TEXAS INSTRUMENTS

Reducing and Eliminating the Class-D Output Filter

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Contents

List of Figures

List of Tables

Reducing and Eliminating the Class-D Output Filter

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ABSTRACT

This application report investigates reducing and eliminating the LC output filter traditionally used in class-D audio power amplifier applications. The filter can be completely eliminated if the designer is using a predominantly inductive speaker; however, the supply current and the EMI are higher than if using the full second-order Butterworth low-pass filter. The designer can use half of the components in the originally recommended second-order Butterworth low-pass filter to reduce the supply current, but the EMI is still higher than that of the full filter. The half and no filter class-D applications outperform the full second-order Butterworth filter in total harmonic distortion plus noise (THD+N) and intermodulation distortion (IMD). This document shows speaker requirements with and without a filter, fidelity and electromagnetic Interference (EMI) results, and indicates what type of filter fits various system requirements.

1 Introduction

A properly designed class-D output filter provides many advantages by limiting supply current, minimizing electromagnetic interference (EMI), and protecting the speaker from switching waveforms. However, it also significantly increases the total solution cost. The current recommended second-order output filter for the TPA005D02 is 30% of the audio power amplifier (APA) solution cost. This application report discusses the recommended second-order Butterworth filter as well as 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 total harmonic distortion plus noise (THD+N) and intermodulation distortion (IMD) of the class-D amplifier with full filter, half filter, and no filter were measured using a Texas Instruments TPA005D02 Class-D APA. Near-field EMI was measured and methods to reduce EMI are suggested for each application. Filter selections were then made based on system requirements.

This document gives speaker and filter component recommendations for each filter application.

2 Second-Order Butterworth Low-Pass Filter

The second-order Butterworth low-pass filter is the most common filter used in class-D amplifier applications. The second-order Butterworth low-pass filter as shown in Figure 1 uses two inductors and three capacitors for a bridged-tied load (BTL) output [1].

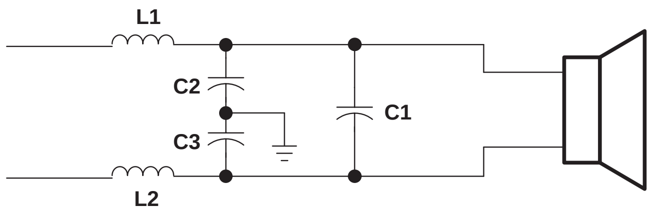

Figure 1. Full Second-Order Butterworth Filter

The primary purpose of this filter is to act as an inductor to keep the output current constant while the voltage is switching. If the amplifier outputs do not see an inductive load at the switching frequency, the supply current will increase until the device becomes 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 also protects the speaker by attenuating the ultrasonic switching signal. Inductors L1 and L2, and capacitor C1 form a differential filter that attenuates the signal with a slope of 40 dB per decade. The majority of the switching current flows through C1, C2, and C3, leaving very little current to be dissipated by the speaker. The filter also greatly reduces EMI, which is discussed in a subsequent section.

3 Half Filter

The half filter, as shown in Figure 2, eliminates one of the inductors and the two capacitors to ground from the full filter.

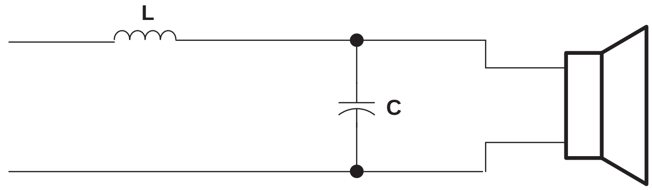

Figure 2. Half Filter

For the cut-off frequency to remain unchanged, the value of the inductor is doubled while the value of the capacitor across the load stays the same. The capacitors to ground are removed to prevent one of the amplifier outputs from seeing a capacitive load, which would greatly increase the supply current. This filter is still inductive at the switching frequency because the capacitor looks like a short at that frequency.

Aside from the primary advantage of reduced system cost, the half filter also decreases the quiescent current. In the case of the full filter, part of the switching current is shunted to ground through one of the capacitors. In the half filter, the absence of a capacitor to ground eliminates this waste. Furthermore, each output sees the full inductance value, which effectively reduces the rate of change in the inductor current, providing less power loss in the filter. Although this filter attenuates the differential signal, which reduces the magnetic field radiation, it does not attenuate the common mode signal, which causes the electric field radiation. Sources of EMI and methods to reduce EMI are covered in Section 9.

4 No Filter

The filter can be completely eliminated if the speaker is inductive at the switching frequency. For example, the filter can be eliminated if the class-D audio power amplifier is driving a midrange speaker with a highly inductive voice coil, but cannot be eliminated if it is driving a tweeter or piezo electric speaker, neither of which are highly inductive. The class-D amplifier outputs a pulse-width modulated (PWM) square wave, which is the sum of the switching waveform and the amplified input audio signal. The human ear acts as a band-pass filter such that only the frequencies between approximately 20 Hz and 20 kHz are passed. The switching frequency components are much greater than 20 kHz, so the only signal heard is the amplified input audio signal.

The main drawback to eliminating the filter is that the power from the switching waveform is dissipated in the speaker, which leads to a higher quiescent current, $I_{DD(q)}$. The speaker is both resistive and reactive, whereas an LC filter is almost purely reactive. A more inductive speaker yields lower quiescent current, so a multilayer voice coil speaker is ideal in this application.

The switching waveform, driven directly into the speaker, may damage the speaker. The rail-to-rail square wave driving the speaker when power is applied to the amplifier is the first concern. With a 250-kHz switching frequency, however, this is not as significant because the speaker cone movement is proportional to $1/f^2$ for frequencies beyond the audio band. Therefore, the amount of cone movement at the switching frequency is insignificant [2]. However, damage could occur to the speaker if the voice coil is not designed to handle the additional power. Section 5 focuses on selecting the speaker and includes a derivation for choosing the power requirements of the speaker when not using an output filter.

Eliminating the filter also causes the amplifier to radiate EMI from the wires connecting the amplifier to the speaker. Therefore, the filterless application is not recommended for EMI sensitive applications. Methods of reducing EMI are discussed in Section 9.

5 Speaker Selection

5.1 Class-D With Full Filter and Half Filter

Selecting an appropriate speaker for a half-filter or full-filter class-D application is approximately the same as specifying a speaker for a class-AB application. First, the speaker should be efficient, or it should provide better than average sound pressure level (SPL) output for a given power input. Second, the speaker must also have a good frequency response, meaning a relatively constant SPL across a wide frequency range for a given input power.

A speaker should have a low inductance voice coil if designing with a filter, as the inductance causes a peak to appear in the output at the corner frequency of the filter. Peaking is not a significant problem in class-D applications though, because the corner frequency of the filter is set outside the audible frequencies. The class-D output filter should have a corner frequency of 25 kHz or higher, so the peaking may slightly affect the upper frequencies of the audio band. However, this peaking should be so small that it has an insignificant effect on the sound quality.

5.1.1 Zobel Networks Reduce Peaking

If the peaking does cause problems in a given system, a simple RC matching network, also called a Zobel network, may be placed in parallel with the speaker, as shown in Figure 3.

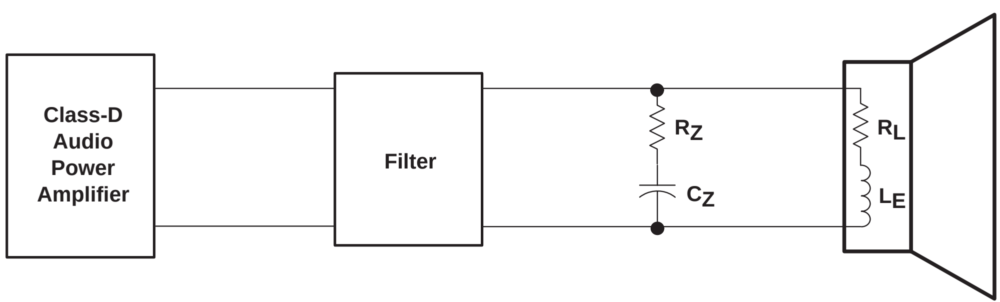

Figure 3. Class-D Amplifier With Zobel Network

The resistor and capacitor act to dampen the reactance of the load. The equations for the components of the Zobel network are shown in equations 1 and 2. R_L is the DC resistance of the speaker, and can be measured with an ohmmeter. L_E is the electrical inductance at DC, and is usually given as a speaker parameter. The power rating of the resistor and capacitor of the Zobel network are dependent upon the selected component values and must be calculated. The power rating of the resistor will be high for many applications, making this solution impractical for many systems in which cost and size are important.

$$R_Z \cong 1.25 \times R_L$$

$$C_Z = \frac{L_E}{{R_L}^2}$$

5.2 Class-D Without Filter

The major difference in selecting a speaker for a class-D amplifier without a filter is that the speaker must have a high inductance. Furthermore, the speaker power rating must be slightly increased to account for the switching waveform being dissipated by the speaker instead of by the filter.

5.2.1 High-Inductance Speakers

The filterless class-D application requires a speaker with a high inductance to keep the output current relatively constant while the output voltage is switching. As a result, the filterless approach may be impractical for use with a tweeter or a piezo electric speaker, both of which typically have small inductances. Without the filter, the peaking problem with the full and half filter application disappears because there is no filter to form a resonant circuit.

The additional quiescent current due to switching waveform power dissipation in the speaker can be calculated by first thinking of the speaker as a complex load. The switching current dissipated in the speaker can be calculated if the impedance and phase of the speaker is known for frequencies greater than the switching frequency. The magnitude and phase of the impedance of the speaker may be measured with a network analyzer from the switching frequency and higher to get an exact measurement on the switching loss in the speaker.

$$P_{DIS} = \sum_{n=1}^{\infty} \frac{V_{SW}\left(n \times f_{SW}\right)^2 \times \cos\left(\phi_{SPKR}\left(n \times f_{SW}\right)\right)}{\left| Z_{SPKR}\left(n \times f_{SW}\right) \right|} \tag{3}$$

The Fourier series needs to be calculated for the switching waveform that is being applied to the speaker. This is not as difficult with the TPA005D02, which has the standard modulation scheme, because the switching waveform voltage, V_{SW}, is a square wave, which is composed of the sum of many sine waves with frequencies of the odd harmonics of the switching frequency. The RMS value of the harmonics are shown in equation 4. The impedance and phase must then be calculated at each odd harmonic of the switching frequency.

$$V_{SW}\left(n \times f_{SW}\right) = \frac{0.707 \times V_{DD}}{n} \qquad \text{for } n = 1,\ 3,\ 5,\ 7,\ 9,\ 11,\ \ldots \tag{4}$$

The impedance and phase of the speaker that Texas Instruments provides with the TI Plug-N-Play Audio Evaluation Platform can be seen in Figure 4 and Figure 5.

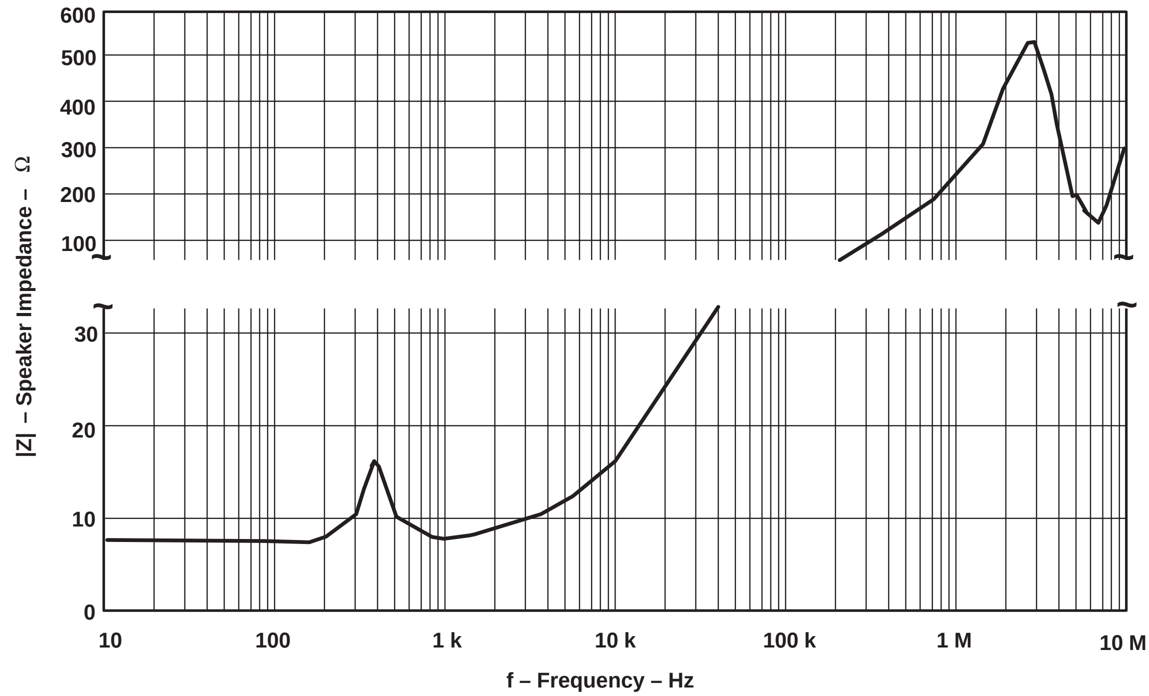

Figure 4. TI Speaker Impedance vs Frequency

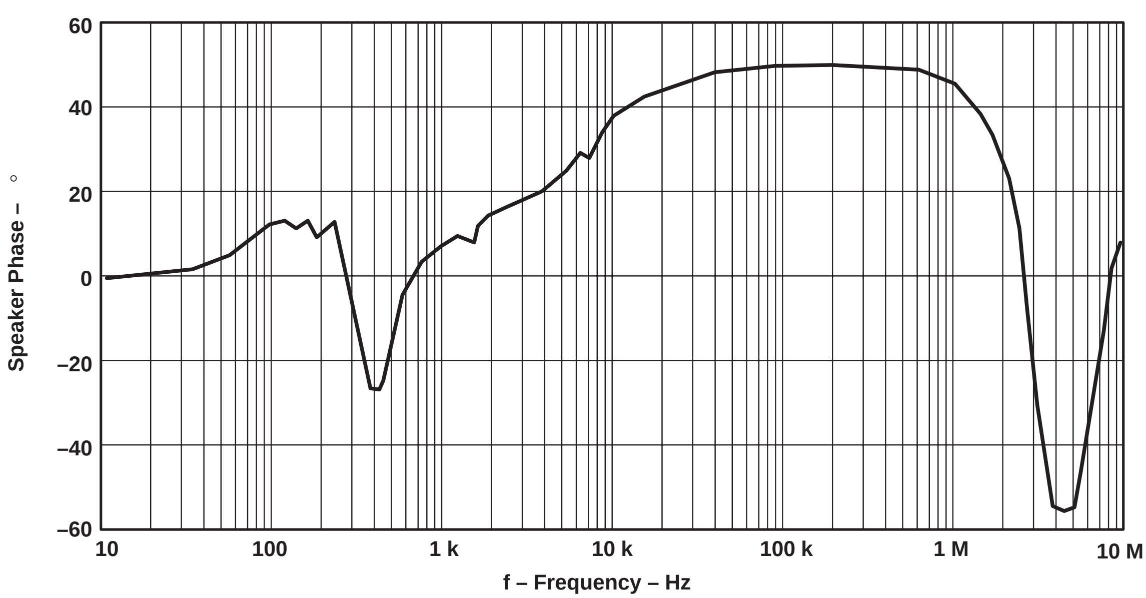

Figure 5. TI Speaker Phase vs Frequency

After measuring and calculating the value of the components at the harmonics, equation 5 can be used to calculate the added current drawn from the supply. The constant 0.58 is required in finding the RMS current from the peak current of a triangle wave.

$$\Delta I_{DD(q)} = \sum_{n=1}^{\infty} \frac{0.58 \times V_{DD} \times \cos\left(\phi_{SPKR}\left(n \times f_{SW}\right)\right)}{n^2 \times \left| Z_{SPKR}\left(n \times f_{SW}\right)\right|} \tag{5}$$

Table 1 shows an example of calculating the added quiescent current drawn when using the TPA005D02 to drive the TI speaker without a filter. The TPA005D02 has 23 mA of quiescent current with no load or filter. The added quiescent current from power dissipated in the speakers is 2 × 22.5 mA (from Table 1). Thus, the total quiescent current when using the TPA005D02 to drive the TI plug-n-play speaker is: 23 + 2 × 22.5 = 68 mA. This value is slightly low because the harmonics over 11 were not realized in the calculation and there were other losses in the class-D amplifier.

Table 1. Additional Quiescent Current per Channel from Switching Loss in Speaker Without Filter

HARMONIC (n)	$\lvert Z_{spkr} \rvert$ (Ω)	ϕ_{spkr} (degrees)	$\Delta I_{DD(q)(n)}$ (mA)
1	90	50	20.71
3	188	45	1.21
5	316	38	0.29
7	420	30	0.12
9	530	10	0.07
11	500	0	0.05
Total per channel:			22.5

As the speaker becomes more inductive, the phase approaches 90 degrees and the power dissipated in the speaker goes to zero (cos(90)=0). Unfortunately, at the switching frequency, most speakers have only approximately 40 degrees of phase shift. An example showing the importance of phase is that the switching current into the LC filter is actually higher than the current into the speaker without a filter. However, the quiescent current of the class-D amplifier with the filter is less than the quiescent current without the filter, because the filter has a much greater phase shift than the speaker.

5.2.2 Speakers with Slightly Higher Power Rating

The additional power from switching signal dissipated by the speaker can overheat and damage the voice coil. The speaker power rating must be specified to ensure that the additional power will not damage the voice coil. The additional power can be calculated using equation 6, 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.

$$P_{SW} < \frac{\left(I_{DD(q)\ (with\ speaker\ load)} - I_{DD(q)\ (no\ load\ or\ filter)}\right) \times V_{DD}}{N} \qquad (6)$$

Using the quiescent current measured in Section 7, the added power from the switching waveform can be calculated. A quiescent current of 83 mA was measured with the TPA005D02 EVM connected to the speakers provided with the TI plug-n-play platform kit. The supply current with no load was measured to be 23 mA. A 5-V supply was used, and the TPA005D02 is a stereo device, so N = 2. Thus, the maximum added switching power dissipated in the speaker is 150 mW. Thus, the filter solution requires 3-W speakers and the filterless solution requires 3.15-W speakers.

Even using the notebook speaker from Section 7, which had a quiescent current of 215 mA in the same example, only requires an additional 0.5 Watts per speaker. As long as the designer allows for the added power dissipated in the speaker, damage to the voice coil can be avoided.

6 Filter Component Effect on Efficiency

Like the speaker for the filterless application, the filter must have a phase shift close to 90 degrees near the switching frequency to limit the amount of power dissipated in the filter. Estimating added quiescent current due to filter loss is much easier than estimating speaker loss without a filter because the inductance and series resistance of the filter is much more constant over frequency than the impedance of a speaker.

The first step in calculating the filter loss is to calculate the ripple current through the inductor. The following calculation will focus on the half filter with a class-D amplifier with the full H-bridge and the A-D modulation scheme. During the first half of the switching period, the voltage across the inductor is at the positive supply voltage, and during the second half of the switching period is the negative of the supply voltage. The rate of change of the inductor current can be calculated using equation 7, where V is the voltage across the inductor, L is the inductor value, and di/dt is the rate of change of the inductor current.

$$V = L \times \frac{di}{dt}$$

The magnitude of the voltage across the inductor is constant over each half of the switching period, only changing in polarity. Thus, di/dt is constant for a constant inductance. The constant inductance generates a triangle wave with a peak-to-peak current given by equation 8.

$$i_{L\,(pk-pk)} = \frac{T_{SW} \times V_{DD}}{2 \times L} = \frac{V_{DD}}{2 \times L \times f_{SW}} \tag{8}$$

Using the inductor current and the resistance of the filter and other components, the power dissipated in the output filter can be calculated. The resistance, R, is a combination of resistances that are in the path from the power supply to ground through the filter. R includes two $R_{DS(on)}$s, the DCR of the inductor, the ESR of the filter capacitor, the resistances of the circuit traces, and the ESR of the power supply capacitor. The ESR of the power supply capacitor is required because the majority of the current from the switching waveform is provided by the power supply capacitor. Equations 7 and 8 show the filter loss when not switching, as a more complicated equation is required to include switching losses. For very low transistor switching times, however, equations 9 and 10 are relatively accurate.

$$P_{Filter} = \frac{{i_{L\,(pk-pk)}}^2 \times R}{6} \tag{9}$$

$$P_{Filter} = \frac{\left(V_{DD}\right)^2}{24 \times L^2 \times {f_{SW}}^2} \times \left(DCR_{filter\ L} + ESR_{filter\ C} + \left(2 \times R_{DS(on)}\right) + ESR_{supply\ C}\right) \tag{10}$$

The change in the quiescent current per channel, shown in equation 11, is the power calculated in equation 10 divided by the supply voltage then multiplied by the number of channels.

$$\Delta I_{DD(q)} = \frac{N \times V_{DD} \times \left(DCR_{filter\ L} + ESR_{filter\ C} + \left(2 \times R_{DS(on)}\right) + ESR_{supply\ C}\right)}{24 \times L^2 \times f_{SW}^{\ 2}} \qquad (11)$$

Note that the value of the inductor and the switching frequency have much more of an effect on the power dissipated than any of the resistive elements in the filter. To demonstrate the effect of the inductor on the change in supply current, consider an example using the TPA005D02. The TPA005D02 is a stereo device that has an $R_{DS(on)}$ of 310 mΩ, a switching frequency of 250 kHz, and an assumed value for $DCR_{filter\ L} + ESR_{filter\ C} + ESR_{supply\ C}$ is 0.38 Ω. If a 15-µH inductor is used, ΔI_{DD} = 6 mA, and if L = 30 µH, ΔI_{DD} = 1.5 mA.

The supply current will be slightly higher than the calculated ΔI_{DD} added to the quiescent current with no filter or load, because there are other losses and the filter components are not ideal. Most inductors are rated at ±20%, which means that a 30-µH inductor could have an inductance between 36 µH and 24 µH.

The total quiescently dissipated power, P_Q, is given by equation 12, where P_{SW} is the switching loss and $P_{Q(No\ load\ or\ filter)}$ is the quiescent power dissipated with no load or filter. P_Q is independent of output power.

$$P_Q = P_{Q\ (No\ load\ or\ filter)} + P_{Filter} + P_{SW} \qquad (12)$$

Switching losses actually increase slightly with output power, but the increase is minimal and is dominated by conduction losses, which are the power dissipated in the output transistors and filter. Due to how the filter components affect efficiency, it is important to select components with low resistance to get the maximum efficiency from a class-D amplifier. The efficiency of a class-D amplifier is shown in equation 13.

$$\text{Efficiency} = \frac{P_{OUT}}{P_{OUT} + \frac{P_{OUT}\left(2 \times R_{DS(on)} + DCR_{filter\ L}\right)}{R_L} + V_{DD}\ I_{DD\ (q)\ (no\ load\ or\ filter)} + P_{Filter} + P_{SW}} \qquad (13)$$

7 Quiescent Current

While the quiescent current of a class-AB amplifier is constant regardless of load, the quiescent current of a class-D amplifier is more complicated and changes with filter and load. The quiescent current of the class-D amplifier takes into account quiescent current with no load or filter, filter loss, and switching loss.

The quiescent current for the full filter, half filter, and no filter applications were measured and appear in Table 2.

Table 2. 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
	Any size resistor or speaker load	22	35
	Any size resistor or speaker load	33	29.5
	Any size resistor or speaker load	47	27
Half Filter (L = DS5022–P–xxx)	Any size resistor or speaker load	68	25
	Any size resistor or speaker load	100	24
	Any size resistor or speaker load	150	23
No Filter	Notebook speaker	N/A	215
	NXT speaker	N/A	199
	TI P-N-P speaker	N/A	83
	Bose 151 speaker	N/A	83
	No speaker	N/A	23
TPA0102	Any load	N/A	19

The quiescent current of the full filter and half filter applications were independent of the load and varied greatly with the filter inductor value. The no filter application quiescent current, however, was dependent on the inductance of the speaker. The full filter quiescent current was measured using the filter designed for a 4-Ω load, where L1 = L2 = 15 μH, C2 = C3 = 0.22 μF, and C1 = 1 μF, with the components labeled in Figure 1. The quiescent current of the half filter application shown in Figure 2 was measured with C = 1 μF, and L was varied to show how increasing inductance decreases ripple current at the output.

The recommended half circuit filter for a 4-Ω load is L = 33 μH and C = 1 μF, which had a quiescent current of 29.5 mA. The recommended half filter for an 8-Ω load is L = 68 μH and C = 0.56 μF, which had a quiescent current of 25 mA. The quiescent current for the filterless application varied with load. The TI P-N-P speaker and the Bose 151 speaker had quiescent current of 83 mA, while the lower inductance flat panel NXT speakers [3] had a quiescent current of 199 mA. A commercial notebook speaker was even less inductive and resulted in 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.

8 Fidelity

Total harmonic distortion plus noise (THD+N) and intermodulation distortion (IMD) are the two most common measurements used to rate the sound quality or fidelity of an amplifier. THD+N and IMD were measured for the full filter, half filter, and no filter applications. Each measurement was done using the TPA005D02 class-D 2-Watt amplifier. A measurement was made in each case with the TPA0102 class-AB amplifier to use as a comparison. The measurement set up and results are discussed for each test.

8.1 Total Harmonic Distortion Plus Noise (THD+N)

THD+N versus output voltage and THD+N versus frequency were measured with the Audio Precision II analyzer. In each measurement, an RC filter with a cutoff frequency of 37 kHz was added between the output to ground to filter out the common mode signal into the analyzer. The bandwidth of the analyzer was set to 10 Hz through 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. In other words, band-limiting the measurement ensured that only the audible harmonic distortion and noise were measured.

Amplifier gain was 22.5 V/V. The gain of the TPA005D02 is fixed at this value and the gain of the TPA0102 was set to this value with external resistors, which put the TPA0102 at a slight disadvantage because it exhibits higher performance at lower gains. THD+N versus output voltage at 1 kHz was measured with the TPA005D02 with full filter, half filter, and no filter. The same test was performed using the TPA0102. The measured THD+N versus output voltage is shown in Figure 6.

The class-D full filter 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.

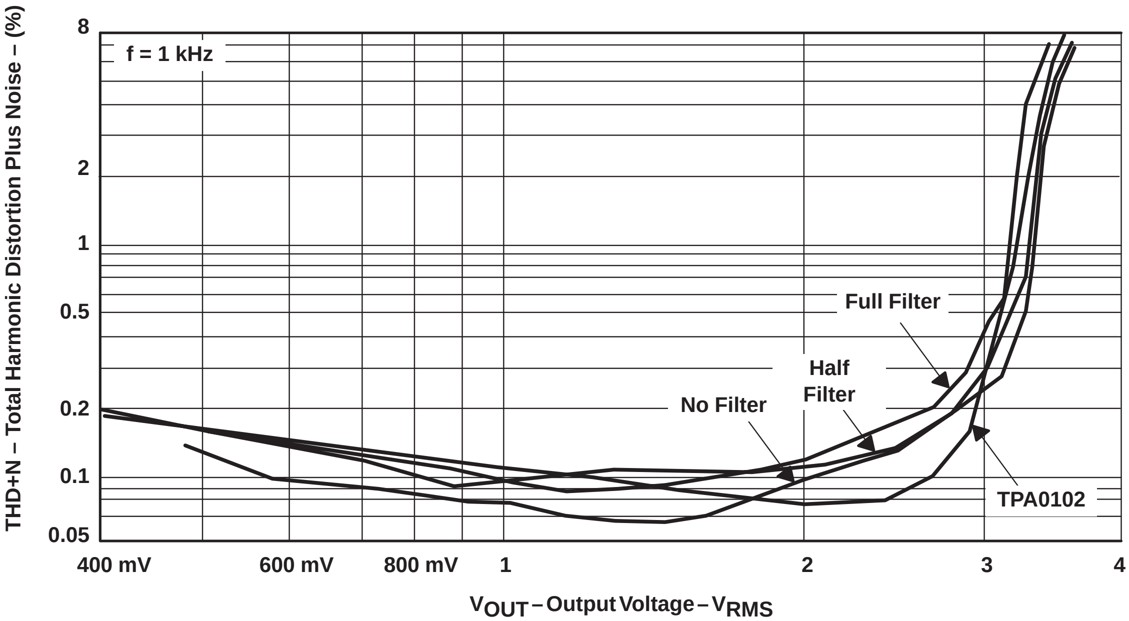

Figure 6. Total Harmonic Distortion Plus Noise vs Output Voltage

THD+N versus frequency was set up the same way that the THD+N versus output voltage was configured, but the output voltage was set to 2.5 V. Figure 7 shows that the THD+N is approximately the same for the different class-D filter options, and the TPA0102 THD+N was less than 0.1% lower than the class-D. The THD+N is relatively constant over frequency for all devices. Then the THD+N decreases at frequencies greater than 10 kHz, because of the filtering done by the Audio Precision II.

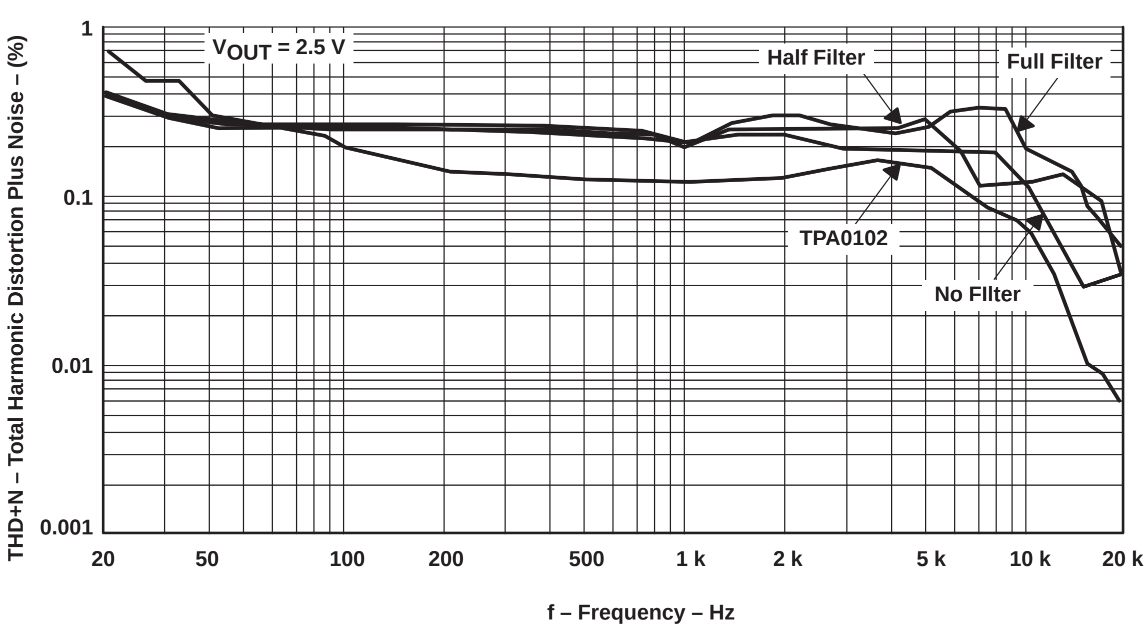

Figure 7. Total Harmonic Distortion Plus Noise vs Frequency

8.2 Intermodulation Distortion (IMD)

Intermodulation distortion (IMD) occurs when two or more signals of different frequencies 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 the ratio of magnitude of the sum and difference signals to the original input signal. The IMD equation is shown below; where V_{f2} is the voltage at the input frequency f2, V_{f2+f1} is the voltage at the sum of input frequencies f1, and f2, V_{f2-2f1} is the voltage at the difference of input frequencies f1 and 2f2, etc.

$$IMD = \frac{\sqrt{\left(V_{f2-f1} + V_{f2+f1}\right)^2 + \left(V_{f2-2f1} + V_{f2+2f1}\right)^2 + \left(V_{2f2-f1} + V_{2f2+f1}\right) + \ldots}}{V_{f2}} \qquad (14)$$

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 (7kHz) 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 filter, half filter, and no filter was measured and is shown in Figure 8.

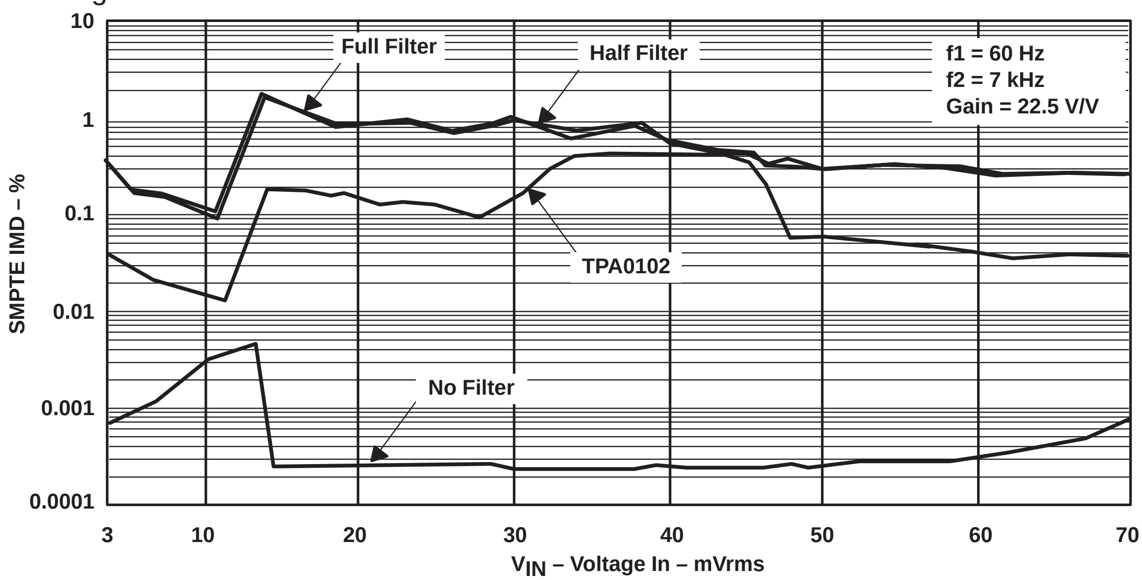

Figure 8. SMPTE Intermodulation Distortion vs Input Voltage

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, and had slightly higher IMD than the class-AB amplifier. The class-D without a filter had the lowest IMD.

The CCIF, or Twin-Tone, IMD is another distortion measurement of the amplifier using two high frequency input signals of equal amplitude. Figure 9 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 %.

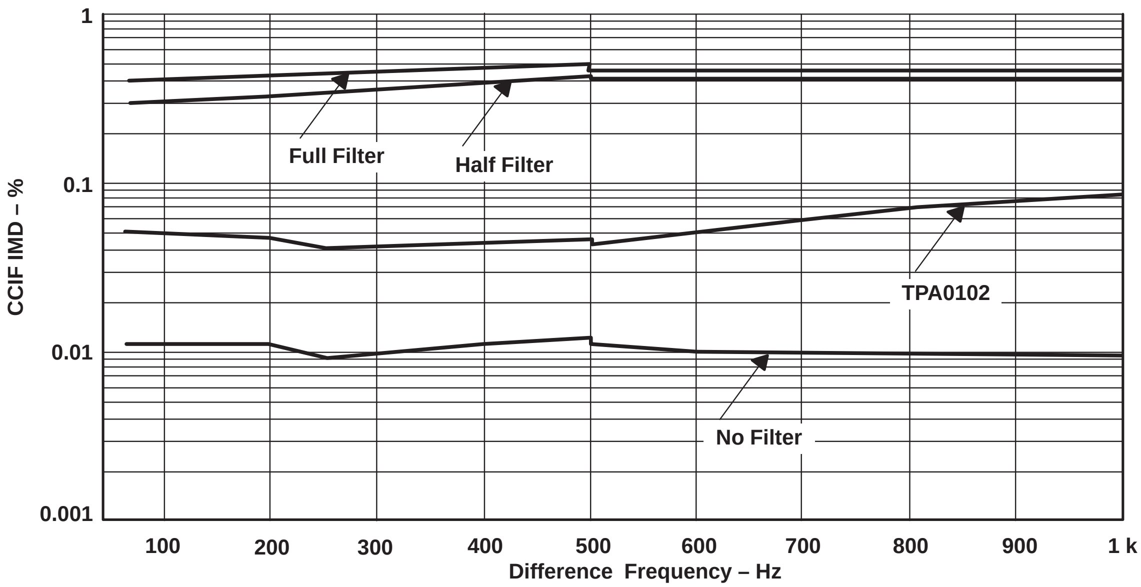

Figure 9. CCIF Intermodulation Distortion vs Difference Frequency

9 Electromagnetic Interference (EMI)

Radiated electromagnetic interference (EMI) is radiation caused by the transfer of electromagnetic energy through a nonmetallic medium, such as air. EMI is caused either by an instantaneous change in current resulting in a magnetic (H) field or by a differential voltage resulting in an electric (E) field. The inductor in the filter, or the inductance in the speaker if not using a filter, keeps the change in current low, which decreases the magnetic field. The electric field, which is a common mode issue, could be quite large due to the switching voltage.

The full filter includes a differential and a common-mode filter, so the E and H fields are attenuated. The half filter has a differential filter, but no common mode filter. The differential filter is good for lowering quiescent current but does not help to decrease EMI. Without the filter, the inductance of the speaker keeps the output switching current low, which reduces the magnetic field and makes the electric field dominant. The good news about the EMI is that the electric field can be easily shielded and common mode methods of reducing EMI will work. If EMI is a problem, the designer should use shielded speaker wires and speakers, and make the amplifier and speaker enclosure into a shield if possible.

The E and H fields of the speaker wires and the traces near the TPA005D02 were measured with the full filter, half filter, and no filter applications, using an oscilloscope and EMCO E and H field probes (EMCO 7405–904 and EMCO 7405–901). The circuit was configured with both channels of the TPA005D02 EVM active with no input to see the EMI generated by the switching waveform.

An 18-inch speaker wire connected the EVM to the speaker. Each speaker was spread apart, away from the EVM board to ensure the EMI from the traces did not add to the EMI measured from the speaker wire and vise versa. The measurements were done in the near field, one-half inch above the traces and speaker wire. The measurements were done in the time domain to enable the system designer to see from what part of the switching waveform the EMI was radiating.

9.1 E and H Field Measurements

Figure 10 shows the E field measured one-half inch above the speaker wires for the full filter, half filter, and no filter applications. Although both channels were active, the EMI was measured over the speaker wire of only one of the channels. The full filter E field at one-half inch was below the noise level of the system. The half filter radiated approximately 5 mV peak-to-peak at the switching edges. The half filter had a maximum peak-to-peak voltage of 25 mV.

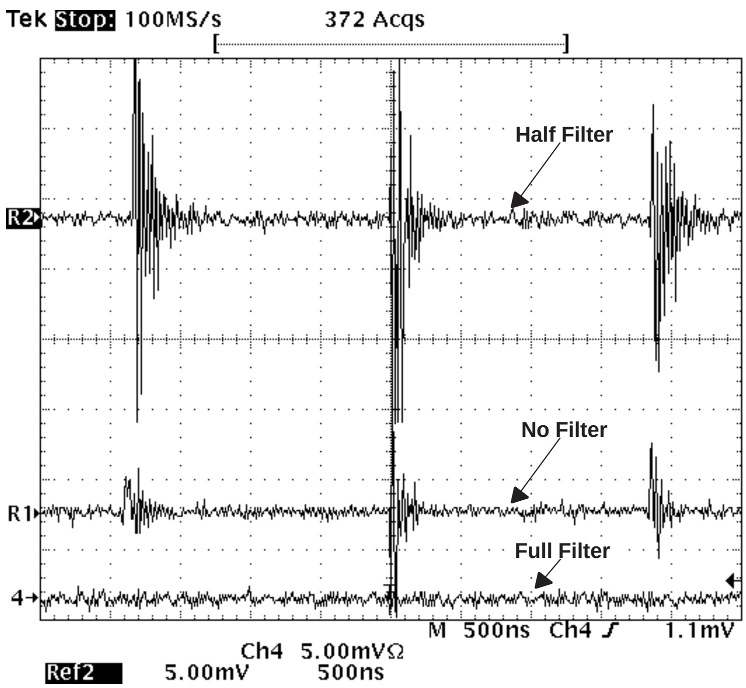

Figure 10. E Field Measured ½ Inch Above Speaker Wire

Figure 11 shows the H field of the full filter, half filter, and no filter class-D applications measured one-half inch above the speaker wire. Again, the EMI of the half and no filter applications is generated from the switching edges and the EMI of the half filter is greater than that of the class-D without the filter. The H field generated by the class-D with the full filter is lower than the noise floor.

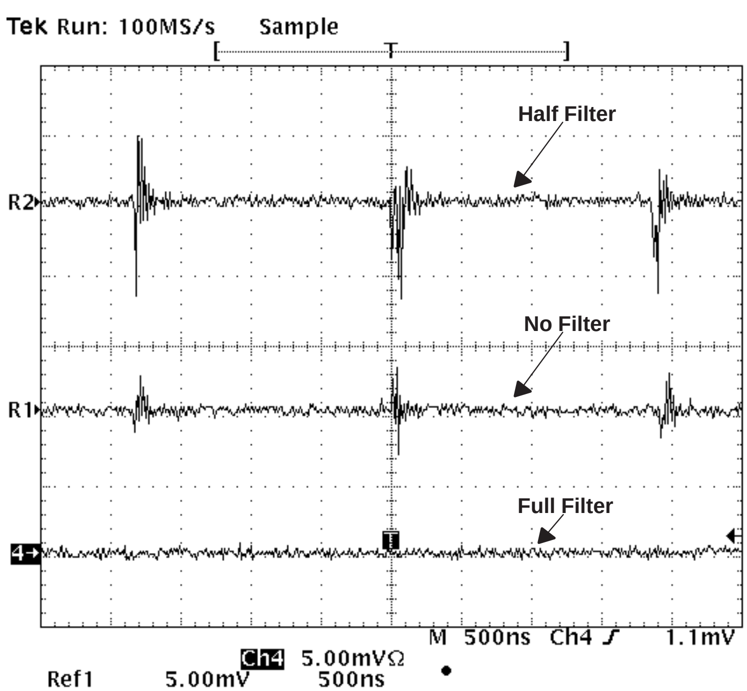

Figure 11. H Field Measured ½ Inch Above Speaker Wire

Figure 12 shows the E field of the full filter, half filter, and no filter applications measured one-half inch above the traces near the TPA005D02 on the TPA005D02 EVM. In this measurement, both channels were active, so unlike the EMI measured from the speaker wire, both channels will add to the measured near-field E and H fields.

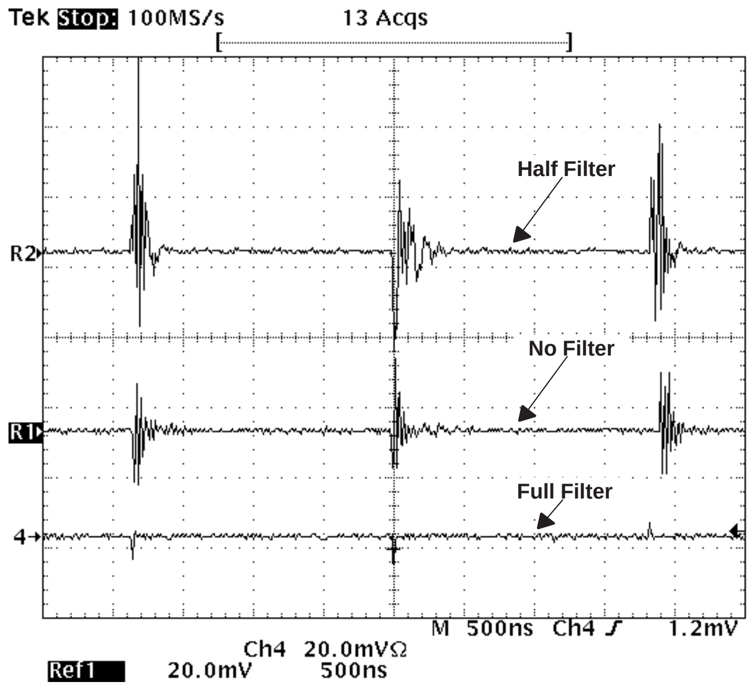

Figure 12. E Field Measured ½ Inch Above Class-D Output Traces

Figure 13 shows the H field generated by the class-D with a full filter, half filter, and without a filter, measured one-half inch above the output traces.

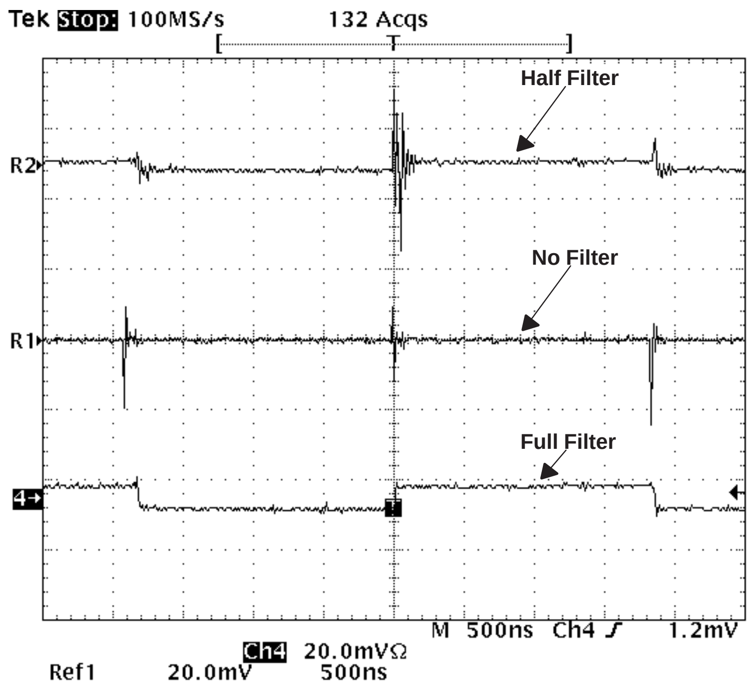

Figure 13. H Field Measured ½ Inch Above Class-D Output Traces

9.2 EMI Measurement Conclusions

Full Filter

The class-D amplifier is designed to have switching MOSFETs create a rail-to-rail square wave that is driven into an inductor. The inductor keeps the current from changing despite the fact that the voltage changes very rapidly at the switching edges. The rapid rise and fall times of the voltage at the input to the inductor in conjunction with the inductor keeping the current constant generates transients at the output. The full filter has capacitors to ground at the output that form a high frequency ac path to ground, which reduces the transients at the output. Unlike the half and no filter applications, the E and H fields radiating from the speaker wire, shown in Figures 10 and 11, are below the system noise floor, which is a direct result of these capacitors to ground.

The EMI above the traces of the full filter application were much worse than above the speaker wire. The E field had small transients at the switching edges. The E field around the output traces was also much smaller than the half and no filter applications because of the capacitor to ground in the full filter. However, the H field measured at one-half inch was much worse than the full and half filters, because the inductors with the H field probe act as a transformer. The windings of the inductors act as the primary and the loop of the H field probe as the secondary. The shielded inductors drop the amplitude of the H field, but it is still very easy to make out the square wave in Figure 13. The H field drops off with distance at a much faster rate than the E field. Therefore, the H field is a concern in a system with a nearby current loop that might pick up the EMI from the inductors, but the EMI due to the H field radiated from the inductors at a distance should not be a major concern.

Half Filter

The major difference between the full and half filter is that the half filter does not have the capacitors to ground, just a differential filter. The positive output is filtered with respect to the negative output, where both outputs are applying the AC transients to each other without giving the transients a path to system ground. These transients at the output, which are caused by the inductor keeping the current constant during switching, caused EMI at the switching times. The EMI at the switching times was evident in both E and H fields, both above the traces and above the speaker wires.

The EMI from the half filter application was even greater than that of the no filter application because the speaker has resistive elements which reduce the sharp voltage transients at the output. The H field above the traces was very similar to that of the full filter. Again, the inductors and the H field probe essentially formed a transformer. The H field of the half filter had approximately half the magnitude of the full filter because there was only one transistor to inductively couple with the probe.

No Filter

Similar to the filtered applications, the EMI from the filterless circuit was generated at the switching edges. The E field was greater than the H field with no filter in all cases. The class-D without a filter had less EMI than the half filter for three main reasons. First, common mode EMI is dominant and the half filter only forms a differential filter with no low impedance AC path to system ground. Second, the filterless application was more resistive, causing less dissipation at the switching times. Third, the half filter has an inductor that creates a transformer effect with any other current loops.

9.3 Reducing EMI

Reduced Wire Length

Reducing the length of the traces and speaker wire will reduce EMI. Shortening and widening the output traces and wires reduces the inductance of the wire, which reduces the E field generation. Shortening the wire also reduces H field because it makes the current loop smaller. Therefore, it is very important to place the speakers as close to the amplifier as possible, reducing the wire length, especially in the half filter and no filter applications.

Shielded and Toroid Inductors

Shielded inductors were used in the EMI measurements described above, which significantly reduced the EMI over the nonshielded inductors. A problem with these inductors, however, is that the windings are wrapped such that the current flow is parallel to the board, causing inductive coupling with any current loop near the inductors. If the inductor were wrapped such that the current flow were perpendicular to the plane of the circuit board, inductive coupling with current loops would be greatly reduced. The inductor should also be shorter. The taller inductor causes a longer the magnetic field path, which causes the EMI to be higher further away from the inductor.

If shielded inductors are not sufficient, a toroid inductor may provide a solution. The toroid is made of a donut-shaped core with a high permeability. The windings are wrapped from the outside through the center of the core, which causes the magnetic field generated from the current flowing through the windings to be confined to inside the core. However, the core is not ideal and must have gaps, which are sources of radiation. A powder core radiates less than a core with a single air gap, because a powder core has several very small air gaps throughout, causing very little radiation compared to one large air gap.

Shielded Speakers

Similar to the filter inductor, the voice coil in a speaker can be a radiator that causes inductive coupling. Shielded speakers were originally designed so they could be placed next to a monitor without the magnet from the speaker affecting the image generated by the cathode ray tube. The shield itself on a shielded speaker is just a metal cap with a high permeability placed over the permanent magnet. The cap does not totally envelop the magnet, but rather provides a path of less magnetic resistance. In other words, the shield keeps more of the magnetic field in the shield itself rather than in the air. Reducing the magnetic field in the air reduces both the magnetic radiation from the magnet and also from the voice coil.

Shielded Speaker Wires

Standard speaker wire is not designed for low EMI radiation because it was intended to carry waveforms of frequencies from 20 Hz to 20 kHz, which have very little EMI problems. When using a class-D amplifier with a half filter or no filter, it may be necessary to shield the wires. A shielded twisted pair cable is recommended for reducing EMI, because the shield reduces the radiation path to ground and the intertwined wires tend to cancel some of the common mode signal.

When using a shielded twisted pair cable, choose a single point to ground the shield as close to earth ground as possible. Also, ensure that the shield does not pick up radiation in routing itself to ground, because it could make the shield into an antenna. It may be necessary to take the ground from another part of the system to avoid pickup in the shielding and to have a good ground reference. In doing this, however, make sure that the pickup from the shield is not injecting the switching noise into that part of the circuit. The recommended circuit diagram showing the shielded wire appears in Figure 14.

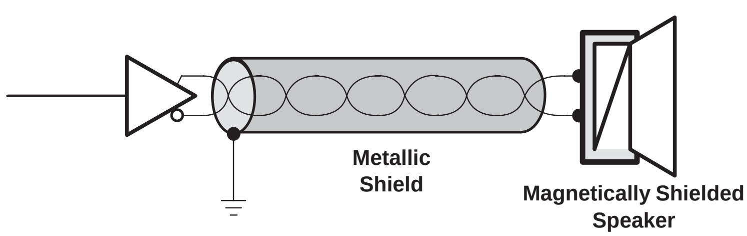

Figure 14. Shielded Twisted Pair Speaker Connection

The E and H fields of the shielded twisted pair and the standard speaker wire were measured using the same method used in the EMI measurements above. Both the E and H fields of the shielded twisted pair were lower than the standard speaker wire. The results are shown in Figures 15 and 16.

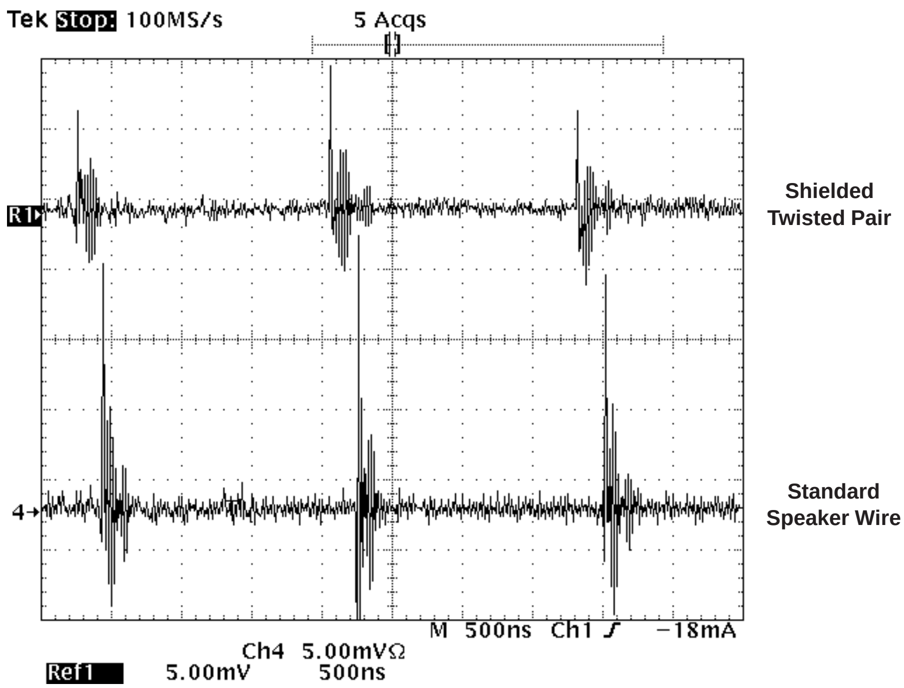

Figure 15. Standard Speaker Wire and Shielded Twisted Pair E Field vs Time

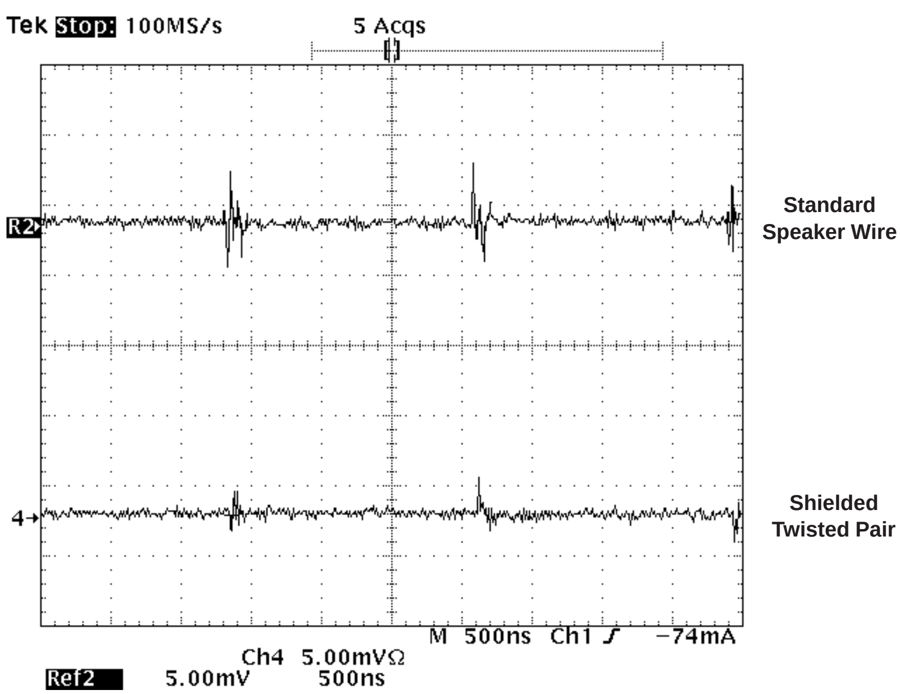

Figure 16. Standard Speaker Wire and Shielded Twisted Pair H Field vs TIme

Shielded Enclosure

The best method of shielding is using what most electronics already have, an enclosure. If coated properly, the enclosure can be made into a Faraday cage. There are many coatings that one can add to an enclosure to make it an effective shield. The higher the permeability of the coating material, the better the shield. The Faraday cage attenuates both the E field and the H field. To attenuate the H field, the shielding must completely enclose the source of radiation, but partial shielding will work in attenuating the E field.

10 Filter Selection from System Requirements

This section provides an overview of the results and provides recommendations on which filter to use with predetermined system constraints. Table 3 ranks each filter by category and shows system concerns that are met by each filter application.

Table 3. Performance Ranking of Full Filter, Half Filter, and No Filter Applications

APPLICATION	COST	$I_{DD(q)}$	THD+N	IMD	EMI	SYSTEM REQUIREMENTS
No Filter	1	3	1	1	2	**Primary:** low cost, low heat, high fidelity **Secondary:** long battery life, low EMI **Example:** stand-alone amplified speaker
Half Filter	2	2	2	2	3	**Primary:** long battery life, low heat **Secondary:** low EMI **Example:** notebook computer
Full Filter	3	1	2	2	1	**Primary:** low EMI, low heat **Secondary:** low cost **Example:** speaker far from amplifier

NOTE:
Applications are ranked by performance from 1 to 3 in each category: best = 1, worst = 3.

10.1 No Output Filter

The class-D without the output filter application not only had lower THD+N and IMD than the class-D with the filter, but also outperformed the class-AB device. The two big 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 that uses a filter. EMI can be lowered using ferrite beads at the output of the amplifier, shielded speakers, and shielded speaker wires. EMI can also be reduced by making the distance from the amplifier to the speaker as short as possible and 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 in which quiescent current and EMI are not important, but system cost, maximum power supply current rating, and heat are important. A good 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 filter or half filter because the filter is eliminated, and is very close to the cost of the class-AB solution, if not less expensive. The heat sink is eliminated and the power supply is reduced in a 10-W class-D filterless application, but the class-D amplifier itself is slightly more expensive than an equivalent class-AB amplifier. As mentioned in Section 9, the speaker inductance must be high, and the amplifier must be close to the speaker.

10.2 Half Filter

Class-D with a half filter had a lower quiescent current and performed as well or better than the class-D with full filter in THD+N and IMD. The quiescent current diminishes as the value of the inductor of the half filter increases. However, 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 when using a speaker load and the filter was designed for a resistive load. The half filter designed for a 4-Ω resistive load uses a 33-μH inductor with a 1-μF capacitor, and the half filter designed for an 8-Ω resistive load uses a 68-μH inductor and a 0.56-μF capacitor.

Each of these examples exhibits peaking at the corner frequency because the speaker is not purely resistive at the corner frequency. An RC Zobel network can be placed in parallel with 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. This will decrease quiescent current and keep 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 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, wire lengths are short, and shielding is used. 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 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.

10.3 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 all primary concerns. An example of this would be in a boombox, 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.

11 Conclusion

It is possible to reduce the output filter in certain applications. The tests and measurements described in this application report prove that reducing the output filter does not mean a 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.

A designer that 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 that 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.

12 References

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