

Reducing the output filter of a Class-D amplifier

By Mike Score

System Specialist, Audio

A properly designed Class-D output filter limits supply current, minimizes EMI and protects the loudspeaker from switching waveforms. However, it also significantly increases the total design cost. The current recommended second-order output filter for the TI TPA005D02 is 30% of the audio power amplifier (APA) solution cost. This application note details the second-order Butterworth filter and two reduced filtering techniques, each providing a different price/performance node. The first alternative to the Butterworth filter reduces the output filter by half and the second option completely eliminates the filter. The filters were tested using Texas Instruments TPA005D02 Class-D APA. Design decisions based on the measured results and conclusions are drawn to provide practical solutions for applications with different price/performance nodes.

Second-order Butterworth low-pass filter

The second-order Butterworth low-pass filter is the most common filter used in Class-D amplifier applications. This filter uses two inductors and three capacitors for a bridged-tied-load (BTL) output, which can be seen

Figure 1. Full second-order Butterworth filter

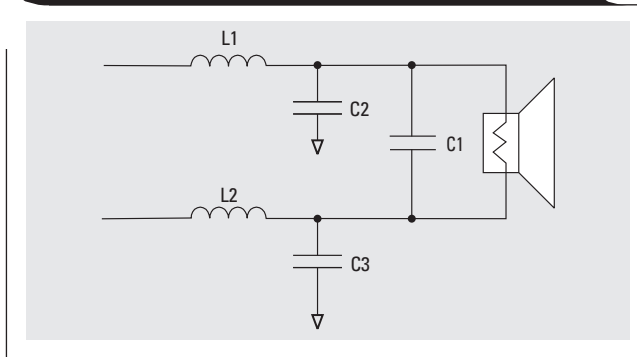
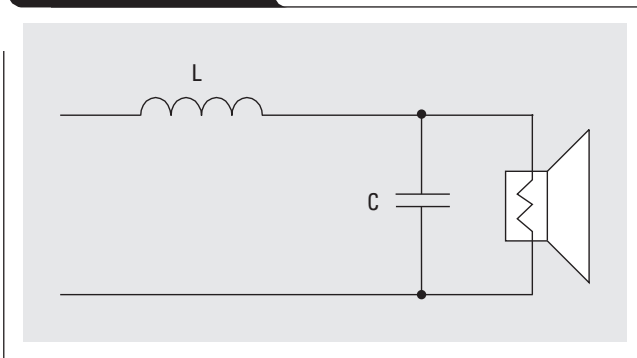


Figure 2. Half filter



in Figure 1. The primary purpose of this filter is to act as an inductor at the switching frequency. The inductor is needed to keep the output current constant while the voltage is switching. If the outputs do not see an inductive load at the switching frequency, the supply current will increase until the device is unstable. Higher inductance at the output yields lower quiescent current (supply current with no input) because it limits the amount of output ripple current. The filter protects the speaker by attenuating the switching frequency. The inductors, L1 and L2, and the capacitor C1 form a differential filter that has an attenuation slope of 40 dB per decade. The majority of the switching current flows through C1, leaving very little current to be dissipated in the speaker. The filter also reduces EMI. The previously described differential filter reduces differential radiation. Inductors L1 and L2 and capacitors C2 and C3 form common-mode filters that further reduce EMI. See the “TPA005D02 Class-D Stereo Audio Power Amplifier Evaluation Module User’s Guide”¹ for details on how the output filter was designed.

Half filter

The half filter (shown in Figure 2) eliminates one of the inductors and the two capacitors to ground. The other inductor must be doubled (for half filter $C = C1$ of the full filter) to obtain the correct cut-off frequency. This filter is still inductive at the switching frequency because capacitor C looks like a short at the switching frequency and each amplifier output sees inductor L. The supply current is even lower for this application because the total inductance stays the same as the full filter but the DC resistance (DCR) from the inductors is reduced causing less power loss in the filter. The speaker is still protected in this application although one of the speaker terminals is directly tied to the switching waveform. The differential signal is still filtered and the audio output rides on the switching waveform. Although this filter attenuates the differential signal, which reduces EMI, it does not attenuate the common mode signal, which could cause EMI problems. Methods to reduce EMI will be discussed in a later section.

No filter

The filter can be eliminated if the speaker is inductive at the switching frequency. How is it possible to eliminate the filter and place a pulse-width modulated (PWM) square wave directly across the speaker? The PWM waveform is the sum of the switching waveform and the input audio signal with gain. The human ear acts as a band-pass filter, hearing only the frequencies between approximately 20 Hz and 20 kHz. The switching frequency is much greater than 20 kHz, so the only signal heard is the input

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audio signal with gain. The main drawback to not using a filter is that the switching waveform is dissipated in the speaker, which leads to a higher quiescent current, $I_{DD(q)}$. This is because the speaker is both resistive and reactive, where an LC filter is almost purely reactive. A more inductive speaker yields lower quiescent current, so it is better to use a two or more layer voice coil speaker for a high inductance in this application. A concern with the switching waveform being dissipated in the speaker is that it may cause damage to the speaker. A primary concern is speaker wear due to a rail-to-rail square wave driving the speaker whenever the amplifier is on. For a 250-kHz switching frequency, this is not an issue because the speaker cone movement is proportional to $1/f^2$ for frequencies beyond the audio band, thus the amount of cone movement at the switching frequency is insignificant.² Damage could occur to the speaker if the voice coil is not designed for the added power. The added power to the load is less than the added power taken from the supply because the device cannot have efficiency greater than 100%. The added power can be calculated using Equation 1, where P_{SW} is the added power dissipated in the speaker, $I_{DD(q)(with\ speaker\ load)}$ is the quiescent current measured with speaker load, $I_{DD(q)(no\ load\ or\ filter)}$ is the quiescent current measured with no load, V_{DD} is the supply voltage and N is the number of channels.

(1)

$$P_{SW} < \frac{(I_{DD(q)(with\ speaker\ load)} - I_{DD(q)(no\ load\ or\ filter)})V_{DD}}{N}$$

The added power from the switching waveform can be calculated. A supply current of 83-mA was measured with the TPA005D02 EVM connected to the speakers available with the TI Plug-n-Play base kit. The supply current with no load was measured at 23 mA. A 5-V supply was used and, because TPA005D02 is a stereo device, $N=2$; therefore, the maximum added switching power dissipated in the speaker is 150 mW. Originally, 3-watt speakers were required. The filterless solution requires 3.15-watt speakers. Another concern is that not filtering causes the amplifier to radiate EMI along the lines from the amplifier to the speaker. The filterless application is not recommended for EMI-sensitive circuits.

Measured results

The quiescent current, total harmonic distortion plus noise (THD+N) and intermodulation distortion (IMD) were measured for the full-, half- and no-filter applications. Each measurement was done using a TPA005D02 Class-D

Table 1. Quiescent current for various filter applications using the TPA005D02 and the TPA0102

APPLICATION	LOAD	L (μH)	$I_{DD(q)}$ (mA)
Full filter	Any size resistor or speaker load	15	39
Half filter L = DS3316-P-xxx	Any size resistor or speaker load	15	42
		22	35
		33	29.5
		47	27
Half filter L = DS5022-P-xxx	Any size resistor or speaker load	68	25
		100	24
		150	23
No filter	Notebook speaker		215
	NXT speaker		199
	TI PnP speaker		83
	Bose 151 speaker		83
TPA0102	Any load		19

2-W amplifier. A measurement was made in each case with the TI TPA0102 used for comparison. The measurement set-up and results will be discussed for each test.

Quiescent current

The quiescent current for the full-, half- and no-filter applications is tabulated in Table 1. The quiescent current of the full- and half-filter applications was independent of the load and varied greatly with inductor value, but the no-filter application's quiescent current was dependent on the inductance of the speaker. The full-filter quiescent current was measured using the filter designed for a 4-ohm load, where $L_1=L_2=15\ \mu\text{H}$, $C_2=C_3=0.22\ \mu\text{F}$, and $C_1=1\ \mu\text{F}$, with the components labeled as shown in Figure 1. The quiescent current of the half-filter application shown in Figure 2 was measured with $C = 1\ \mu\text{F}$, and L was varied to show how increasing inductance decreases ripple current at the output. The recommended half-circuit filter for a 4-ohm load is $L=33\ \mu\text{H}$ and $C=1\ \mu\text{F}$, which had a quiescent current of 29.5 mA. The recommended half filter for an 8-ohm load is $L=68\ \mu\text{H}$ and $C=0.56\ \mu\text{F}$, which had a quiescent current of 25 mA. The quiescent current for the filterless application varies with load. The TI PnP speaker and the Bose 151 speaker had quiescent current of 83 mA while the lower inductance flat panel NXT speakers³ had a quiescent current of 199 mA. A commercial notebook speaker was even less inductive and exhibited a quiescent current of 215 mA. The Class-AB amplifier had a quiescent current of 19 mA, which was much lower than the Class-D with no filter and is less than half the Class-D with full filter, but not much lower than the Class-D with half filter.

Total harmonic distortion plus noise (THD+N)

Total harmonic distortion plus noise (THD+N) was measured with the Audio Precision II analyzer. In each measurement, an RC filter with a cut-off frequency of 37 kHz was added between the output to ground to filter the common-mode signal into the Audio Precision. The bandwidth of the Audio Precision was set from 10 Hz to 22 kHz and an internal 20-kHz low-pass filter was also used to ensure that the switching frequency did not influence the THD+N measurement. Band-limiting the measurement ensured that only the audible harmonic distortion and noise were measured. The amplifiers were set at a gain of 22.5 V/V. THD+N versus output voltage at 1 kHz was measured with the TPA005D02 with full, half and no filter. The same test was performed using the TPA0102.

Both can be seen in Figure 3. The Class-D full- and half-filter applications had approximately the same THD+N across all power levels. The Class-D without the output filter actually had lower THD+N at the lower power levels than the TPA005D02 with the filter and the TPA0102. The TPA0102 had approximately the same THD+N as the TPA005D02 with the full and half filters at low to mid powers, and lower THD+N at the higher powers.

IMD

Intermodulation distortion (IMD) occurs when two or more signals are input into an amplifier and the sum and difference of the input frequencies are present at the output. IMD is a good measurement of linearity (the lower the IMD, the more linear the device under test). IMD is

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Figure 3. THD+N vs. V_{out}

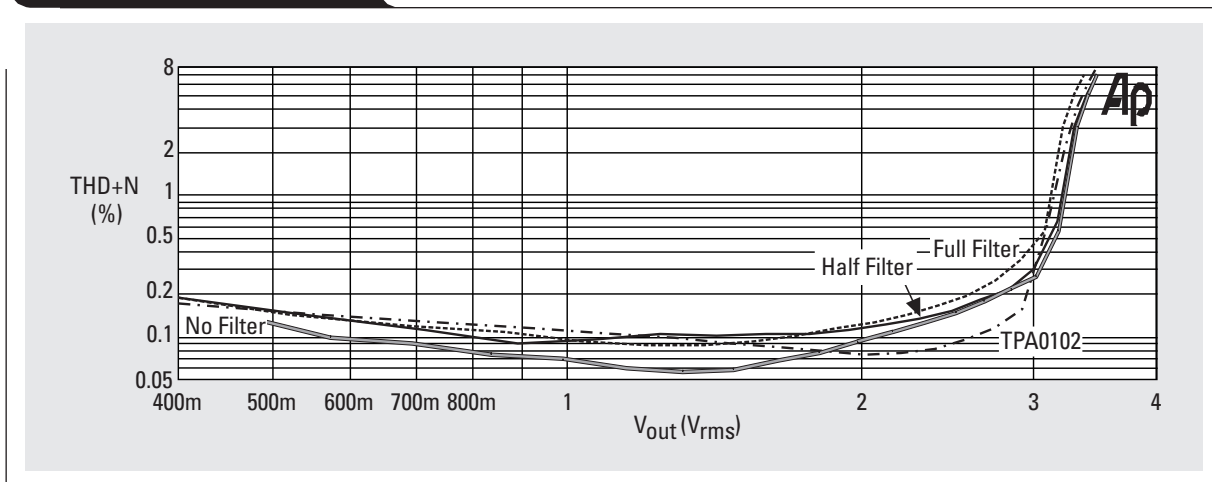
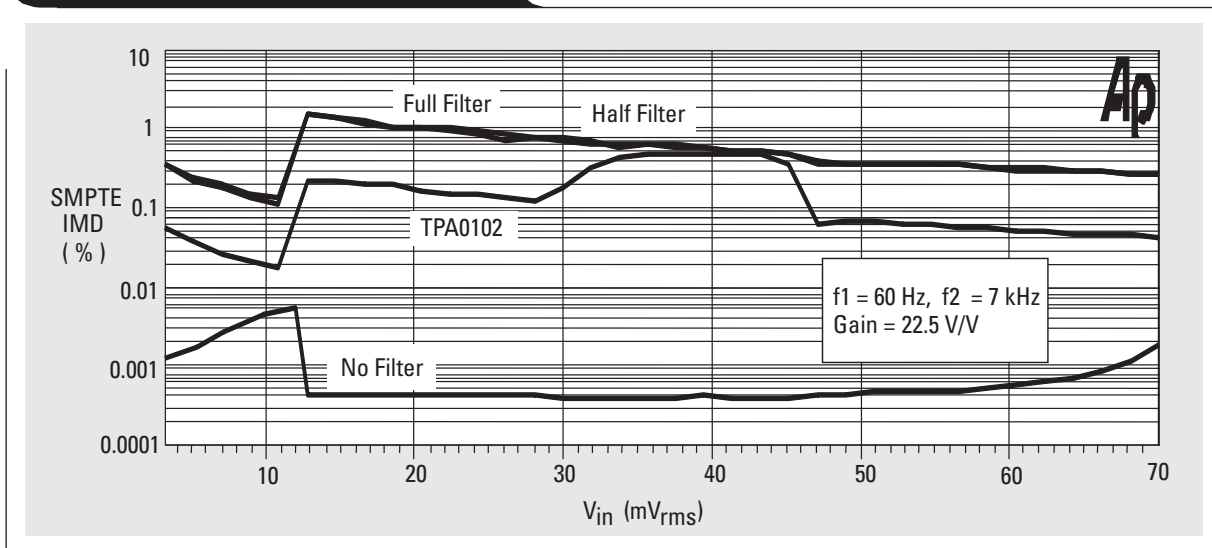


Figure 4. SMPTE IMD vs. input voltage



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the ratio of magnitude of the sum and difference signals to the original input signal.

$$\text{IMD} = [(V_{f_2-f_1} + V_{f_2+f_1})^2 + (V_{f_2-2f_1} + V_{f_2+2f_1})^2 + (V_{f_2-3f_1} + V_{f_2+3f_1})^2 \dots]^{0.5}/V_{f_2} \quad (2)$$

where V_{f_2} is the voltage at the input frequency f_2 , $V_{f_2+f_1}$ is the voltage at the sum of input frequencies f_1 and f_2 , $V_{f_2-2f_1}$ is the voltage at the difference of input frequencies f_1 and $2*f_2$, etc.

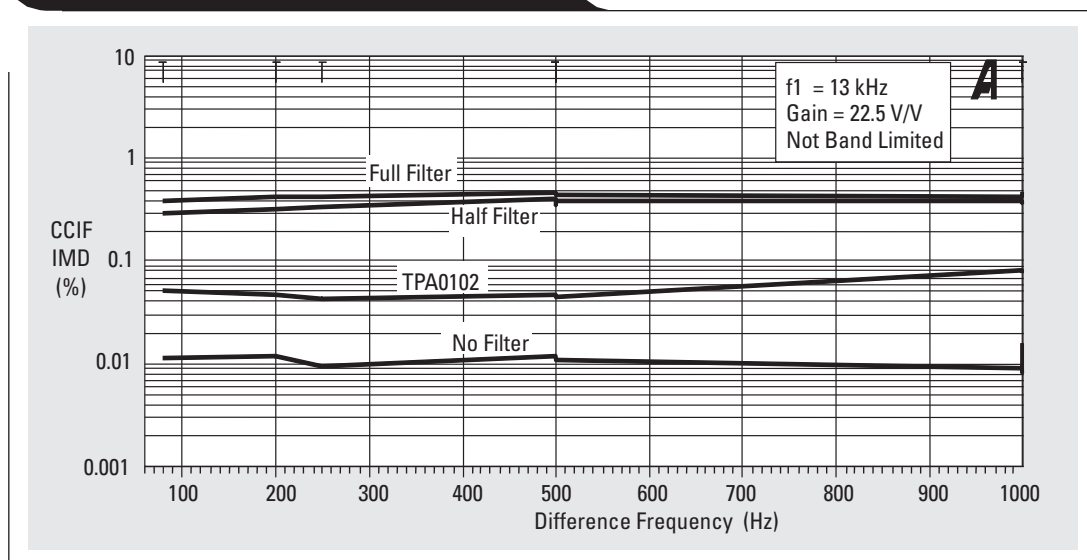
The Society of Motion Picture and Television Engineers (SMPTE) standard IMD test is the most common IMD measurement. The SMPTE IMD test inputs a low-frequency 60-Hz and high-frequency 7-kHz sine wave into the device. The low-frequency sine wave has four times the amplitude of the high-frequency sine wave.⁴ The SMPTE IMD versus input voltage of the Class-AB and Class-D amplifier with the full, half and no filter was measured and can be seen in Figure 4. The same set-up used for the THD+N measurement was used for the IMD measurements. The full- and half-filter circuits had equal IMD that was slightly higher than the Class-AB amplifier. The Class-D without a filter had the lowest IMD.

The CCIF, or twin-tone, IMD measures IMD of the amplifier using two high-frequency input signals of equal amplitude. The plot in Figure 5 shows CCIF IMD versus difference frequency. The center frequency was set to 13 kHz and the difference frequency was swept from 80 Hz to 1 kHz. The Class-D amplifier with full filter had the highest CCIF IMD, ranging from 0.4% to 0.5%, and the half-filter application CCIF IMD was approximately 0.1% lower over the tested frequency range. The Class-AB amplifier had a lower CCIF IMD, which was 0.05%. The

Class-D without an output filter had the lowest CCIF IMD, which was 0.01%.

Design decisions based on results**Class-D without output filter**

The Class-D without the output filter not only had lower THD+N and IMD than the Class-D with the filter, it also outperformed the Class-AB device. The two disadvantages of using the Class-D amplifier without the output filter are high quiescent current and high EMI. Quiescent current can be lowered using a speaker with a high inductance, but it is doubtful whether it could ever be lower than an application with a filter. EMI can be lowered using ferrite beads at the output of the amplifier, shielded speakers and shielded speaker wires running to the speakers. EMI can also be reduced by making the distance from the amplifier to the speaker as short as possible and by keeping the positive and negative output wires very close together to reduce common-mode radiation. A good application for a Class-D amplifier without a filter is one where quiescent current and EMI are not important, but system cost, maximum power supply and heat are important (e.g., powered speakers). An example of this is a powered speaker. The Class-D without the filter is less efficient than the Class-D with the filter at lower output levels, due to the higher quiescent current. However, the Class-D efficiency is approximately the same with and without the filter at high output levels (2 to 3 times more efficient than Class-AB). A 10-W powered speaker could use a Class-D amplifier without the output filter or heat sink and use a lower-rated power supply than a Class-AB amplifier. The system cost of this application is less than the Class-D with the full or half filter because the filter is eliminated, and less expensive than the system cost of the Class-AB solution. The heat sink is eliminated and the

Figure 5. CCIF IMD vs. difference frequency

power supply is reduced in a 10-W Class-D filterless application, but the Class-D amplifier is slightly more expensive than an equivalent Class-AB amplifier. The speaker inductance must be high, and the amplifier must be close to the speaker in this application.

Class-D with half filter

Class-D with a half filter had a lower quiescent current and performed as good as or better than the Class-D with full filter in THD+N and IMD. The quiescent current lowers as the inductor of the half filter increases. As inductance increases, peaking occurs at the corner frequency of the filter. The corner frequency can be set outside the audio band so the peaking has no effect on sound quality. Peaking occurs regardless of LC design with a speaker load when designing for a resistive load. The half filter designed for a 4-ohm resistive load uses a 33- μ H inductor with a 1- μ F capacitor, and the half filter designed for an 8-ohm resistive load uses a 68- μ H inductor and a 0.56- μ F capacitor. Each of these examples exhibits peaking at the corner frequency because the speaker is not purely resistive at the corner frequency. An RC network can be used across the load to reduce reactance of the load to limit peaking. If quiescent current is very important, the designer can increase L and lower C, decreasing the quiescent current and keeping the corner frequency in place. The designer should design the filter with the speaker load to ensure the corner frequency peaking is outside the audio band. The only disadvantage with the half-filter application is that it has higher common-mode EMI than the full filter due to the filter not having a common-mode filter. The common-mode EMI should not be a problem in most systems if the positive and negative output signal paths are very close together to cancel common-mode radiation. The filter should be as close to the amplifier as possible to reduce EMI. EMI can be further reduced with ferrite beads, shielded speaker wire and using good board layout. The Class-D with half filter is an ideal circuit where battery life, heat and system cost are primary issues. The Class-D with half filter is the most efficient circuit at low and high powers and has a lower cost than the Class-D with full filter. These issues make the half filter Class-D the ideal circuit for notebook PCs. Notebook PCs are very concerned with battery life and heat, while system costs are still important. EMI issues are well understood by notebook designers, so the additional EMI generated by the half-filter implementation should not be a problem.

Class-D with full filter

Class-D with full filter had lower IMD than the Class-D without a filter and higher quiescent current than Class-D with a half filter. It also has a higher system cost than either circuit. Designers should use Class-D with the full output filter when heat, battery life and EMI are concerns. An example of this would be a boom-box, where the amplifier is in the same location as an AM receiver, where the switching frequency is close to the band of frequencies that the AM receiver is demodulating. Another example would be any device that has wires connecting the amplifier to the speakers. The wires act as an antenna, and if not filtered, the switching frequency could radiate to other devices in the vicinity.

Conclusion

It is possible to reduce the output filter in certain applications. This application note has shown that reducing the output filter does not mean reduction in quality. The Class-D amplifier with and without the output filter had approximately the same THD+N. The Class-D amplifier actually had lower IMD without the output filter. The quiescent current of the Class-D amplifier was lower using the half filter than the full filter, making the Class-D amplifier even more efficient. The designer who is primarily concerned with maximum heat and power-supply constraints and is not concerned with EMI and quiescent current could use the Class-D amplifier without a filter to save cost. A designer who is primarily concerned with heat and battery life and has EMI as a secondary concern could use a Class-D amplifier with a half filter. Applications that are very EMI-sensitive and/or have devices operating around the switching frequency of the Class-D amplifier should use a full filter.

References

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