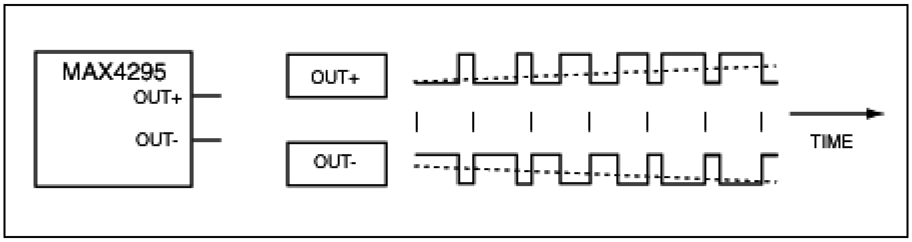


Figure 1. Output waveforms

Do I Have to Use an Output Filter?

The answer to this question is, it depends on the load. The MAX4295 and MAX4297 use a classic pulse-width modulation (PWM) approach, with complementary output MOSFETs. Consider the situation with a zero input signal applied, when the output waveforms will approximate a 50/50 duty cycle. In order to maintain reasonable efficiency, the MOSFETs should be presented with a high impedance *at the switching frequency*. Otherwise, if a resistor were connected directly across the outputs (for instance), with no other components present, the output stages would be conducting almost 100% of the time, independent of any duty-cycle changes.

The main advantage of using class-D amplifiers is to obtain high-efficiency operation over and above that of class-AB devices. The minimum condition that these parts require to achieve their advertised efficiency is to see a high-impedance load at the switching frequency and a low-impedance load at audio frequencies.

Let's examine the impedance plot of a typical speaker that the MAX4295 and MAX4297 might drive. Figure 2 shows the results of an 8-ohm, 1.75" cone transducer. Notice how the impedance rises up to and beyond 1MHz but presents a low-impedance load below 20KHz.

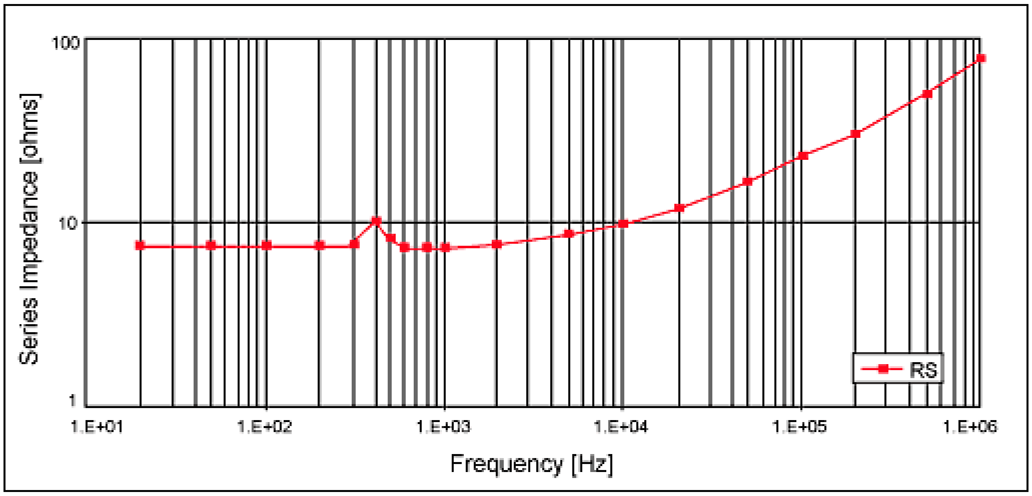


Figure 2. Loudspeaker impedance, 1.75" cone diameter

From the previous discussion, the implication is that this load should be capable of being driven directly from the output terminals of the MAX4295 and MAX4297 with no filtering, and this is indeed the case. The series inductance of the loudspeaker voice coil allows efficient operation for this loudspeaker *with no output filter.* From Figure 2, the value of inductance for this particular unit is of the order of 10µH. However, there are some limitations to this "filterless" mode of operation:

- The impedance at and above the switching frequency should be verified for the particular speaker to be driven. Remember that excessively long speaker leads could add a parallel capacitive load that could affect the efficiency adversely.
- The speaker leads and voice coil will be carrying signals with very high dv/dt; these can and will radiate high levels of RF emissions.
- A small amount of power due to the switching will be dissipated in the loudspeaker voice coil. With switching set to 500KHz and above, this is negligible; however, at lower switching frequencies, this should be factored in when calculating the maximum power the speaker is being asked to handle.

Minimum Implementation with Resistive Loads

If the load is mostly resistive in nature or looks capacitive at high frequencies, then other components must be added to ensure reasonable efficiency. A series inductor would be an obvious choice as an additional component. The inductor passes current to the load at audio frequencies and provides increasing impedance at high frequencies.

Let's take the example of an 8-ohm resistive load driven by the MAX4295 from a 5V supply. In calculating the series-inductor value, we could simply assume that the 3dB roll-off point due to the inductor should be placed just outside the audio band, say, at 30KHz. This would make the inductor value:

$$L = 8/(2 \cdot p \cdot f) \text{ or } 8/(2 \cdot pi \cdot 30x10^{3}) = 42.4\mu H$$

If we set our class-D amplifier to have a 250kHz switching frequency, the impedance seen by the output devices at this point is mostly due to the inductor:

$$X_L = 2 \cdot pi \cdot 250x10^{3} \cdot 42.4x10^{-6} = 66.7 \text{ ohms}$$

Or more than eight times the load impedance, so no significant power is lost at the switching frequency.

We can now look at the other parameters necessary for selecting the inductor. The data sheet tells us that the MAX4295 can deliver 1.2W into 8 ohms from a 5V supply. This means that the inductor must be sized to handle around 387mA RMS (and 550mA peak) without saturation, otherwise distortion of the output waveform will result.

Therefore, we could choose the PM54-470L, a 47µH SM power inductor from J.W. Miller Magnetics. It has a rated current of 720mA (so it will handle the peak current all right) and a DC resistance of 0.37 ohms (less than 5% of the load, thus not a big efficiency loss). The inductor's physical dimensions are about 5.8mm x 5.2mm, with a height above the PC board of 4.5mm. In portable products, where space both on and above the PC board is usually at a premium, this can be unacceptably large; in contrast, the MAX4295 in the QSOP package measures only 6mm x 5mm x 1.5mm. So, how can we reduce the physical size of the inductor?

Mounting the inductor in a hole or a notch in the PC board is one way. Thus, for a 1.6mm PC board, the total height above the PC board is reduced to around 2.9mm.

Another approach is to increase the switching frequency of the class-D stage. Both the MAX4295 and MAX4297 allow the user to set the switching frequency to one of four values, the highest of which is 1MHz. This would allow the value of the inductor to be decreased, as the switching frequency is now four times higher than the previous example. It does not necessarily follow that decreasing the value by four times will result in an inductor selection that is one-fourth of the physical size. As footprints get smaller, thinner wire is used in the windings, so DC resistance increases, but some improvement should be possible.

With the switching frequency now set to 1MHz, we can choose our inductor value to be four times less than in our initial example; this way, the impedance at the switching frequency is maintained:

$$42.4/4 = 10.6\mu H$$

The current handling and DC resistance requirements are unchanged, however. Choosing to switch at 1MHz has little effect on efficiency but does degrade THD+N performance slightly. (Refer to the MAX4295/MAX4297 data sheet for details; to access the data sheet, see "References and Further Reading" toward the end of this article.) So, does this save board space? We could now look at using Toko part A914BYW-100M, a 10µH part with a current rating of 760mA and a DC resistance of 0.125 ohms. Our inductor X-Y dimensions are still roughly the same at 5mm x 5mm. But we now have a lower profile part with only a 2mm height above the PC board, without resorting to special mounting techniques. Thus, this solution is less than half the *volume* of the previous inductor. We have a physically smaller solution, even though the necessary PC-board area is about the same.

Output-Filter Design

The above examples showed minimum implementations where basic device operation was required; there is little or no filtering of the RF spectrum due to the output devices' rapid switching. This energy can be radiated on speaker leads and PC-board traces, causing electromagnetic interference (EMI) problems. Controlling this unwanted effect can be important for two reasons:

- The amplifier is to be used in a portable device where other RF circuitry can be corrupted.
- The product it is used in is subject to FCC/CE or any other RF emissions-standards testing.

Most applications will require RF suppression filtering on the outputs for the above reasons. Our single inductor previously discussed can be readily turned into a lowpass filter by the addition of a capacitor to the complementary output, as in Figure 3.

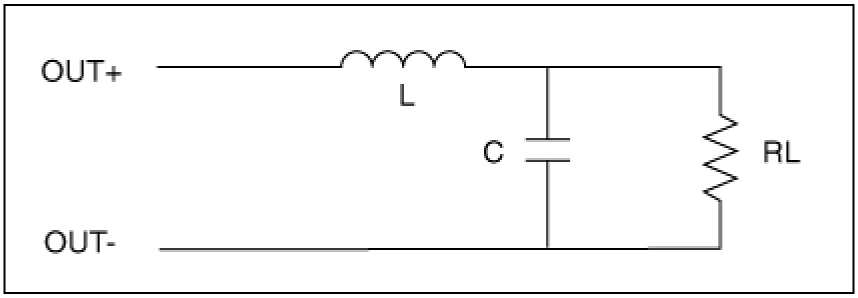


Figure 3. Single-ended 2-pole filter

However, the out- lead of the speaker still sees the full switching voltage waveform, so radiation problems are still likely. A more effective implementation is the balanced 2-pole filter in Figure 4.

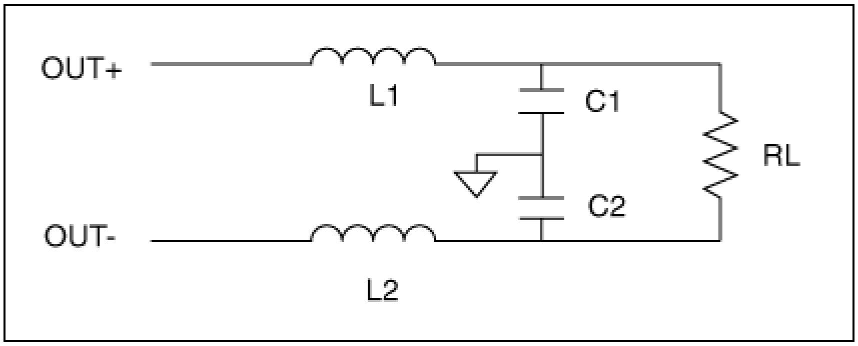


Figure 4. Balanced 2-pole filter

This provides lowpass filtering before the waveform reaches either speaker lead, so the EMI performance will be much improved. Now consider what effect selecting and incorporating these extra filtration components will have on PC-board area.

Two inductors are now required, and the previously discussed benefits of the load (and LP filter) having a high impedance at the switching frequency are still valid. Retaining the 1MHz switching frequency on the MAX4295, we could halve our 10µH inductor value (as there will effectively be two inductors in series between the MOSFET outputs) and use two 5µH parts. From the Coilcraft catalog, we can choose the DT1608C-472, a 4.7µH inductor with a current rating of 1.2A and a DC resistance of 0.085 ohms; both specifications are more than adequate for the application.

Note that the contribution of the DC resistance will be doubled, as both inductors are in series with the load, giving a 0.17-ohms total. This is around 2% of total load resistance, so it will affect efficiency very little.

The capacitance value can now be chosen to define the filter high-frequency (HF) roll-off. If we consider only half of the differential output drive, the math becomes more straightforward, and we realize a 2nd-order LCR filter:

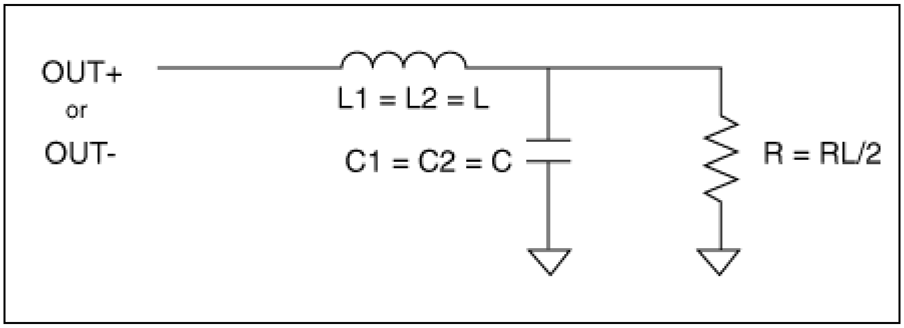


Figure 5. Equivalent 2-pole filter for each output

In the figure above, both R and L are known, so we just need to define the value of C. A Butterworth, maximally flat filter is a reasonable approach, the 4% or so voltage overshoot in response to a step input being acceptable. The math is detailed elsewhere (see the appendix and refer to the MAX4295/MAX4297 data sheet), but the value of C ends up being:

$$C = L/(4R^2\xi^2) = 4.7\text{x}10^{-6}/(4 \bullet 4^2 \bullet (0.707)^2) = 0.146\mu\text{F}$$

where ξ is 0.707 for Butterworth. This value can be realized using a combination of a capacitor across the inductors, as well one to GND from each output (referred to as "alternate balanced 2-pole filter" in the data sheet). The bill of materials is simplified by using three 0.047µF caps, as in Figure 6.

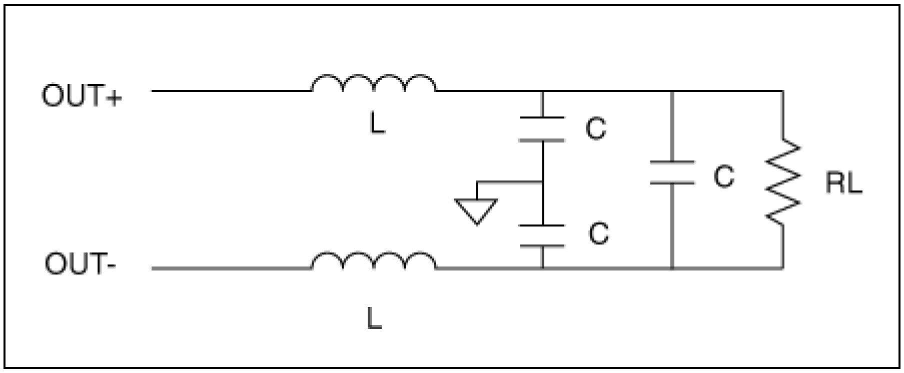


Figure 6. Final 2-pole filter: L = 4.7µH, C = 0.047µF, RL = 8 ohms

Each + and - phase subsequently see a capacitance of 0.141µF. The "corner" frequency for the filter is at 192KHz, so it will start attenuating above that frequency. The inductors chosen do not go self-resonant until 60MHz; therefore, the filter should attenuate switching noise over two and a half decades, at which point the switch energy should be falling rapidly anyway (the rise/fall times on the part are around 30ns).

To minimize radiation, the PC-board layout should have the inductors placed as close to the MAX4295 as possible. The tracking between the inductors and the capacitors should also be minimized. The physical size (and cost) of the capacitors is much less of an issue than that of the inductors. For the 0.047µF required, surface-mount, 16V 0402 ceramics are available with X7R dielectrics from AVX Corporation and many other manufacturers.

Note: If filter optimization is important for the application, any calculations should take the HF load impedance into account. Further accuracy would be gained from modeling the DC resistance and self-resonant behavior of the inductors, as well as capacitor equivalent series resistance (ESR).

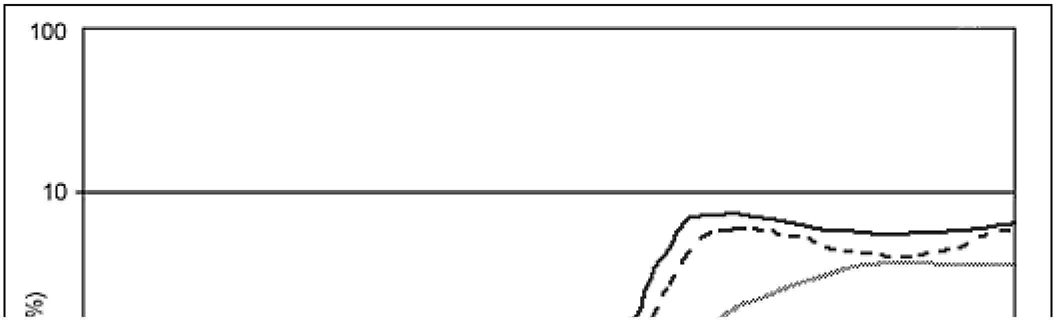
Results

The 2-pole filter in Figure 5 was tested with Coilcraft DT1608C-472 inductors, driving an 8-ohm resistive load from one channel of a MAX4297 EV kit set for 1MHz switching frequency. The efficiency was calculated with a sine wave of 2V applied at four different frequencies (see Table 1).

Table 1. Measured Efficiency

Input Frequency (KHz)	**Efficiency (%)**
1	74.9
5	84.3
10	86.3
15	86.7

The above results show the high efficiency that class-D devices can achieve—much higher than traditional class-AB amplifiers. The distortion performance was also checked; Figure 7 shows the result of measuring THD+N using an Audio Precision System One, while the output power is varied. This is shown at three different frequencies: 1KHz, 5KHz, and 10KHz. The measurement bandwidth was set to 22Hz-22KHz. The results are in broad agreement with the data sheet, with distortion dominating the noise over most of the range. The distortion remains below 1% for all frequencies up to a 0.7W output power level.



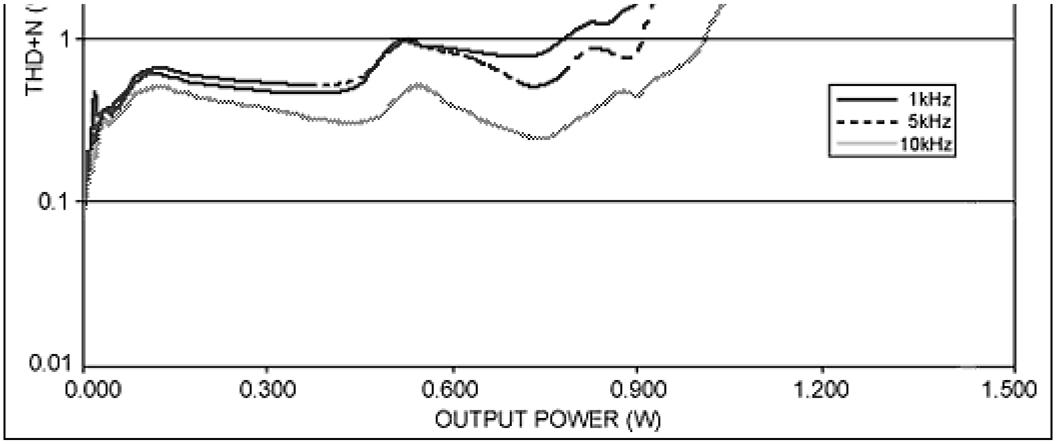


Figure 7. THD+N vs. output power

Figure 8 shows THD+N versus frequency, again measured with a 22Hz-22KHz bandwidth. The output power was set to 0.7W at 1KHz.

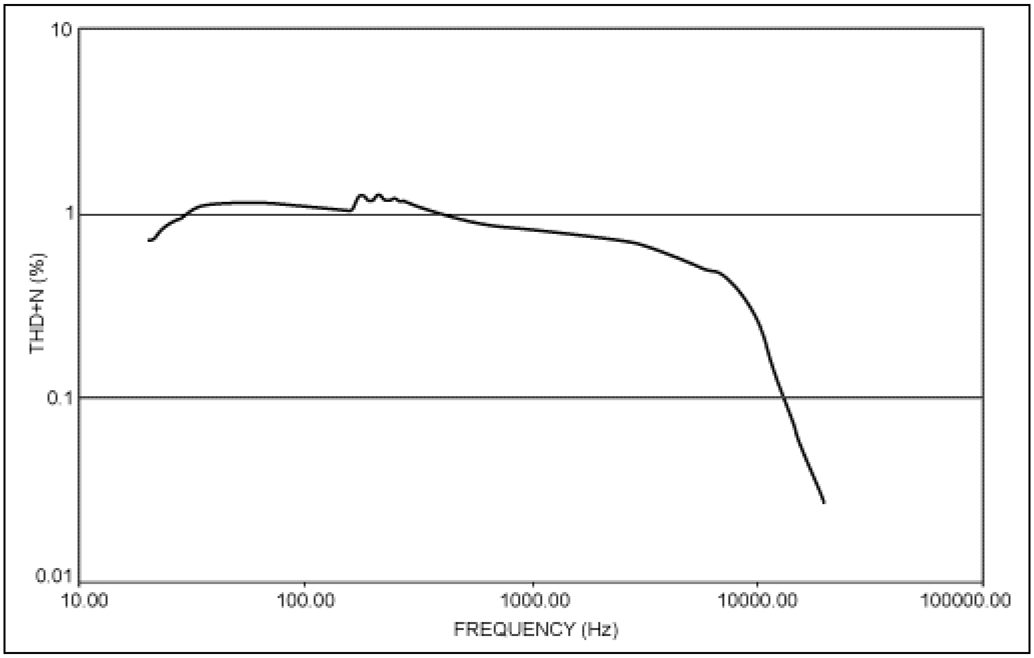


Figure 8. THD+N vs. frequency

Summary

Becoming familiar with the design concepts, advantages, and limitations of class-D amplifiers allows the user to optimize any output filtering for a given application. The often conflicting needs of maintaining amplifier efficiency, minimizing PC-board area and meeting height restrictions, keeping component costs low, and controlling the HF output spectrum can be weighed against one another, leading to informed design decisions.

Appendix: 2nd-Order Filter Calculations

The transfer function for the filter in Figure 5 can be expressed as:

$$H(s) = (1/LC)/(s^2 + s(1/CR) + (1/LC))$$

This can be equated to the generic 2nd-order system equation:

$$G(s) = \omega_n^2/(s^2 + 2\omega_n \xi s + \omega_n^2)$$

R and L are known, so we can solve for C:

$$C = L/(4R^2\xi^2)$$

Also, ω_n is a useful parameter:

$$\omega_n = 1/(\sqrt{LC}) \text{ rads}^{-1}$$

References and Further Reading

1. MAX4295/MAX4297 data sheet
2. *Principles of Active Network Synthesis and Design*, Gobind Daryanani (John Wiley & Sons, Inc.), 1976

Filter-Component Manufacturers

1. Coilcraft
2. J.W. Miller Magnetics
3. Toko
4. AVX Corporation

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