Application Report

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Class-D LC Filter Design

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ABSTRACT

An LC filter is critical in helping you reduce electromagnetic radiation (EMI) of Class-D amplifiers. In some Class-D amplifiers, you also need the LC filter to ensure high efficiency outputs. This application report presents the implementations and theories of LC filter design for Class-D audio amplifiers using the AD (Traditional) and BD (Filter Free) Class-D modulation designs.

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1 LC Filters Implementation

Figure 1 shows the LC filter circuit for AD (Traditional) modulation and Figure 2 shows the BD (Filter Free) Class-D modulation The corresponding Butterworth LC filter recommended component values are listed in (Table 1). See Section 3, Types of Class-D Modulation Techniques for additional analysis.

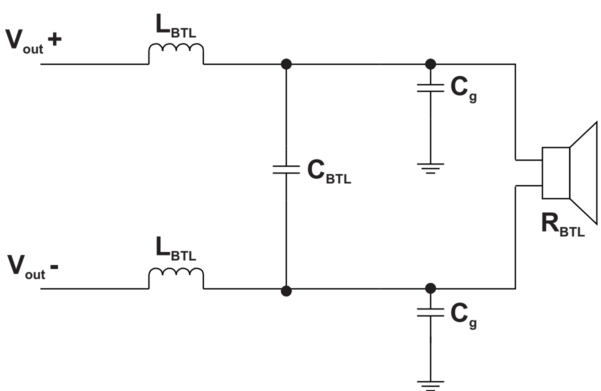

Figure 1. BTL LC Filter for AD Modulation

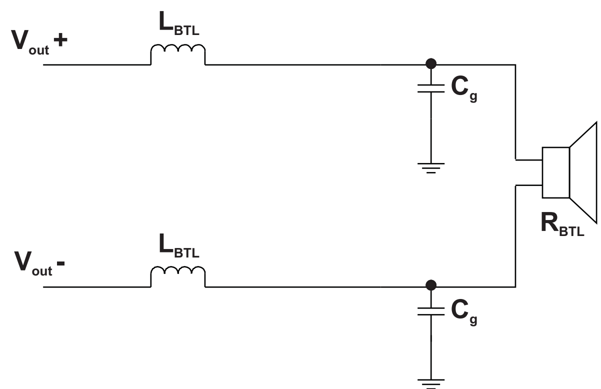

Figure 2. BTL LC Filter for BD Modulation

Table 1. Recommended Butterworth LC Filter Component Values

R_{load} (Ω)	f_{cutoff} (kHz)	L_{BTL} (µH)	C_{BTL} (µF)	C_g (µF)	Modulation Mode
8	28	33	-	1	BD
6	31	22	-	1.2	BD
4	31	15	-	1.8	BD
8	28	33	0.47	0.1	AD
6	31	22	0.68	0.1	AD
4	31	15	1.0	0.18	AD

1.1 *Terminology*

AD modulation (traditional)—modulation scheme with a differential output, where each output is 180 degrees out-of-phase and changes from ground to the supply voltage, V_{CC}. Therefore, the differential pre-filtered output varies between positive and negative V_{CC}, where filtered 50 percent duty cycle yields zero volts across the load. This class-D modulation scheme has the maximum differential voltage at 0 V output (50-percent duty cycle). The large differential voltage causes high peak output current, which in turn causes filter loss, thus increasing supply current and lowering efficiency. An LC filter is required with the traditional modulation scheme so the high switching current is re-circulated in the LC filter instead of being dissipated in the speaker.

BD modulation (filter-free)—modulation scheme developed to greatly reduce or eliminate the output filter. The filter-free modulation scheme minimizes switching current, which allows a speaker to be used as the storage element in place of an LC filter and still lets the amplifier be very efficient.

BTL (bridge-tied load)—an output configuration for power amplifiers, used mainly in audio applications. The load (for example, a speaker) is connected between two amplifier outputs, bridging the two output terminals. This can double the voltage swing at the load (compared with SE amplifier operation) if the outputs are driven in opposite phases.

EMI (electromagnetic radiation)—radiation that is emitted by electrical circuits carrying rapidly changing signals, such as the outputs of a class-D audio power amplifier. EMI must be below limits set by regulatory standards such as CISPR 22 or FCC Part 15 Class B.

SE (single-ended)— signaling that is the simplest method of transmitting electrical signals over wires. One wire carries a varying voltage that represents the signal, while the other wire is connected to a reference voltage, usually ground. The alternative to single-ended output configuration is the bridge-tied load (BTL) configuration. SE signaling is less expensive to implement; however the signal cannot be transmitted over long distances or quickly, it has poorer low-frequency response, and a smaller voltage swing (compared to the BTL amplifier operation).

1.2 Related Documentation

Quek, Yang Boon and Belnap, Kevin. "Flat panel audio design—where only the screen is flat, not the audio, EMI Performance and LC Filters" Audio Design. May, 2006.

Score, Mike. "Filter-free design helps class-D audio amplifier implementations" Planet Analog. August, 2004

TPA3007D1 6.5-W Mono Class-D Audio Power Amplifier Data Sheet, TI literature number SLOS418, available on the TI Internet site www.ti.com.

TPA3106D1 40-W Mono Class-D Audio Power Amplifier Data Sheet, TI literature number SLOS516, available on the TI Internet site www.ti.com.

TPA3100D2 Audio Power Amplifier EVM with LC Filter User's Guide, TI literature number SLOU179, available on the TI Internet site www.ti.com.

TPA312xD2 device family employs AD modulation: TPA3120D2, TPA3122D2, and TPA3123D2

2 Frequency Response of LC Filters

An LC output filter attenuates the high-frequency switching frequency of a Class-D amplifier for single-ended (SE) operation (Figure 3).

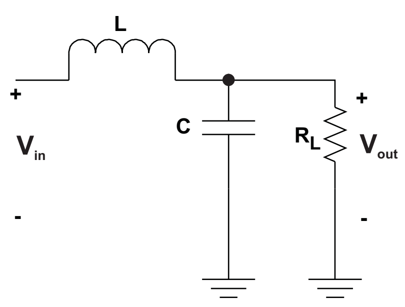

Figure 3. LC Filter for Single-Ended Operation

You can derive the transfer function by using a voltage divider equation in which the load impedance is a parallel combination of R_L and C.

This transfer function reduces to this equation.

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{1 + s \times \frac{L}{R_L} + L \times C \times s^2} = \frac{\frac{1}{L \times C}}{s^2 + s \times \frac{1}{R_L \times C} + \frac{1}{L \times C}} \tag{1}$$

We can equate Equation 1 to the characteristic equation of a second-order network in a standard form.

$$H(s) = \frac{A}{s^2 + s \times \frac{\omega_o}{Q} + \omega_o{}^2} = \frac{\frac{1}{L \times C}}{s^2 + s \times \frac{1}{R_L \times C} + \frac{1}{L \times C}} \tag{2}$$

where $\omega_o = \frac{1}{\sqrt{L \times C}}$ is the cutoff frequency in radians.

$Q = R_L \sqrt{\frac{C}{L}}$ and $A = \frac{1}{L \times C} = \omega_o^2$ is a constant.

At the cutoff frequency, $\omega = \omega_o$,

$$\left| H(j\omega_o) \right| = \left| \frac{\omega_o^2}{-\omega_o^2 + j \times \frac{\omega_o^2}{Q} + \omega_o^2} \right| = \left| -j \times Q \right| = Q \tag{3}$$

The circuit is critically damped at $Q = \frac{1}{\sqrt{2}}$ and experiences peaking for $Q > \frac{1}{\sqrt{2}}$ (Figure 4).

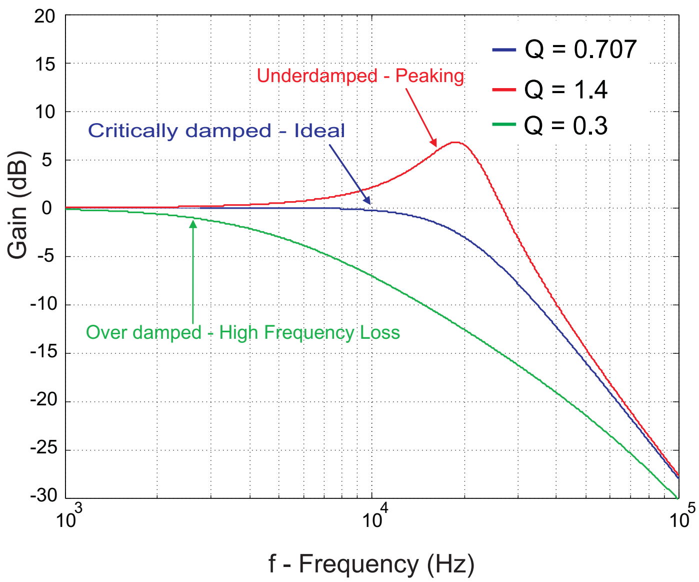

Figure 4. Effect of Q on Frequency Response

TI does not recommend using an LC filter that peaks excessively. Tests have shown that high frequency audio signals generally sound harsh to the human ear. Additionally, high peaking may cause the amplifier to malfunction, by triggering its over current or short circuit protection circuitry. An overdamped filter can result in the loss of high frequency audio signals.

TI recommends you use a 2nd-order Butterworth Low-Pass filter, because of its flat pass-band and phase response. The Butterworth filter can be designed by using Equation 4 and Equation 5 to determine LC values.

$$C = \frac{1}{\omega_o \times R_L \times \sqrt{2}} \tag{4}$$

$$L = \frac{R_L \times \sqrt{2}}{\omega_o} \tag{5}$$

Note: The Butterworth filters are critically damped when $Q = \frac{1}{\sqrt{2}}$.

3 Types of Class-D Modulation Techniques

The Class-D Modulation Technique section describes how analog signals are converted to PWM signals to drive the MOSFETs in the H-bridge. Most Class-D amplifiers can be classified as using one of two modulation techniques, AD (Traditional) or BD (Filter Free) modulation.

3.1 AD (Traditional) Modulation

The traditional switching technique (AD modulation) modulates the duty cycle of a rectangular waveform, such that its average content corresponds to the input analog signal. The bridge-tied load (BTL) outputs (Figure 5) are the inverse of each other. AD modulation has no significant common mode content in its output. The TPA312xD2 family employs AD modulation. All TAS modulators can be configured for AD modulation.

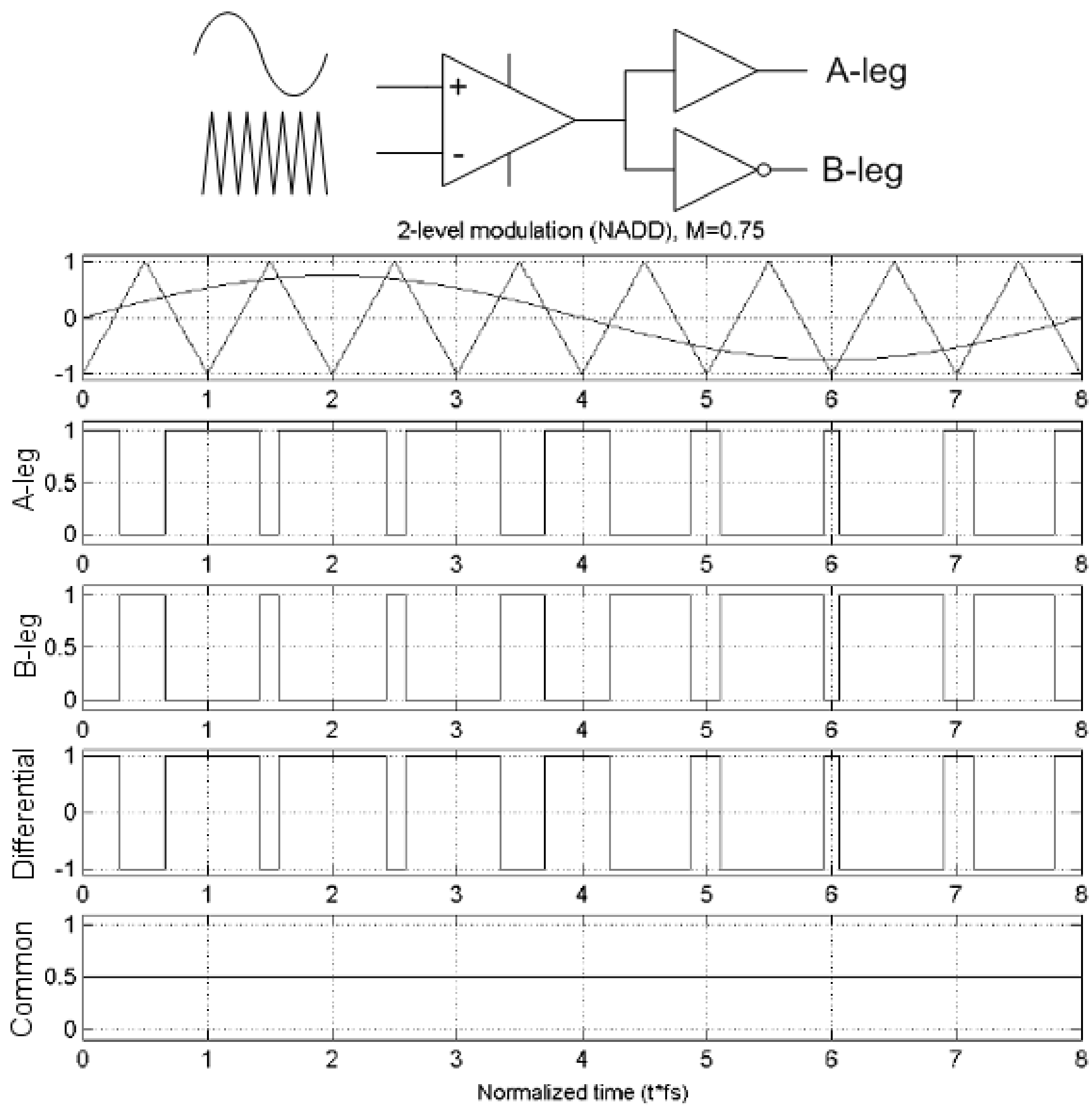

Figure 5. AD (Traditional) Modulation

3.2 BD (Filter Free) Modulation

The BD modulation switching technique modulates the duty cycle of the difference of the output signals such that its average content corresponds to the input analog signal. The bridge-tied load (BTL) outputs (Figure 6) are not the inverse of each other. BD modulation has significant common mode content in its output. Most TPA amplifiers employ BD modulation. Some TAS modulators can be also be configured for BD modulation.

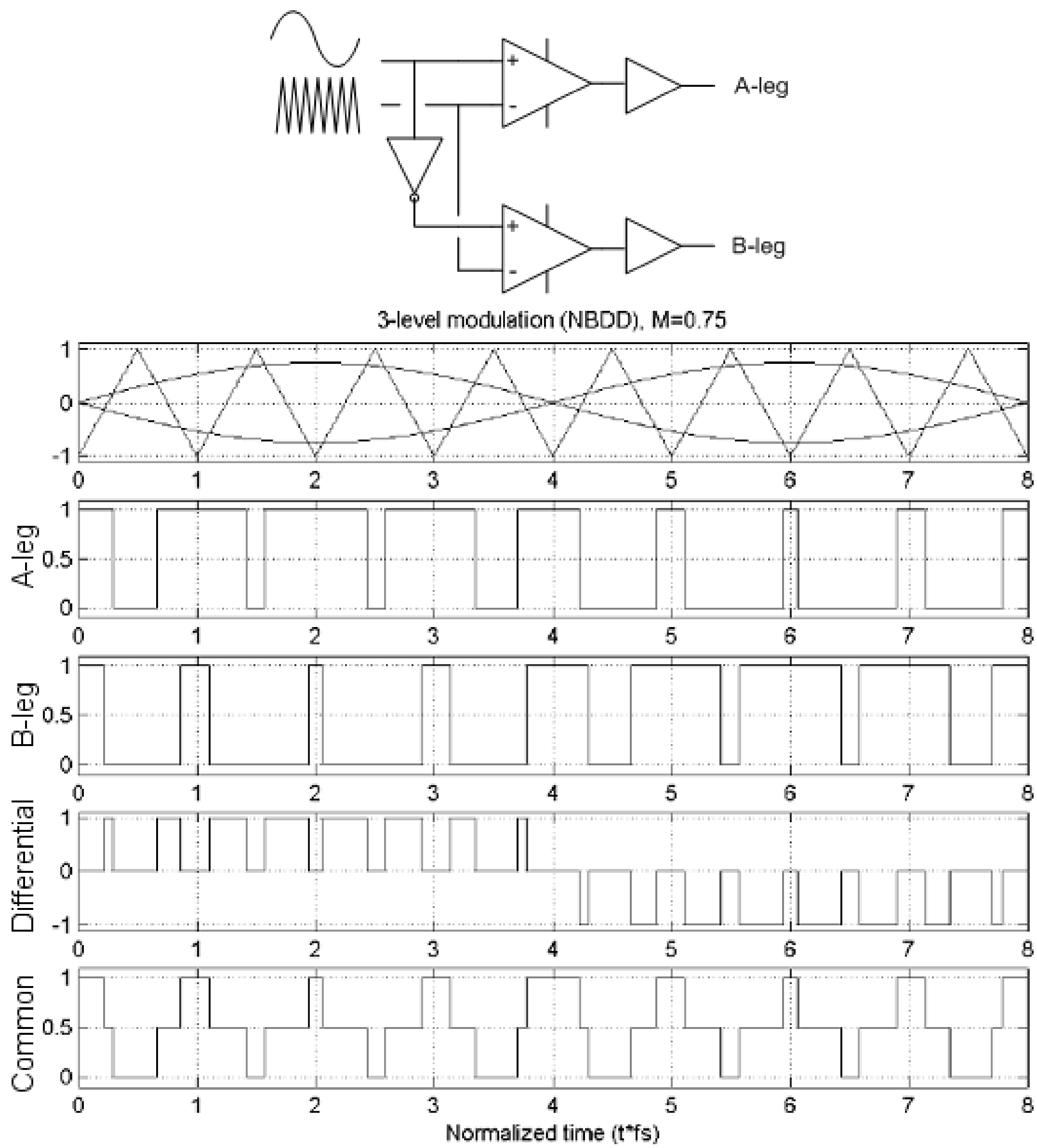

Figure 6. BD (Filter Free) Modulation

4 LC Output Filter for Bridged Amplifiers

4.1 LC Filter for AD (Traditional) Modulation

For a bridge-tied load (BTL) amplifier, a filter is needed for the positive and negative output. Figure 7 shows LC filter topology for AD Modulation.

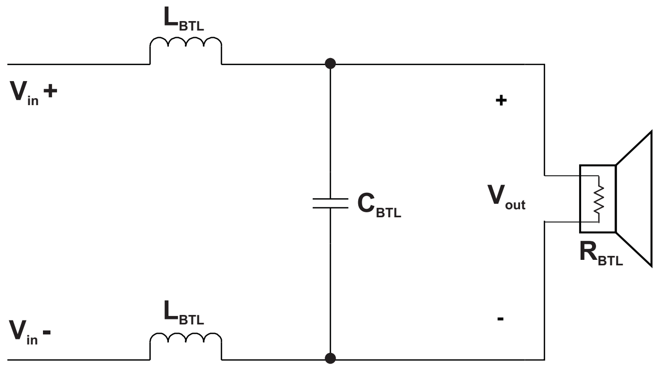

Figure 7. LC Filter for AD Modulation

Because V_{in}+ and V_{in}– are the inverse inputs of each other, the circuit is actually symmetrically equivalent to two SE output circuits, as shown in Figure 8.

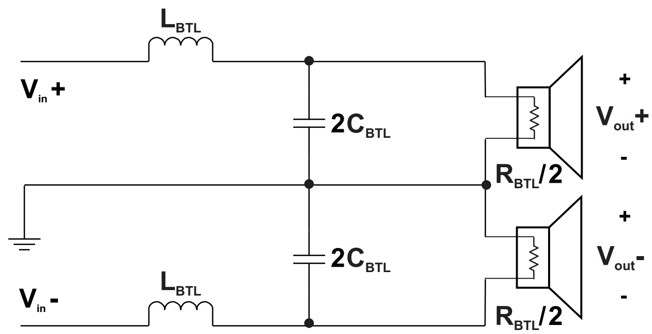

Figure 8. Equivalent Circuit for AD Modulation

Computing LC values for BTL operation from SE operation analysis:

1. Using $R_L = R_{BTL}/2$, compute C and L for the appropriate cutoff frequency and damping factor as in the SE operation analysis.
2. Compute C_{BTL} and L_{BTL} using Equation 6 and Equation 7, respectively.

$$C_{BTL} = \frac{C}{2} \tag{6}$$

$$L_{BTL} = L \tag{7}$$

Additional capacitors are employed on each side of the R_{BTL} to ground paths, to provide high-frequency decoupling. These additional C_g capacitors should be approximately 10% of the two C_{BTL} (Figure 9).

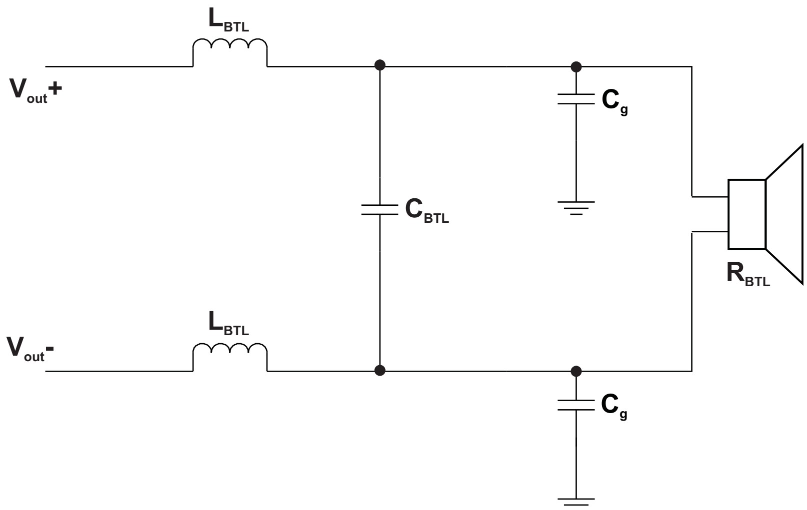

Figure 9. Recommended Low-Pass Filter for AD Modulation BTL Application

4.2 LC Filter for BD (Filter Free) Modulation

The BD Modulation output contains significant differential and common mode contents. Therefore, it must be analyzed in two steps. Figure 10 shows the LC filter configuration for BD Modulation.

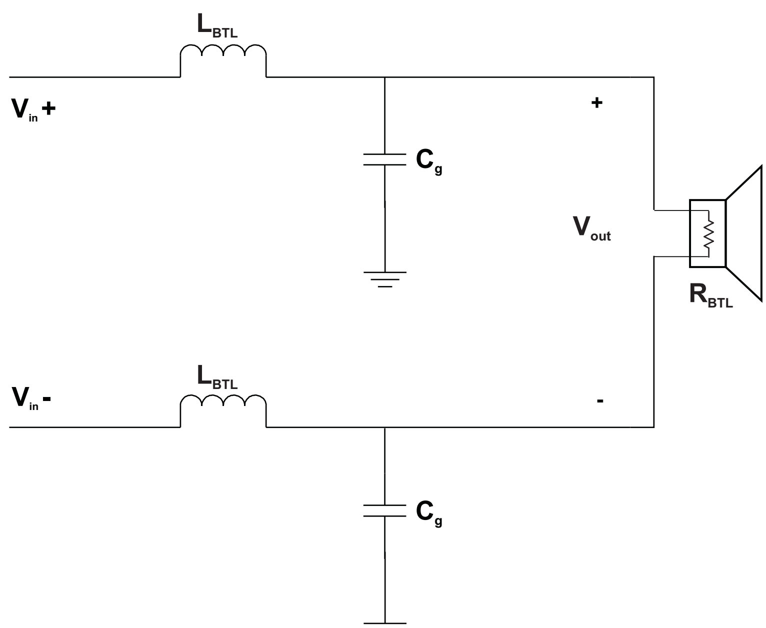

Figure 10. LC Filter for BD Modulation BTL Application

4.3 Differential Mode Analysis

When only differential signals are considered, V_{in}+ and V_{in}– are inverse input voltages of each other and the circuit is again symmetrically equivalent to two SE output circuits (Figure 11). See Section 4.1, LC Filter for AD (Traditional) Modulation for analysis of this circuit.

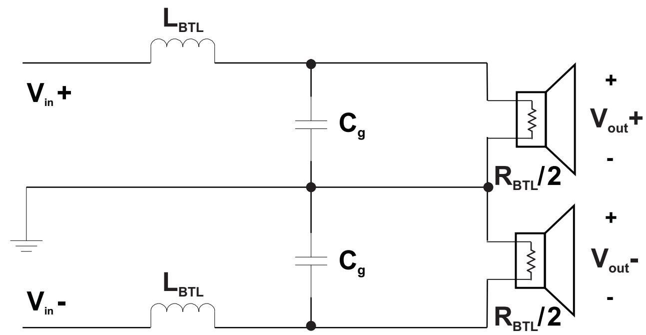

Figure 11. Equivalent Circuit for Differential Mode Analysis

The impedance seen by V_{in}+ or V_{in}– is

$$Z_{Diff}(s) = sL_{BTL} + \frac{R_{BTL}/2}{1 + sC_gR_{BTL}/2} \tag{8}$$

The transfer function is

$$H_{Diff}(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{1 + s \times \frac{L_{BTL}}{R_{BTL}/2} + L_{BTL} \times C_g \times s^2} \tag{9}$$

4.4 Common Mode Analysis

When considering only common mode signals, V_{in}+ and V_{in}– are equal to each other and R_{BTL} can be removed. Figure 12 shows the equivalent circuit is just a basic LC circuit.

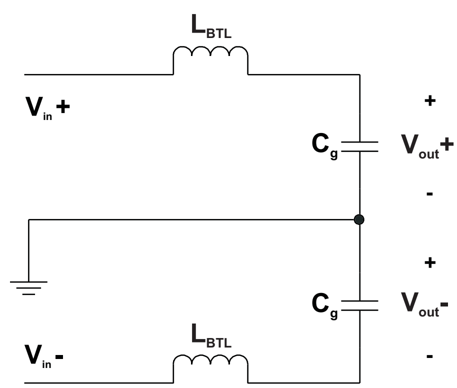

Figure 12. Equivalent Circuit for Common Mode Analysis

The impedance seen by V_{in}+ or V_{in}– is

$$Z_{CM}(s) = sL_{BTL} + \frac{1}{sC_g} \tag{10}$$

The transfer function is

$$H_{CM}(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{1 + s^2 L_{BTL} C_g} \quad (11)$$

5 Selecting Filter Components

This section describes key elements involved with selecting AD and BD modulation filter components. A series of tables (Table 2 through Table 7) provides recommended filter component values for each modulation type and for three R_{Load} values (8 Ω, 6 Ω, and 4 Ω speakers). Figure A-1 through Figure A-12 display the total harmonic distortion graphed against frequency and power for each of the modulation types and R_{Load} combinations.

5.1 Selecting Filter Components for BD Modulation

TI recommends the Butterworth filter for BD modulation. Figure 13 displays an example of the impedance and gain response for both common and differential modes.

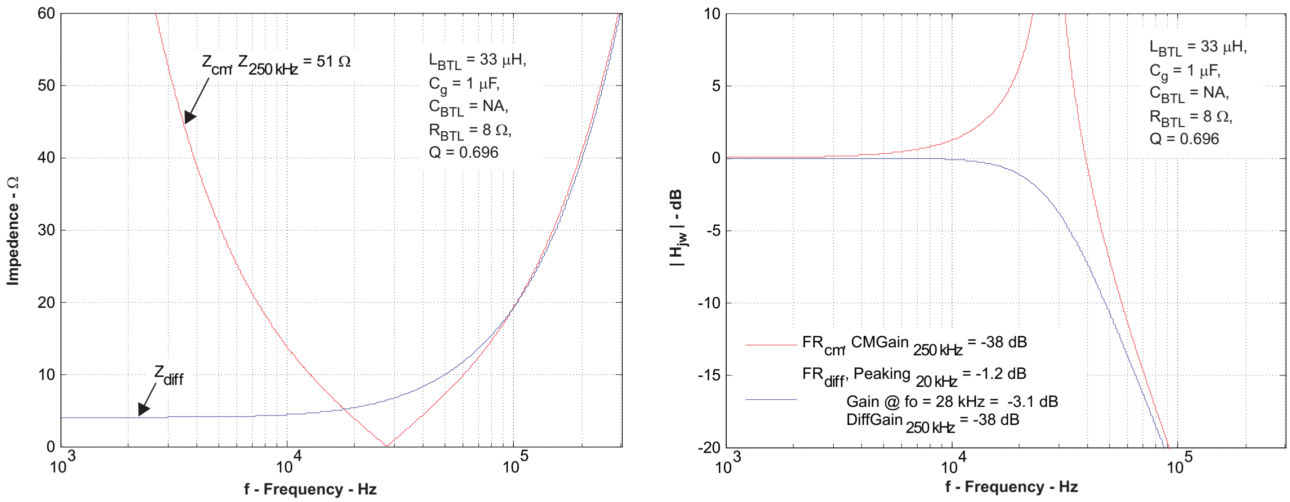

Figure 13. Impedance and Frequency Responses of Butterworth Filter

Z_{cm} at 250 kHz represents the impedance seen by the amplifier at the switching frequency. It should be kept at a high value as it affects the switching current drawn by the LC filter. $CMGain_{250kHz}$ and $DiffGain_{250kHz}$ represent the common mode and differential mode gain at the switching frequency. A high attenuation is preferred to ensure sufficient attenuation of the switching signals which affects the EMI performance of the amplifier.

Note: A –40 dB gain implies an attenuation of the switching signals by a factor of 100.

$Peaking_{20kHz}$ represents the amount of gain at 20 kHz and is related to Q of the LC filter.

The drawback to a Butterworth filter for 8 Ω speakers is the use of 33 µH inductors, that are usually large and bulky. In most audio applications, slight peaking of less than 2 dB at 20 kHz can be tolerated to reduce the size of the inductors. Allowing some peaking can also help increase the attenuation at the Class-D switching frequency 250 kHz.

Note: Reducing the size of the inductors generally increases the total harmonic distortion (THD) of audio outputs. See Chapter A for Total Harmonic Distortion responses graphed against frequency and power.

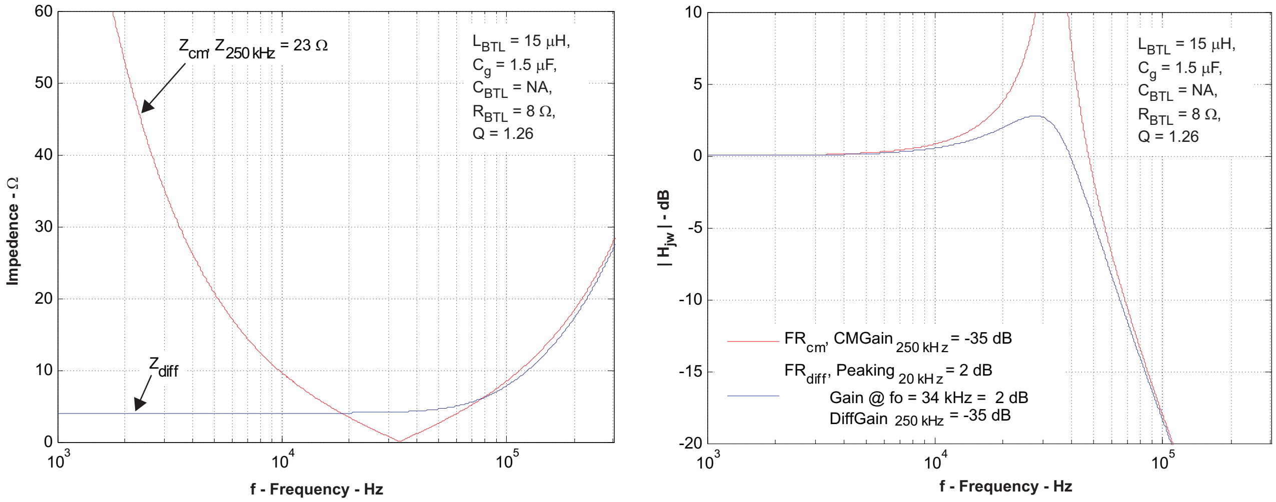

Figure 14. Impedance and Frequency Responses, Filter With Slight Peaking

5.2 Selecting Filter Components for AD Modulation

The AD modulation has no significant common mode content in its output, thus only the differential mode impedance and frequency responses need to be analyzed. We can use the differential mode results from BD Modulation filters to find the values of the components for AD Modulation filters.

5.3 Recommended BD Modulation Filter Components

These tables show TI's recommended Butterworth filter component values for BD modulation and the different speaker loads (8 Ω, 6 Ω, and 4 Ω).

Table 2. BD Modulation for R_{BTL} = 8 Ω

8 Ω								
Q	f_o (kHz)	PEAKING AT 20 kHz (dB)	L_{BTL} (µH)	C_g (µF)	Z_{CM_250kHz} (Ω)	$Gain_{CM\_250kHz}$ (dB)	$Gain_{Diff\_250kHz}$ (dB)	THD+N at 1W, 1kHz(1) (%)
0.7(2)	28	–1.2	33	1	51	–38	–38	0.050
0.7(2)	41	–0.28	22	0.68	34	–31	–31	0.075
1.26	34	2	15	1.5	23	–35	–35	0.096

(1) Measured with TPA3106D1 EVM. See Appendix A for THD vs. Frequency and THD vs. Power plots.
(2) Butterworth Filters

Table 3. BD Modulation for R_{BTL} = 6 Ω

6 Ω								
Q	f_o (kHz)	PEAKING AT 20 kHz (dB)	L_{BTL} (µH)	C_g (µF)	Z_{CM_250kHz} (Ω)	$Gain_{CM\_250kHz}$ (dB)	$Gain_{Diff\_250kHz}$ (dB)	THD+N at 1W, 1kHz(1) (%)
0.7(2)	31	–0.75	22	1	34	–36	–36	0.063
0.7(2)	45	–0.19	15	1	23	–29	–30	0.090
1.15	28	2	15	2	23	–38	–38	0.090
1.27	38	1.6	10	2	15	–33	–33	0.080

(1) Measured with TPA3106D1 EVM. See Appendix A for THD vs. Frequency and THD vs. Power plots.
(2) Butterworth Filters

Table 4. BD Modulation for R_{BTL} = 4 Ω

4 Ω								
Q	**f_o (kHz)**	**PEAKING AT 20 kHz (dB)**	**L_{BTL} (µH)**	**C_g (µF)**	**Z_{CM_250kHz} (Ω)**	**$Gain_{CM\_250kHz}$ (dB)**	**$Gain_{Diff\_250kHz}$ (dB)**	**THD+N at 1W, 1kHz[(1)] (%)**
0.7[(2)]	31	–0.85	15	2	23	–36	–36	0.090
0.94	23	0.29	15	3.3	23	–42	–42	0.090
0.7[(2)]	46	–0.22	10	1	15	–29	–29	0.082
1.15	28	2	10	3.3	16	–38	–38	0.087

(1) Measured with TPA3106D1 EVM. See Appendix A for THD vs. Frequency and THD vs. Power plots.
(2) Butterworth Filters

5.4 Selecting Filter Components for AD Modulation

These tables show TI's recommended filter component values for AD modulation and the different bridge tied-loads (8 Ω, 6 Ω, and 4 Ω).

Table 5. AD Modulation for R_{BTL} = 8 Ω

8 Ω							
Q	**f_o (kHz)**	**PEAKING AT 20 kHz (dB)**	**L_{BTL} (µH)**	**C_{BTL} (µF)**	**C_g (µF)**	**$Gain_{Diff\_250kHz}$ (dB)**	**THD+N at 1W, 1kHz[(1)] (%)**
0.7[(2)]	28	–1.2	33	0.47	0.1	–38	0.0579
0.7[(2)]	41	–0.28	22	0.33	0.068	–31	0.05638
1.26	34	2	15	0.68	0.1	–35	0.0856

(1) Measured with TPA3123D2EVM (BTL configuration). See Appendix A for THD vs. Frequency and THD vs. Power plots.
(2) Butterworth Filters

Table 6. AD Modulation for R_{BTL} = 6 Ω

6 Ω							
Q	**f_o (kHz)**	**PEAKING AT 20 kHz (dB)**	**L_{BTL} (µH)**	**C_{btl} (µF)**	**C_g (µF)**	**$Gain_{Diff\_250kHz}$ (dB)**	**THD+N at 1W, 1kHz[(1)] (%)**
0.7[(2)]	31	–0.75	22	0.68	0.1	–36	0.0648
0.7[(2)]	45	–0.19	15	0.39	0.082	–30	0.0915
1.15	28	2	15	1.0	0.18	–38	0.0949
1.27	38	1.6	10	1.0	0.18	–33	0.1312

(1) Measured with TPA3123D2EVM (BTL configuration). See Appendix A for THD vs. Frequency and THD vs. Power plots.
(2) Butterworth Filters

Table 7. AD Modulation for R_{BTL} = 4 Ω

4 Ω							
Q	**f_o (kHz)**	**PEAKING AT 20 kHz (dB)**	**L_{BTL} (µH)**	**C_{BTL} (µF)**	**C_g (µF)**	**$Gain_{Diff\_250kHz}$ (dB)**	**THD+N at 1W, 1kHz[(1)] (%)**
0.7[(2)]	31	–0.85	15	1.0	0.18	–36	0.0776
0.94	23	0.29	15	1.5	0.27	–42	0.07612
0.7[(2)]	46	–0.22	10	0.56	0.1	–29	0.09049
1.15	28	2	10	1.5	0.27	–38	0.10625

(1) Measured with TPA3123D2EVM (BTL configuration). See Appendix A for THD vs. Frequency and THD vs. Power plots.
(2) Butterworth Filters

6 Conclusions

The analysis of LC filters for Class-D AD (Traditional) and BD (Filter Free) Modulation techniques have been presented. Although peaking is generally undesirable, allowing a small amount of peaking can reduce the size and cost of inductors. Several filter component values are suggested to allow you (system designer) flexibility and to help you decide the optimal values for your designs.

As a system designer, it is important that you are aware of the tradeoffs among:

- Cost
- EMI performance
- Idle current
- Audio distortion

Appendix A Total Harmonic Distortion Plots for AD and BD Modulation

A.1 BD Modulation for 8-, 6-, and 4-ohm Bridge-Tied Loads

This section contains Total Harmonic Distortion vs. Frequency and Total Harmonic Distortion vs. Power plots for BD modulation that corresponds to the values in Table 2 through Table 4.

Note: All measurements made with Toko 11RHBP inductors and Metal Poly capacitors.

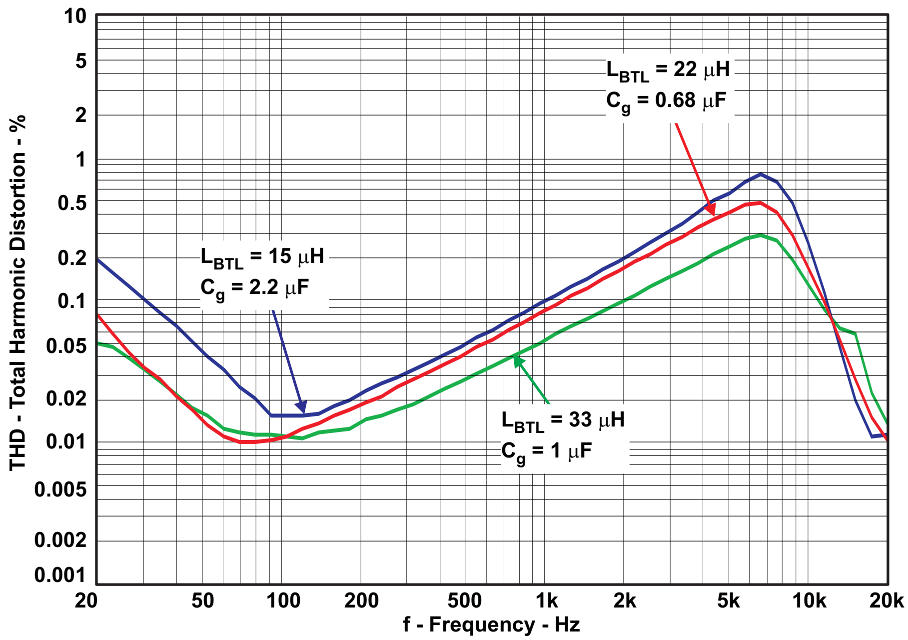

Figure A-1. THD vs Frequency, BD Modulation, R_{BTL} = 8 Ω

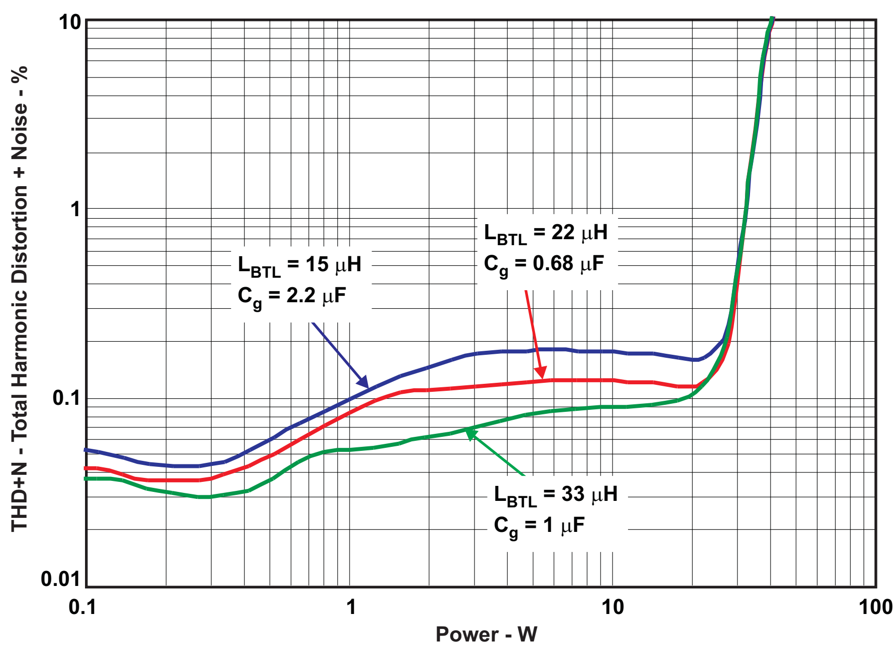

Figure A-2. THD vs Power, BD Modulation, R_{BTL} = 8 Ω

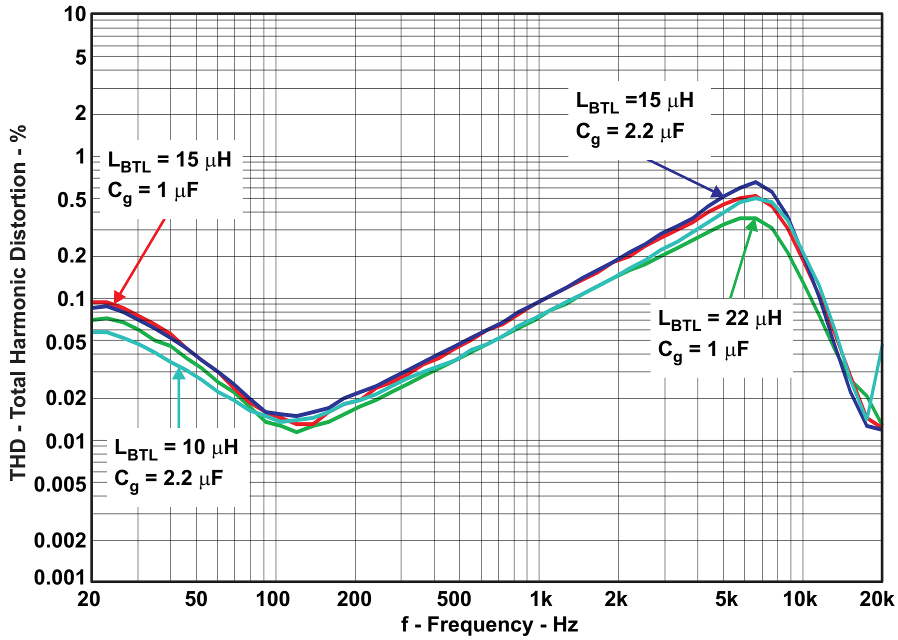

Figure A-3. THD vs Frequency, BD Modulation, R_{BTL} = 6 Ω

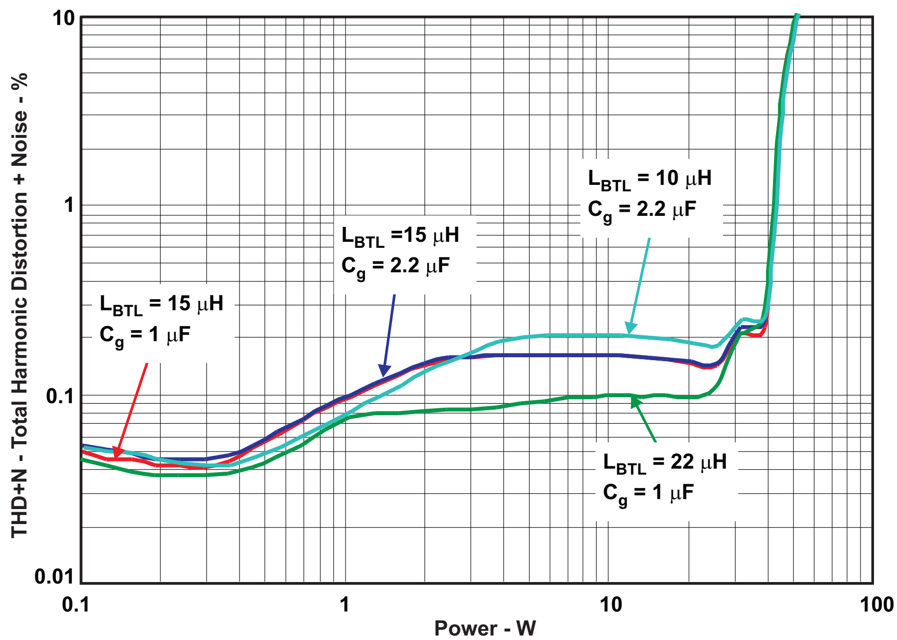

Figure A-4. THD vs Power, BD Modulation, R_{BTL} = 6 Ω

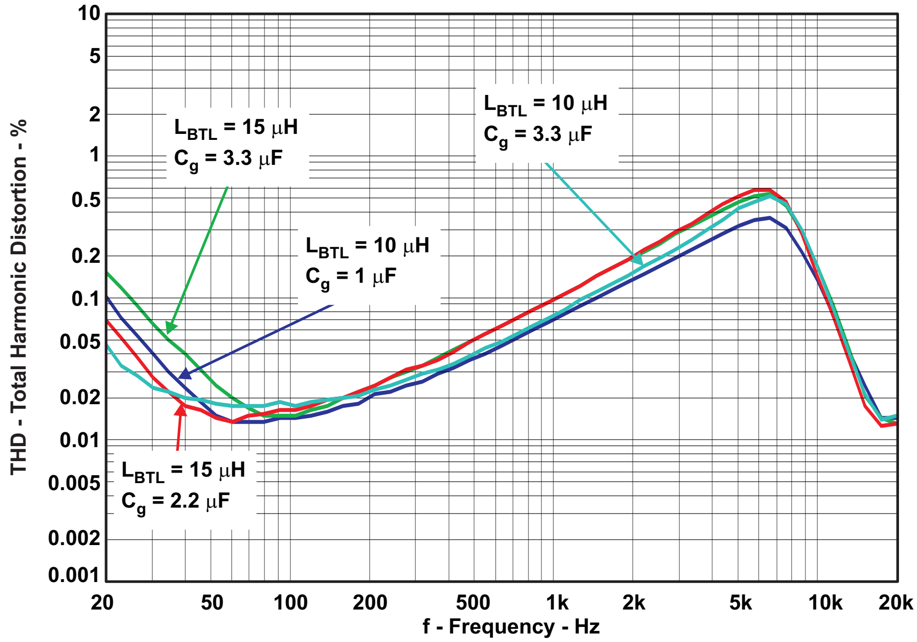

Figure A-5. THD vs Frequency, BD Modulation, R_{BTL} = 4 Ω

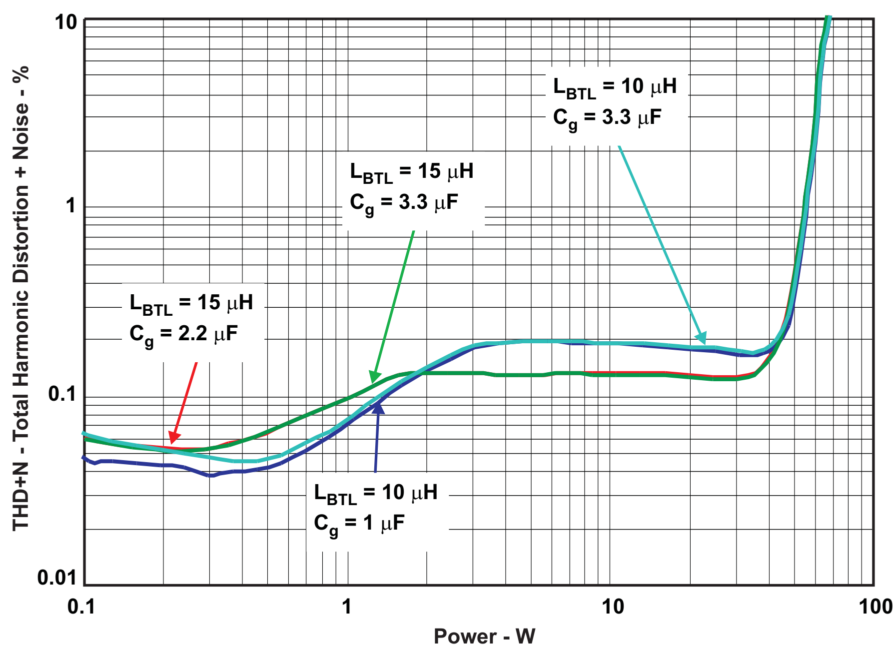

Figure A-6. THD vs Power, BD Modulation, R_{BTL} = 4 Ω

A.2 AD Modulation for 8-, 6-, and 4-ohm Bridge-Tied Loads

This section contains Total Harmonic Distortion vs. Frequency and Total Harmonic Distortion vs. Power plots for AD modulation that corresponds to the values in Table 5 through Table 7.

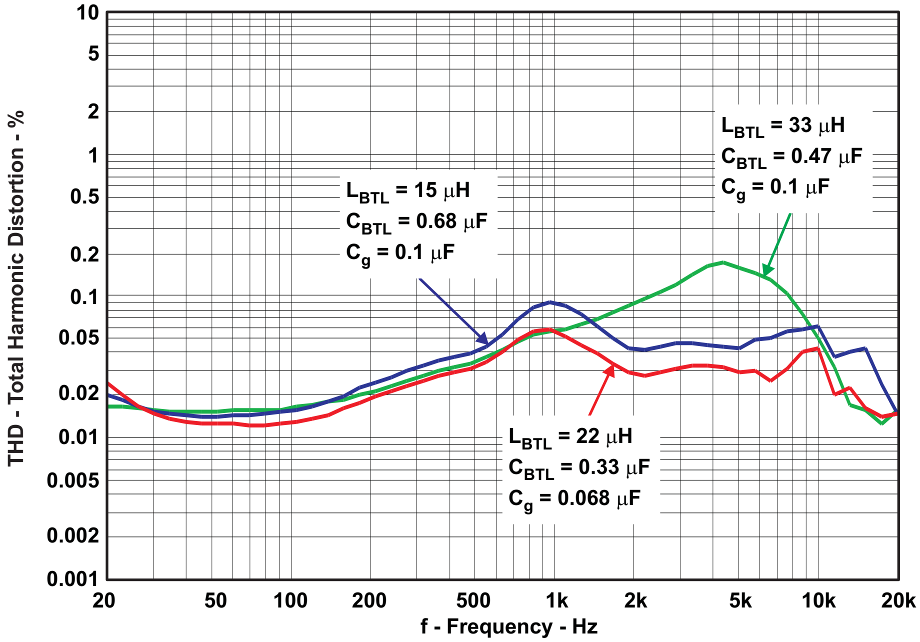

Figure A-7. THD vs Frequency, AD Modulation, R_{BTL} = 8 Ω

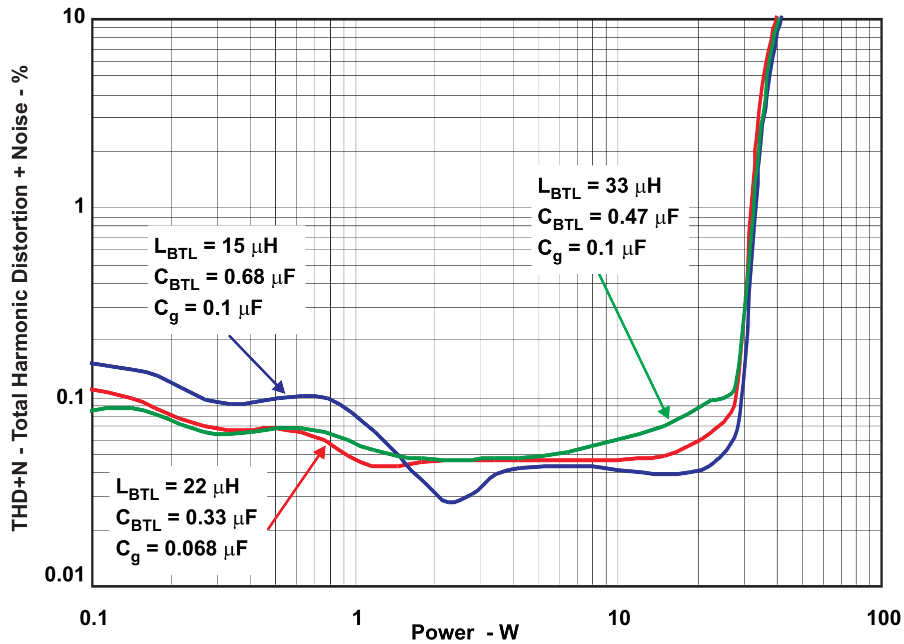

Figure A-8. THD vs Power, AD Modulation, R_{BTL} = 8 Ω

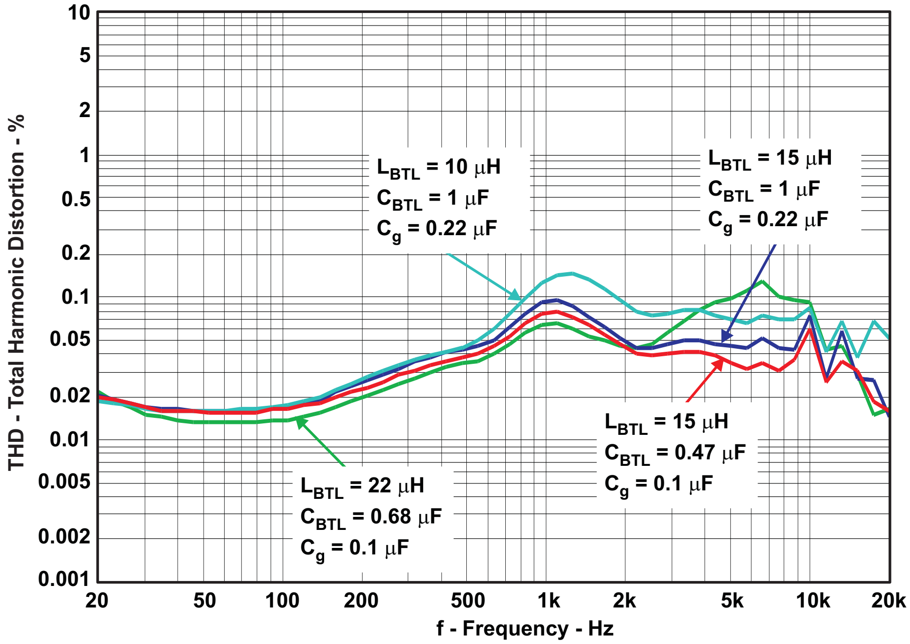

Figure A-9. THD vs Frequency, AD Modulation, R_{BTL} = 6 Ω

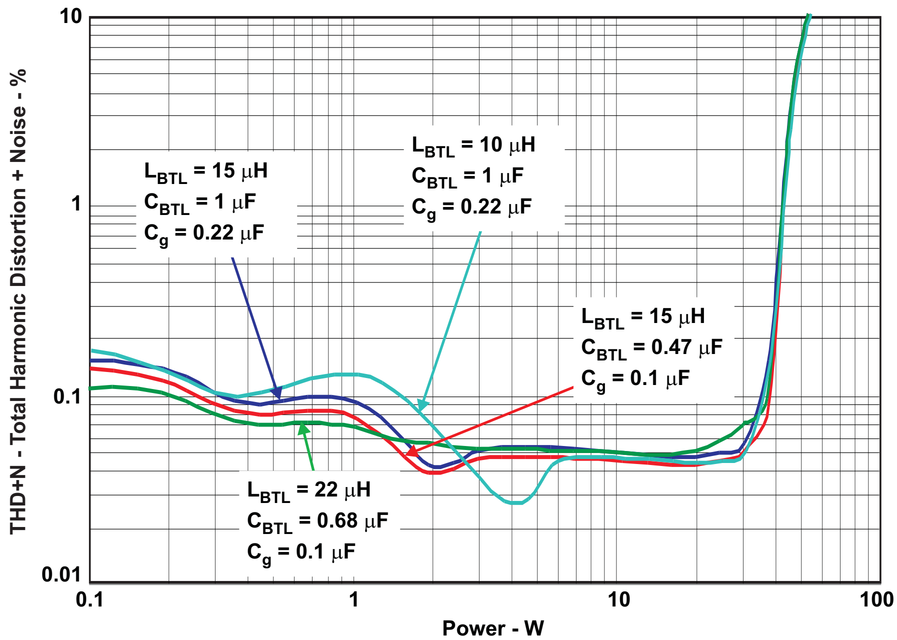

Figure A-10. THD vs Power, AD Modulation, R_{BTL} = 6 Ω

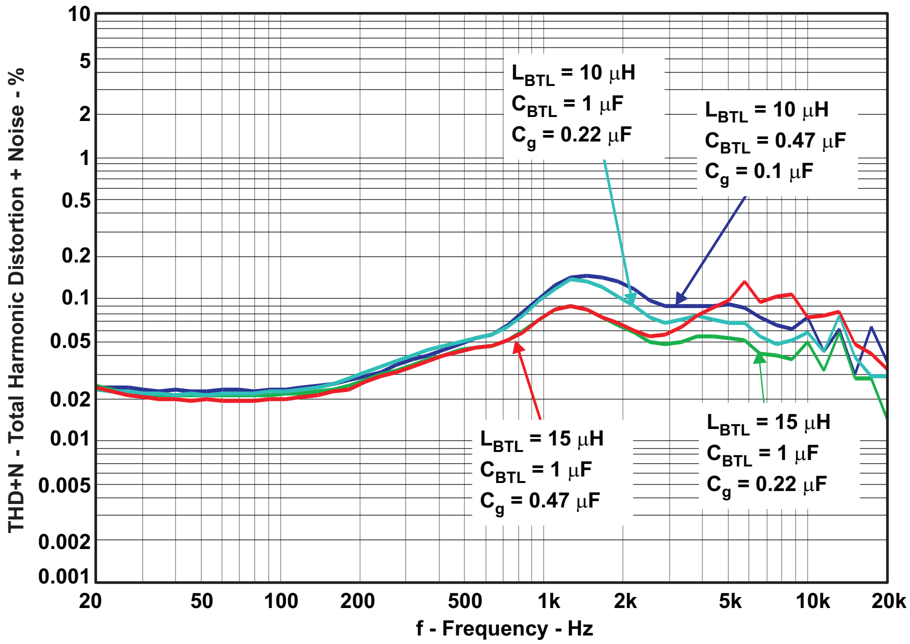

Figure A-11. THD vs Frequency, AD Modulation, R_{BTL} = 4 Ω

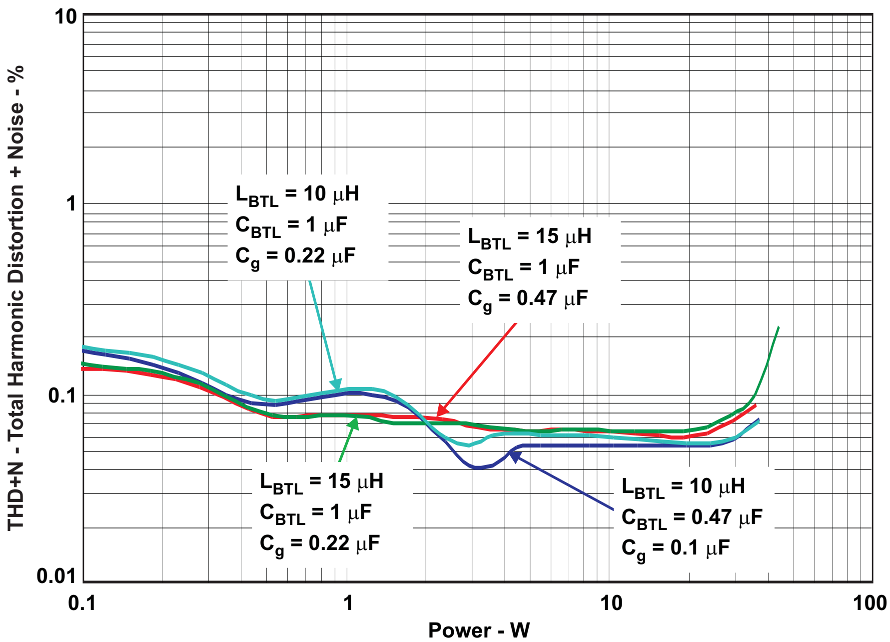

Figure A-12. THD vs Power, AD Modulation, R_{BTL} = 4 Ω