Power supply decoupling and audio signal filtering for the Class-D audio power amplifier

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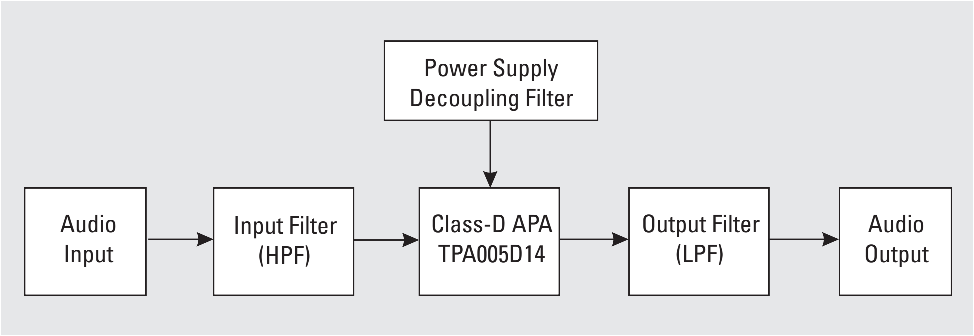
Introduction

Figure 1. Simplified Class-D system overview

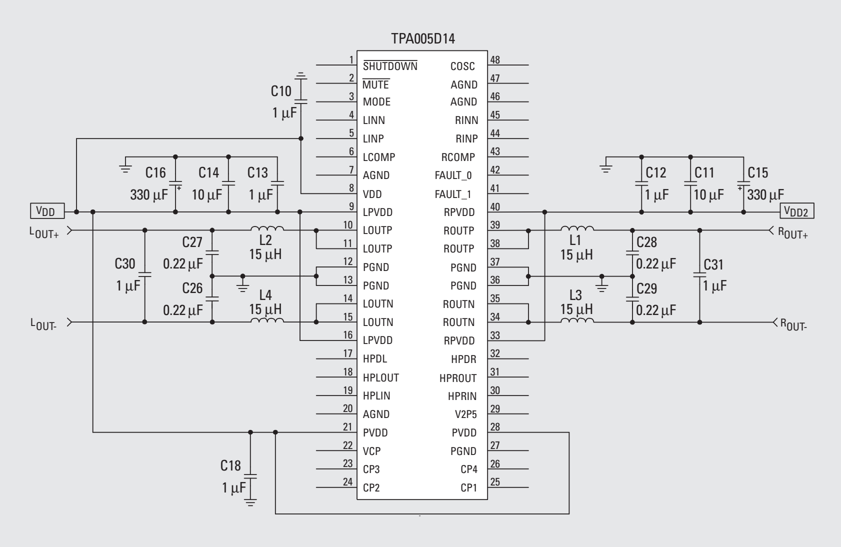


Class-D audio amplifiers are very similar to switch-mode power supplies in that both compare an input signal with a reference to create an error voltage that controls a pulse-width modulation (PWM) circuit. The PWM signal controls the switching action of the output power stage consisting of DMOS power transistors in an H-bridge configuration. The result is a square wave output which, when passed through a low-pass filter (LPF), produces an amplified version of the audio input. The Texas Instruments website has information available on the operation of the Class-D audio power amplifiers.[1]

This application note describes proper decoupling of the power supply, selection and implementation of audio input and output filters, and some basic layout considerations for the TI TPA005D14 Class-D stereo audio power amplifier. Figure 1 shows the major function blocks that support the Class-D amplifier in the audio system. Each of the filter functions will be explained with emphasis on selection and placement of components.

A partial schematic of the TPA005D14 EVM, SLOP 204, is shown in Figure 2. The 5-V device is capable of delivering 2 watts of continuous output power into a 4-Ω load with less than 0.5% total harmonic distortion across the 20-Hz to 20-kHz audio frequency range. The full EVM schematic and performance characteristics can be found in the user's guide.

Figure 2. Power supply decoupling capacitor circuit



Power supply decoupling[2]

Power supply decoupling requires providing the bulk capacitance needed to supply the low-frequency charge and the capacitance needed for the switching transient response.

Bulk capacitance

Power supply decoupling plays a key role in achieving top performance from Class-D amplifiers. The capacitance at the power inputs provides a low-impedance voltage source for the device that reduces the ripple of the power supply voltage created by the pulse currents of the Class-D device. This reduces the distortion in the output and produces a much cleaner audio output. Capacitors are modeled using equivalent series resistance (ESR), equivalent series inductance (ESL), capacitive reactance (X_C) and inductive reactance (X_L). The equivalent impedance of a capacitor over frequency is simply modeled using Equation 1.

$$Z = \sqrt{\mathrm{ESR}^2 + (X_C - X_L)^2} \tag{1}$$

X_L is small for frequencies below 1 MHz and can be neglected since the switching frequency range of the TPA005D14 is 100 to 500 kHz. X_C is maximum and dominates at DC, and decreases as the frequency increases until resonance is reached ($X_C = X_L$), at which point Z = ESR. The ESR of a capacitor is considered to be constant over the 100-kHz to 500-kHz switching frequency range of the Class-D amplifier. Capacitors C15 and C16 in Figure 2 provide the bulk capacitance required for each channel. Assuming that the power supply current is constant and has negligible ripple, the capacitor current is negligible, and the switching frequency and dc load resistance are known, the peak power for a given load is used to calculate the peak current as shown in Equation 2.

$$I_{\mathrm{Peak}} = \sqrt{P_{\mathrm{Peak}}/R_L} \tag{2}$$

The minimum capacitance, shown in Equation 3, needed to maintain a specified ripple voltage, assuming ESR = 0, is then:

$$C \geq (I_{\mathrm{Peak}} \times T_D \times D_{\mathrm{Max}})/V_{\mathrm{Ripple}} \tag{3}$$

where $T_D = 1/f_{\mathrm{switch}}$ is the period, D_{Max} is the maximum duty cycle and V_{Ripple} is the desired ripple voltage. In almost every case the ripple voltage caused by the ESR will dominate. The ESR required to achieve the same V_{Ripple} for the I_{Peak} from Equation 2 is:

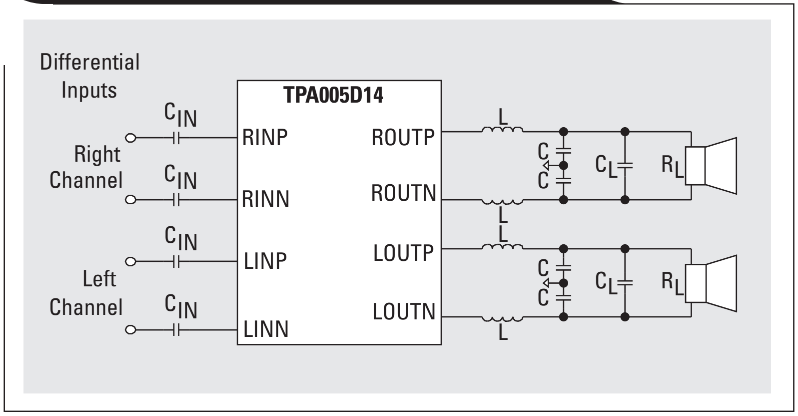
$$\mathrm{ESR} \leq V_{\mathrm{Ripple}}/I_{\mathrm{Peak}} \tag{4}$$

This value assumes that the capacitor ripple is ≤10% of the ESR ripple (the capacitance is ≥10 × C of Equation 3). The capacitor ESR should be 30 to 50% lower than Equation 4 to allow for increases due to temperature, ESL and aging. Capacitors can be paralleled to reduce ESR and power dissipation.

Transient response of the decoupling capacitors

The bulk capacitor C15 (or C16) of Figure 2 is large and requires an electrolytic capacitor. The time required to transfer the charge of C15 to the load is long due to the time constant created between the capacitance and the equivalent resistance of the trace, ESR and load. This can deteriorate the output signal and cause distortion. The solution is to add two ceramic capacitors to the filter, one immediately adjacent to the power supply pin (C12 and C13 in Figure 2), and the other between the pin and the bulk electrolytic capacitor (C11 and C14 in Figure 2). Capacitor C12 (or C13) is chosen to be very small to provide a short time constant and, consequently, the available charge is small and is quickly depleted by a large current transient. As charge is depleted from C12, charge from C11 (or C14) begins to arrive at the power pin. The charge from C15 then arrives as the charge for C11 is being depleted. The result is a smooth output signal. The voltage on the power pin will drop if the time constant of C11 or C15 is too long. The long time constant of C15 ensures that plenty of charge will be available for the power pin during the remainder of the transient.

Figure 3. Audio signal input and output filters



Filtering in the audio signal path

Each channel consists of differential amplifier inputs and bridge-tied load (BTL) outputs. Filtering of the inputs is required to avoid DC offsets. The output filter is recommended for applications requiring minimization of quiescent current and EMI. Figure 3 shows the filtering scheme used in the TPA005D14 EVM.

Input filter

The differential input requires filters for both the non-inverting and the inverting inputs of the amplifier. The input filters set the low frequency corner and block DC voltages and currents. Each filter consists of one external capacitor (C_{IN}) in series with the fixed internal resistance (R_{IN}) of the amplifier input. This creates a first-order high-pass filter (HPF) with a –3-dB corner frequency shown in Equation 5 of:

$$f_{\mathrm{LO}} = 1/(2\pi R_{\mathrm{IN}} C_{\mathrm{IN}}) \tag{5}$$

where R_{IN} = 10 kΩ (typical), and C_{IN} = 1 µF for a –3-dB value of 15.9 Hz. f_{LO} can be easily adjusted by changing C_{IN}. The inverting input should be AC grounded for single-ended inputs using the same value of C_{IN} as the non-inverting input.

Output filter

Several choices of filters exist and are characterized by the cutoff frequency (–3-dB point), passband gain and ripple, and stop band attenuation. In this case an L-C filter with a Butterworth approximation was chosen for its maximally flat magnitude response and the small number of components required to implement the filter. The order of the filter determines how many poles exist at the same frequency. Each pole increases the attenuation above the cutoff frequency (in the stop band) by 20 dB per decade. A second-order LPF reduces f_s by –40 dB per decade (a 5-V signal will be reduced to 50 mV). The switching frequency (f_s) impacts the choice of the filter order—the higher the f_s, the lower the order required to achieve a given attenuation. The trade-off is a decrease in efficiency and increases in EMI.

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The transfer function and –3-dB cutoff frequency are derived in Equation 6 using a half-circuit model and found to be

$$H(s) = \frac{1}{s^2+\sqrt{2}s+1} \times \frac{V_O(s)}{V_I(s)}$$

$$= \frac{1/(2LC_L)}{s^2 + \left[1/(R_L C_L)\right]s + \left[1/(2LC_L)\right]} \qquad \textbf{(6)}$$

$$f_C = \frac{1}{2\pi\sqrt{2LC_L}} \qquad \textbf{(7)}$$

where R_L is the DC resistance of the speaker. The factor of $2L$ is due to the conversion from the half circuit to BTL values. Frequency scaling $\omega_0 = 2\pi f_C$ gives the final Equations 8 and 9 for determining C_L and L. Table 1 shows various values for L and C_L for a given f_C and R_L.

$$C_L = \frac{1}{\sqrt{2} \times R_L \omega_0} = \frac{1}{2\sqrt{2} \times \pi R_L f_C} \qquad \textbf{(8)}$$

Table 1. Second-order Butterworth *L*-*C*$_L$ values

DC LOAD RESISTANCE, R_L (Ω)	CUTOFF FREQUENCY, f_C (kHz)	INDUCTOR VALUE, L (µH)	CAPACITOR VALUE, C_L (µF)
4	20	22.5	1.41
4	25	18.0	1.13
4	30	15	0.94
4	35	12.9	0.80
8	20	45	0.70
8	25	36	0.56
8	30	30	0.47
8	35	26	0.40

$$L = \frac{\sqrt{2} \times R_L}{\omega_0} = \frac{\sqrt{2} \times R_L}{4\pi f_C} \qquad \textbf{(9)}$$

Figure 4 shows the measured response of the TPA005D14 EVM for $R = 4\ \Omega$ and $f_C = 30$ kHz using an Audio Precision System II. The response shows a gain of 10 V/V, input corner frequency of 15.9 Hz and an output cutoff frequency of 28 kHz.

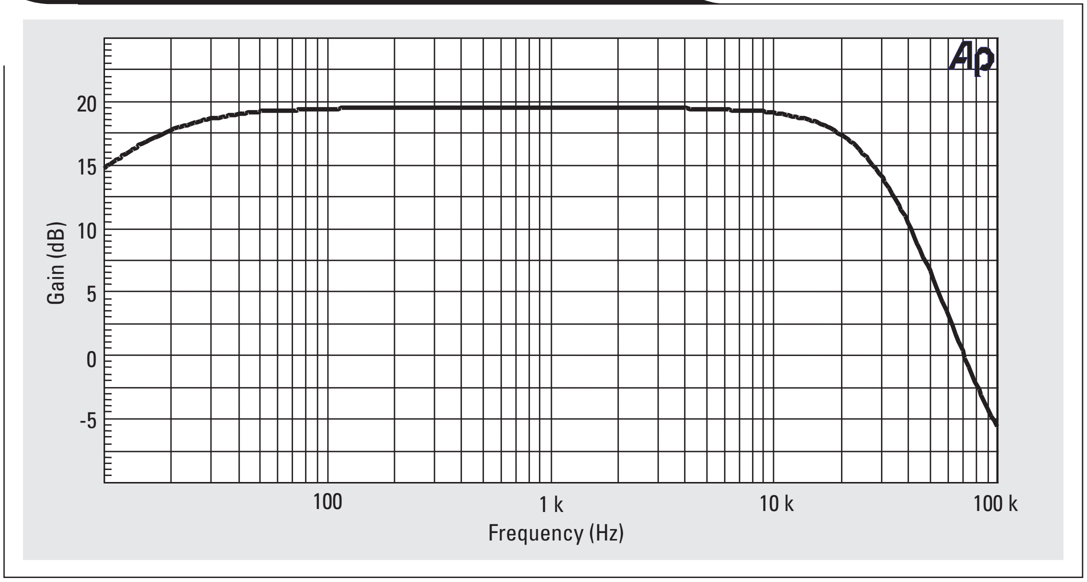
Component selection

The output inductors are key elements in the performance of the Class-D audio power amplifier system. The most important specifications for the inductors are the DC and peak current ratings. These must be chosen to avoid magnetic saturation of the inductor. Magnetic saturation greatly increases distortion in the circuit as the power is increased and can be minimized by choosing an inductor with a current rating greater than the sum of the DC and AC current components. Shielded inductors will also help reduce distortion and EMI and minimize cross-talk. The output filter capacitors, C, in Figure 3 provide high-frequency paths for the switching frequency and noise and assist in supplying charge to the load. Capacitors with a low equivalent series resistance (ESR) and stability over the required voltage and temperature are recommended. These capacitors are empirically chosen to be approximately 20% of C_L.

Layout considerations

Good layout practices and a well thought-out design are critical toward obtaining maximum performance levels from the TPA005D14 amplifier. The main areas of concern are the ground plane, power plane and the audio input and output. Each is discussed briefly below. Refer to Figure 2 for pin numbers and names. See the Class-D application notes and user guides at the Texas Instruments website[1] for more information on the Class-D APA.

Figure 4. Measured response of the TPA005D14 EVM



Ground plane

Experimentation with several types of ground planes has shown that with good planning and layout practices a solid ground plane works as well as other types of grounding schemes. This is due in part to the system's relatively low frequencies of operation and to the careful layout of the components and traces. The solid ground plane also serves to assist the PowerPAD™ [3] in the dissipation of heat, keeping the amplifier relatively cool and eliminating the need for an external heat sink. The pinout of the TPA005D14 allows good separation of the inputs and outputs, minimizing ground return paths and high frequency loops. It is important that any components connecting an IC pin to the ground plane be connected to the nearest ground for that particular pin. Table 2 lists the ground pins for the main sections of the Class-D audio power amplifier. Care should be taken to prevent the ground return path of any high current components (e.g. the output filter capacitors) from directly passing through other ground connections of the IC, particularly the input.

Table 2. Ground pins

GROUND PIN	APPLICABLE CIRCUITS	RELATED IC PINS
47	Controls (shutdown, mute, mode)	1, 2, 3
	Class-D inputs	4, 5, 44, 45
	Ramp generator	6, 43, 48
	Grounds	7, 46
	Input power (VDD)	8
	Fault indicators	41, 42
12, 13, 36, 37	Output power (LPVDD, RPVDD)	9, 16, 33, 40
	Class-D outputs	10, 11, 14, 15, 34, 35, 38, 39
20	Headphone	17, 18, 19, 29, 30, 31, 32
27	Charge pump	21, 22, 23, 24, 25, 26, 28

Power plane

The chip has three main power sections: the input circuit power pins (VDD), the output stage power pins (LPVDD and RPVDD) and the power for the headphone and charge pump circuits (PVDD). When the device is fully operational, the VDD pin draws only a few milliamps of current and the PVDD pins draw several tens of milliamps, in contrast to the amps of current drawn by the LPVDD and RPVDD pins. The power traces should be kept short and the decoupling capacitors placed as close to the power pins as possible. It is important to terminate the capacitor ground close to the ground for the particular power section while paying attention to ground return current paths. This minimizes ground loops and provides very short ground return paths and high-frequency loops. The VDD pin supplies power for sensitive analog circuitry. It is the most sensitive pin of the device and must be kept as noise free as possible. The PVDD pins are not as sensitive to noise as the VDD pin and supply the current for the headphone regulator and control circuits when the device is in Class-AB mode and for the charge pump circuit when in Class-D mode. The power traces for the VDD and PVDD power inputs should be connected to the main power bus at a point near the large decoupling capacitor. The small inductance of the traces and the charge supplied by the large decoupling capacitor greatly reduce the ripple current of the main power bus at these pins. The demand for transient currents is small and is satisfied by placing 1-µF capacitors adjacent to the VDD pin and PVDD pin 21. The main power bus should terminate into the LPVDD and RPVDD pins, with a 1-µF capacitor placed adjacent to each pair of pins. A 10-µF capacitor is then placed between the power pins and the large decoupling capacitor. These traces should be symmetric and wide to facilitate even power distribution and should be directly over the ground to reduce EMI and minimize the ground return path.

Inputs and outputs

The Class-D input traces should be kept as short as possible between the ac coupling capacitors and the amplifier inputs to reduce noise pickup. The inputs must be separated from the outputs, particularly the inductors, to minimize magnetic coupling. The headphone traces may be in close proximity to the Class-D output since the two amplifiers are not active at the same time. It is critical to minimize the trace lengths between the device output pins and the LC filter components, particularly those that contain the full 250-kHz square wave. These traces should be capable of handling a maximum rms current of at least 0.7 amps without distorting the signal, and peak currents of at least 1 amp. The traces to the inductors should be kept short but separated from the input circuit as much as possible and should be placed on adjacent layers so that they overlap to reduce the EMI.

Summary

The methods described have been successfully used in the design of the TPA005D14 Class-D Audio Power Amplifier EVM, SLOP 204, providing typical THD+*N* measurements of 0.1% for a 1-kHz, 1-watt output into a 4-ohm load. Three power decoupling capacitors provide a quick, smooth response to the large current demands of the output circuit and, with proper layout, are able to supply the transients to the input circuit and charge pump. A solid ground plane is effective when components are placed close to the ground pin for their circuit, and ground and high-frequency bypass loops are minimized. EMI and distortion are greatly reduced by keeping the input traces short and ac-coupling all inputs, minimizing the output trace lengths to the filter and overlapping the output traces to the inductors of each channel on adjacent layers.

References

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