

# HiFi Audio Circuit Design

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## ABSTRACT

With the increase in personal electronic devices, HiFi audio is more popular than ever in many applications, such as smartphones, music players, home theaters, and even car infotainment. Many engineers and consumers devote themselves to the endless journey in HiFi audio. This document will help engineers understand, judge, design, and optimize a HiFi audio circuit.

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## 1 Introduction

An audio signal is a representation of sound—typically an electrical voltage. Audio signals usually have frequencies in the range of approximately 20 Hz to 20,000 Hz, which is audible to most humans. Audio signals may be synthesized directly or may be originated at a transducer, such as a microphone, musical instrument pickup, phonograph cartridge, or tape head. Loudspeakers or headphones convert an electrical audio signal to sound.

High Fidelity or HiFi is a term used by home stereo listeners, audiophiles, and home audio enthusiasts to refer to high-quality reproduction of sound to distinguish it from the lower quality sound produced by inexpensive audio equipment. Ideally, high-fidelity equipment has inaudible noise and distortion, and a flat (neutral, uncolored) frequency response within the intended frequency range.

A sound system is mainly composed of the auditory system (human ears), hardware system (equipment), software system (signal source) and listening environment. Figure 1 shows the typical block diagram of an audio reproduction hardware system, which converts the digital audio source to the voltage signal that drives the headphone. This article only focuses on this hardware system, which contains the DAC, current to voltage (I/V) transimpedance amplifier, and difference amplifier.

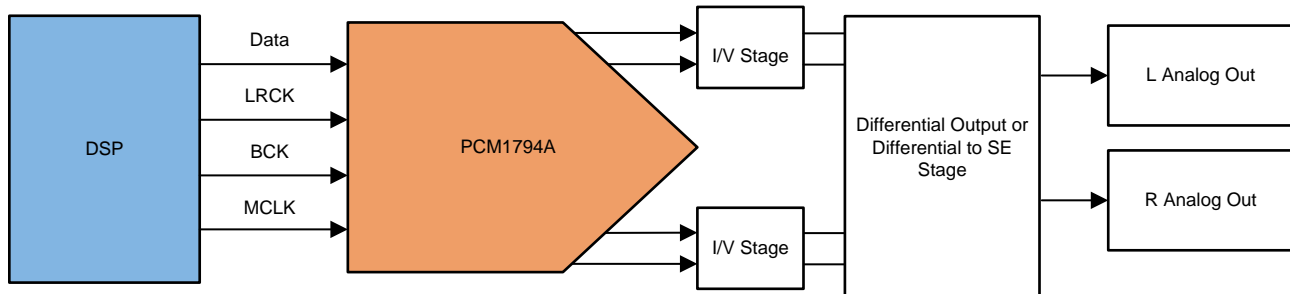


Figure 1. Audio Reproduction Hardware System

## 2 HiFi Audio Specifications

To ideally reproduce the audio signals, the key is to design a HiFi sound system that delivers ultra-low distortion, excellent signal-to-noise ratio (SNR), flat frequency response, high-dynamic range, quick transient response, low stereo crosstalk, good stereo balance, and proper output. The topic of this section is how to achieve these goals.

### 2.1 Excellent THD+N

THD+N is the most important parameter of signal quality. Theoretically HiFi requires excellent THD+N ( $< -110$  dB) to reproduce lossless audio signal. A high-quality audio source, an ultra-low noise and distortion DAC and amplifiers, ultra-low noise power supply, proper PCB layout, and attention to external circuits of the amplifiers are all required to achieve excellent THD+N performance.

### 2.2 Excellent SNR

Audible idle and background hiss noises are not allowed. Excellent SNR means no audible hiss noise at any time. As with THD+N, a high-quality audio source, an ultra-low noise DAC and amplifiers and power supply, proper PCB layout, and proper external circuit of the amplifiers are all required to achieve the excellent SNR performance. If  $\text{SNR} = 110$  dB is required, and the signal amplitude is 1 Vrms, according to the formula  $\text{SNR} = 20 \log (\text{signal power} / \text{noise power})$ , the rms noise power is 3.16  $\mu\text{V}$  from 20 Hz to 20,000 Hz. If  $\text{SNR} \equiv 115$  dB is required, the rms noise power is 1.78  $\mu\text{V}$ , which is also achievable.

### 2.3 Flat Frequency Response

A flat frequency response is very important to reproduce the most original audio signals from low frequency to high frequency. The bandwidth of amplifiers and low-pass filters must be high enough to avoid high-frequency signal attenuation. The matching circuits in the audio signal chain should also be well designed to avoid the ripple in the audio band.

### 2.4 Excellent Dynamic Range

The dynamic range allows a HiFi audio system to accurately reproduce both quiet and loud sounds simultaneously (dynamically). This dynamic range is especially important for classical music. The dynamic range of human ears is 120 dB, which could be achieved by a 24-bit, HiFi DAC and ultra-low noise amplifier with proper gain.

## 2.5 Quick Transient Response

Quick transient response shows the explosive force, which is the ability to reproduce quick, explosive sound and quickly restore silence when the explosive sound ends. This specification is determined by a high-output current and high bandwidth headphone driver, high bandwidth DAC and I/V amplifier, and power supply with quick transient response.

## 2.6 Low Stereo Crosstalk

Left and right channel crosstalk causes the sound field distortion, which results in narrow sound field. Because the frequency of audio signal is lower than 20 kHz, 100-dB isolation between left and right channel is high enough and can easily be achieved by proper PCB layout and power supply decoupling.

## 2.7 High Stereo Balance

The sound field will shift to the larger volume if the volume of the left and right channels is not same. This shift is especially bad for symphony music, which can be easily mixed by imbalanced volume. This specification can be achieved by matching the gain and PCB layout in the two channels' DAC, amplifier, and external circuits. For resistor matching, 0.1% precision thin-film feedback resistors are recommended.

## 2.8 Output Power

Output power is a recognizable parameter to consumers, so buying decisions are often made on this number. This specification is determined by high output current headphone driver and power supply. Designing a high output power audio system despite good THD+N performance is very easy, but too high of an output power will significantly worsen the THD+N performance for a given audio system, so always consider the impact on THD+N when designing the output power.

# 3 HiFi Audio Circuit Design

## 3.1 DAC Circuit Design

The DAC is the source of the analog audio signal chain, and the DAC is the performance bottleneck in the chain because the THD+N performance of the best DAC in the world is 10 + dB worse than the best amplifier. The DAC contains both analog and digital functional blocks and needs ultra-low noise clock, power supply, and careful PCB layout to achieve less than -110dB THD+N performance. TI PCM1794A is one of the best audio DACs in the world. With simple and clear illustrations of external circuitry on its datasheet, designers can achieve a dynamic range of 129 dB and THD+N of -116 dB by following the design guide.

## 3.2 Transimpedance Amplifier Circuit Design

Usually ultra-high performance audio DACs are differential current output, so a transimpedance amplifier is required to convert the current to voltage.

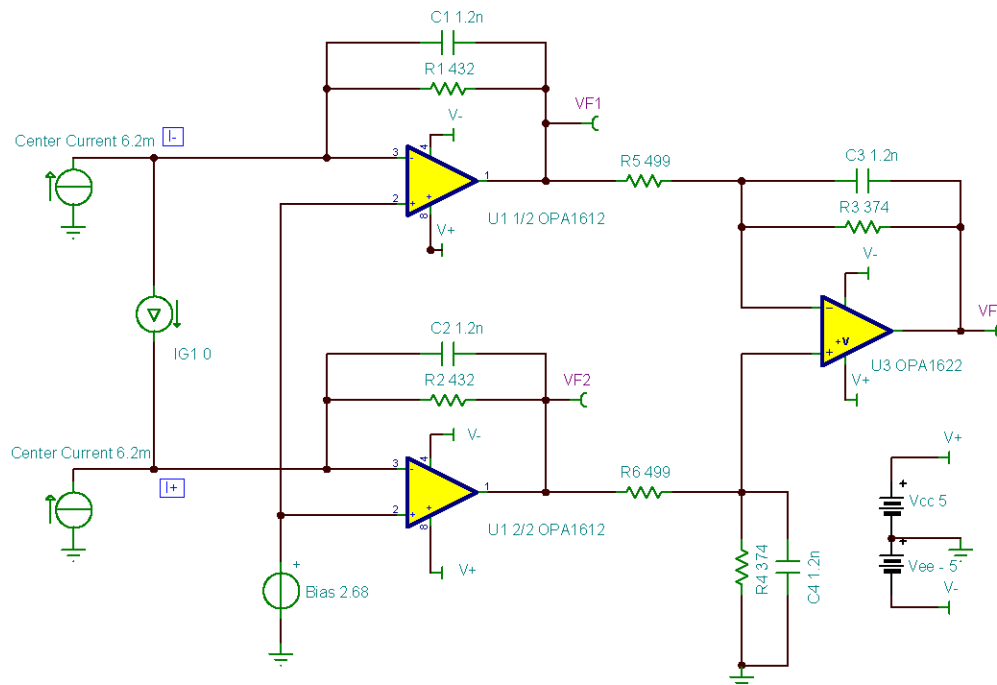
Some design rules for the I/V transimpedance amplifier:

1. The amplifier will have ultra-low noise and distortion to achieve excellent system SNR, THD+N, and dynamic range. The amplifier should have high slew rate to achieve excellent system transient response, high bandwidth to achieve flat system frequency response, and in-portable, system low-quiescent current to achieve low system power consumption. Sometimes high power supplies supported to get high output voltage swing thus get high system SNR. Low output drive capability is acceptable because its load is the second stage driver amplifier. OPA1612 is a good choice for this application.
2. To get the best SNR, the output voltage of this first-stage amplifier should be maximized according to the simulation, so the output voltage swing of the I/V transimpedance amplifier should be as high as possible, thus the center current output of DAC will also be the center output voltage of the first stage amplifier, this also makes the center input voltage of the second stage driver amplifier 0 V.

This section offers two design examples to meet different requirements. One example uses  $\pm 5$ -V power supply for the I/V amplifier to get a performance and cost balanced system and another one uses  $\pm 10$ -V power supply to get the lowest noise system. Each helps show how to design a proper HiFi circuit. Because the left and right channels are identical, only one channel is analyzed, as shown in Figure 2 and Figure 3.

The output current swing of DAC PCM1794A is  $\pm 3.9$  mA, and the center current is 6.2 mA. The best output linear range of OPA1612 is  $[(V-) + 0.6 \text{ V}, (V+) - 0.6 \text{ V}]$ , and the common mode voltage range is  $[(V-) + 2, (V+) - 2]$ .

The output voltage swing of OPA1612,  $V_{\text{swing}}$ , is 4.4-V peak to peak, so the feedback resistors  $R1 = 4.4 / 3.9 \text{ mA} = 1128 \Omega$ . Therefore, the bias voltage of OPA1612  $V_{\text{bias}}$  in the positive input pin will be  $6.2 \text{ mA} \times 1128 = 6.99 \text{ V}$ , which exceeds the common mode range of OPA1612  $[-3 \text{ V}, 3 \text{ V}]$ . Because the voltage exceeds the range, it is not suitable, so  $V_{\text{bias}}$  must be reduced to less than 3 V by reducing the feedback resistors  $R1$ . This reduction also reduces  $V_{\text{swing}}$  to its maximum allowed value of  $4.4 - V_{\text{bias}}$ , where  $V_{\text{bias}} = 6.2 \text{ mA} \times R1$ , and  $V_{\text{swing}} = 3.9 \text{ mA} \times R1$ . Because  $R1 = 4.4 \text{ V} / (6.2 + 3.9) \text{ mA} = 436 \Omega$ , a general smaller 432  $\Omega$  will be used in the actual circuit. This configuration generates  $V_{\text{swing}} = 1.685 \text{ V}$ , and  $V_{\text{bias}} = 2.678 \text{ V}$ .



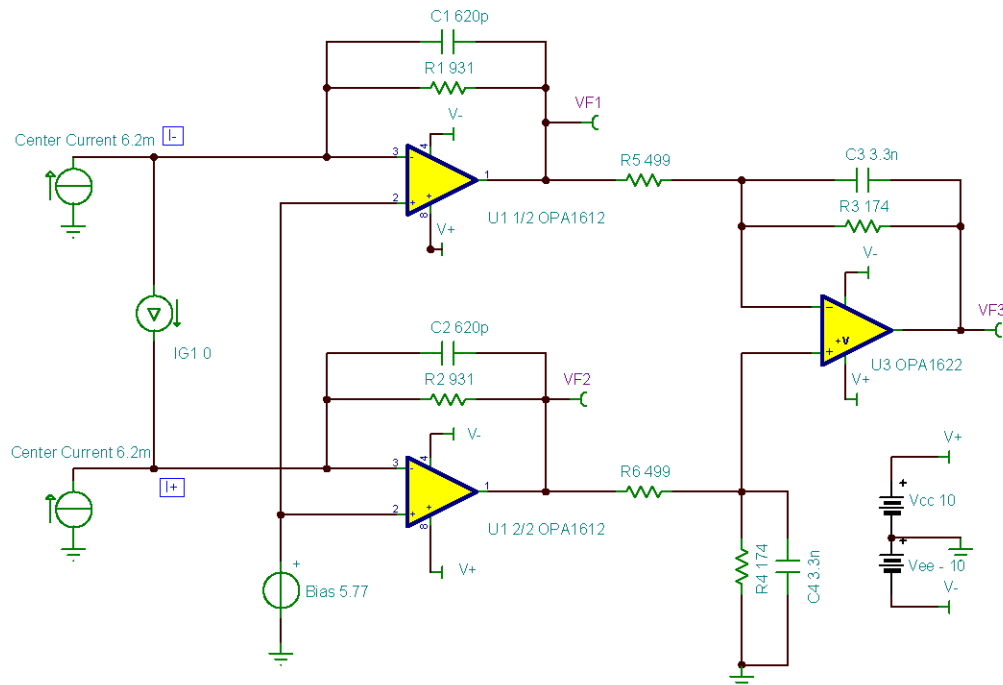
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**Figure 2. Amplifiers Schematic ( $\pm 5$ -V Power Supply)**

The feedback capacitors  $C1$  forms a pole in transfer function at Equation 1.

$$f_p = \frac{1}{2\pi R_F C_F} \quad (1)$$

The capacitors must be large enough to maintain stability but not introduce too much phase shift and amplitude attenuation at audio frequency. With a 1.2-nF capacitor, the  $f_p = 308 \text{ kHz}$ , the phase shift at 20 kHz is  $7^\circ$ , and the amplitude attenuation is 0.03 dB; this is a very good, balanced solution.



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**Figure 3. Amplifiers Schematic (±10-V Power Supply)**

Figure 3 is the ±10-V power supply application schematic. The best output linear range of OPA1612 is [−9.4 V, 9.4 V], and the common mode voltage range is [−8 V, 8 V], so in this case assume:

The output voltage swing of OPA1612  $V_{\text{swing}}$  is 9.4-V peak to peak, so the feedback resistors  $R1 = 9.4 / 3.9 \text{ mA} = 2410 \Omega$ . The bias voltage of OPA1612  $V_{\text{bias}}$  in the positive input pin should be  $6.2 \text{ mA} \times 2410 = 14.9 \text{ V}$ , which exceeds the common mode range of OPA1612 [−8 V, 8 V], and is not suitable.  $V_{\text{bias}}$  must be reduced to less than 8 V by reducing the feedback resistors R1, which also reduces the  $V_{\text{swing}}$  to its maximum allowed value of  $9.4 - V_{\text{bias}}$ .  $V_{\text{bias}} = 6.2 \text{ mA} \times R1$  and  $V_{\text{swing}} = 3.9 \text{ mA} \times R1$ , so  $R1 = 9.4 \text{ V} / (6.2 + 3.9) \text{ mA} = 931 \Omega$ , which is just a general value. This configuration generates  $V_{\text{swing}} = 3.630 \text{ V}$  and  $V_{\text{bias}} = 5.772 \text{ V}$ .

The feedback capacitors C1 forms a pole in transfer function at Equation 1.

The capacitors must be large enough to maintain stability but not introduce too much phase shift and amplitude attenuation at audio frequency. With a 620-pF capacitor, the  $f_p = 276 \text{ kHz}$ , the phase shift at 20 kHz is  $8^\circ$ , and the amplitude attenuation is 0.02 dB; this is a very good balanced solution.

Circuits I+ and I− are same, so  $R2 = R1$  and  $C2 = C1$ .

### 3.3 Difference Amplifier Design

The purpose of the difference amplifier is to convert differential signal to single ended output voltage signal and provide proper gain and enough current to drive the headphone. Like the I/V transimpedance amplifier, this second stage amplifier should be ultra-low noise and distortion to achieve excellent system SNR, THD+N and dynamic range, high slew rate to achieve excellent system transient response, high bandwidth to achieve flat system frequency response, and low quiescent current to achieve low power consumption.

The values of the resistors in the difference amplifier external circuit are determined by the output current swing of the DAC as well as the gain of first stage amplifier and maximum output voltage desired at the headphone output. One important difference between the first and second stage amplifiers is that the second stage amplifier chosen must be capable of delivering the necessary current to the headphone and remain stable into typical headphone loads that can have capacitances as high as 400 pF.

Below is a detailed example calculation for the feedback resistors and capacitors. 1.789 Vrms or 2.529 Vp-p output voltage is required for a 32-Ω headphone to achieve 100 mW rms output power capability. So the gain of the 2nd stage difference amplifier is  $V_{out} \text{ (single ended)} / V_{in} \text{ (differential)} = R_3 / R_5$ . The values of  $R_3$  and  $R_5$  cannot be too small because they will load the transimpedance amplifier, they cannot be too big because they will generate thermal noise.

For the  $\pm 5\text{-V}$  example of  $R_3 / R_5 = 2.529 / (1.685 \times 2) = 0.75$ , the calculated balanced values  $R_5 = 499 \text{ } \Omega$  and  $R_3 = 374 \text{ } \Omega$  are reasonable. Choose capacitor  $C_3 = 1.2 \text{ } \mu\text{F}$ , and the simulated system cutoff frequency is 211 kHz. The simulated total noise generated by the amplifiers and resistors is 1.010  $\mu\text{V}$  rms from 20 Hz to 20,000 Hz as shown in Figure 4. The calculated SNR is  $20 \log (1.789 \times 1,000,000 / 1.01) = 125 \text{ dB}$ .

For the  $\pm 10\text{-V}$  example of  $R_3 / R_5 = 2.529 / (3.63 \times 2) = 0.348$ , the calculated balanced values  $R_5 = 499 \text{ } \Omega$  and  $R_3 = 174 \text{ } \Omega$  are reasonable. Choose capacitor  $C_3 = 3.3 \text{ } \mu\text{F}$ , and the simulated system cutoff frequency is 273 kHz. The simulated total noise generated by the amplifiers and resistors is 0.69  $\mu\text{V}$  rms from 20 Hz to 20,000 Hz as shown in Figure 5. The calculated SNR is  $20 \log (2.529 \times 1,000,000 / 0.69) = 128 \text{ dB}$ . Figure 6 is an actual harmonic test result. The THD is dominated by the second harmonic, which is  $-119\text{dB}$ .

The maximum output current required for the 32-Ω headphone and 100 mW rms output power is  $2.529 / 32 = 79 \text{ mA}$ , which is in the best linear range of OPA1622, so OPA1622 meets this requirement.

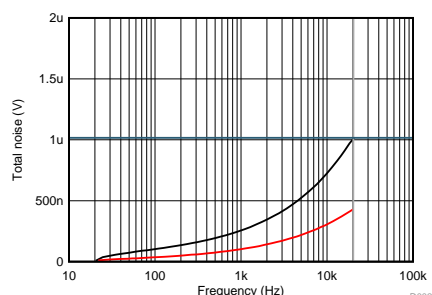
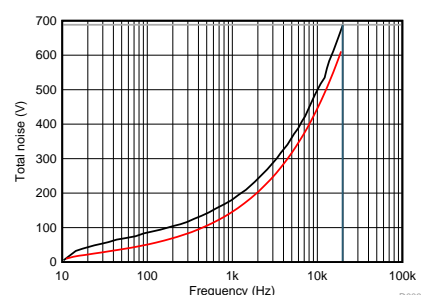
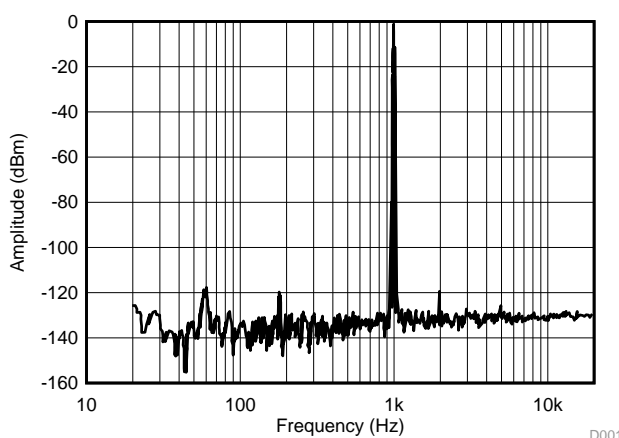
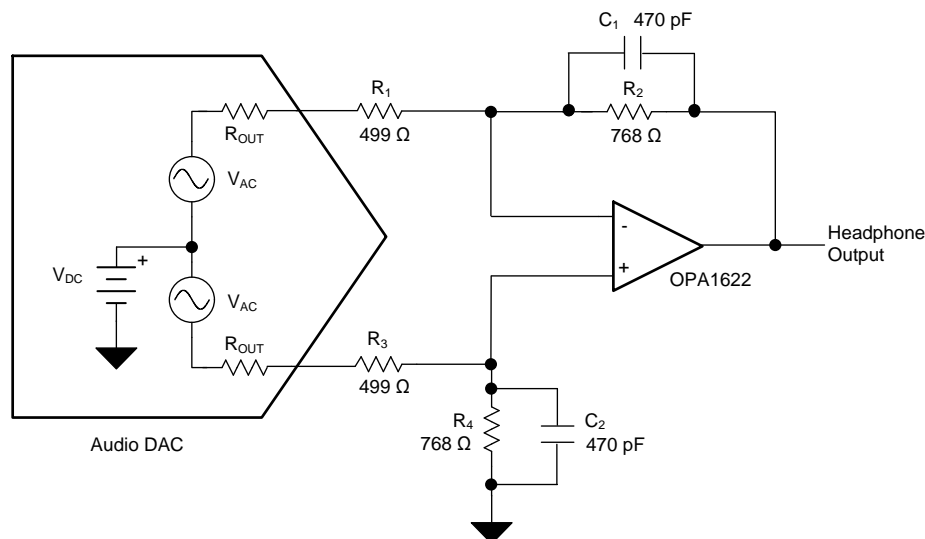

Figure 4. Output Total Noise ( $\pm 5\text{-V}$  Power Supply)

Figure 5. Output Total Noise ( $\pm 10\text{-V}$  Power Supply)


Figure 6. FFT of 5-mW, 1-kHz tone Into 32-Ω Headphone

### 3.4 Voltage Output DAC

Voltage output DAC requires less external circuitry; therefore, there are advantages in cost, power consumption, and solution size. However, the voltage output DAC has a slightly lower performance than current output configurations. Differential outputs double the output signal levels that can be delivered on a single, low-voltage supply and also allow for even-harmonics common to both outputs to be cancelled by external circuitry. A simplified representation of a voltage output audio DAC is shown in Figure 7. Two AC voltage sources ( $V_{AC}$ ) deliver the output signal to the complementary outputs through their associated output impedances ( $R_{OUT}$ ). Both output signals have a DC component as well, represented by DC voltage source  $V_{DC}$ . The headphone amplifier circuit connected to the output of an audio DAC must convert the differential output into a single-ended signal and be capable of producing signals of sufficient amplitude at the headphone to achieve reasonable listening levels.

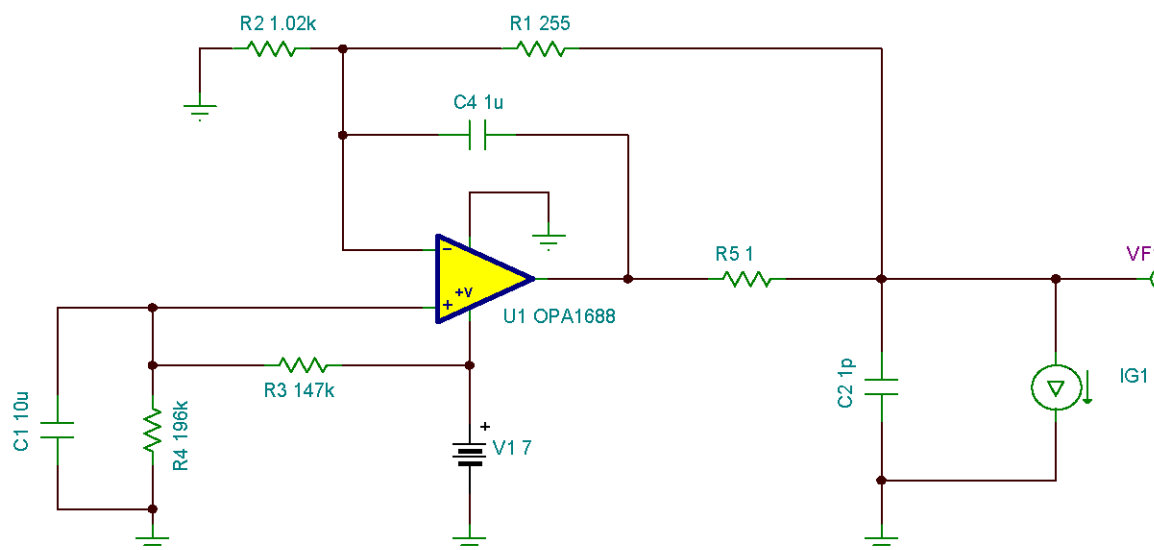


**Figure 7. Voltage Output DAC**

### 3.5 Power Supply Design

HiFi DAC requires ultra-low noise voltage reference and power supply;  $< 3 \mu\text{V}$  rms noise (20 Hz to 20,000 Hz) and high PSRR and CMRR ( $> 80 \text{ dBc}$  at 20 to 20,000 Hz) are desirable for the system. Ultra-low noise LDOs are recommended to drive the DAC and amplifiers. TI LDO TPS7A4701 is a good candidate with an output rms noise of only  $2.47 \mu\text{V}$  for 20 to 20 kHz when the output is 5 V.

There are few LDOs that meet these extreme requirements, and they are not cost effective. Using a low-noise amplifier to generate a clean power supply is a good idea. Figure 8 is the detailed schematic and simulation result to achieve this function by using the OPA1688. The output noise of this circuit is only  $0.966 \mu\text{V}$  rms from 20 Hz to 20,000 Hz.



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**Figure 8. OPA1688 Generates Ultra-Low Noise Power Supply**

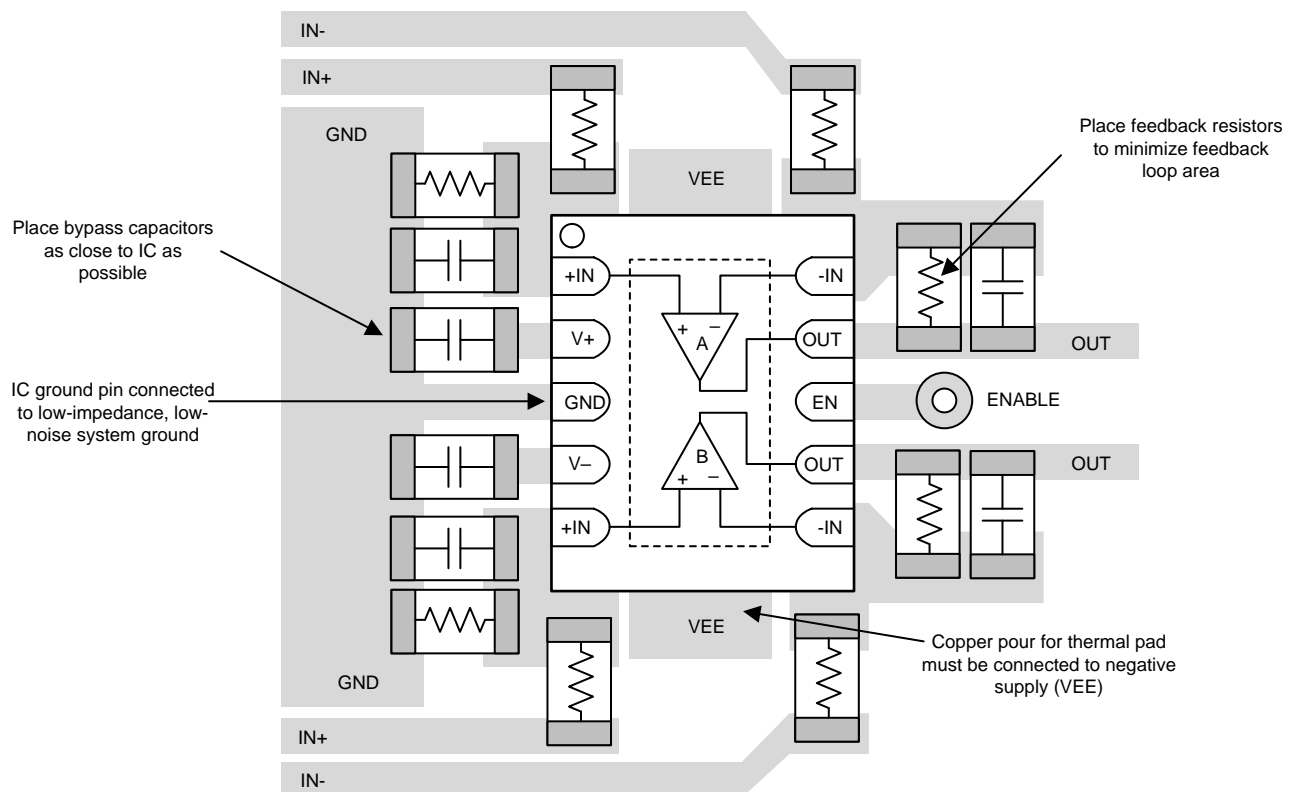


### 3.6 Layout Guidelines

For the best operational performance of the audio circuits, good PCB layout practices are required, which include:

- Connect low-ESR ceramic bypass capacitors between each supply pin and ground—placed as close to the device as possible. The bypass capacitors reduce the coupled noise by providing low impedance power sources local to the analog circuitry.
- Connect the ground pins to a low-impedance, low-noise system reference point.
- Place the external components as close to the device as possible. Keep feedback resistors close to the inverting input to minimize parasitic capacitance and the feedback loop area.
- Keep the length of input traces as short as possible. Always remember that the input traces are the most sensitive part of the circuit.
- For proper amplifier function, connect the package thermal pad to the most negative supply voltage (V<sub>-</sub>).
- The differential traces should be routed as differential signal pairs to reject the common mode noise.

Figure 9 is a typical layout example for an amplifier.



**Figure 9. Typical Layout Example for Amplifier**

## 4 Noise and THD Optimizations

People have different preferences, some care more about bass, some care more about human voice, some care more about piano sound effects, so there is no one perfect audio system satisfies everyone's subjective preferences. However, all of the objective preferences (specifications) are measurable, if some of the measured specifications don't meet the designer's expectation, tuning is necessary and effective. The most frequent and complex problems are THD+N and SNR degrading, other specifications degrading rarely occurs and is easy to be optimized according to Section 2, so this section only analyzes the noise and THD optimizations.

## 4.1 Noise Optimization

Audible noise is a frequent and critical problem in HiFi circuit. Resistors, capacitors, power supply, ground, space radiation, amplifiers themselves, DAC itself, and audio digital source file are all noise sources. If the output noise is higher than expectation, check the sources one by one:

1. Higher resistance has higher resistance thermal noise and reducing the resistance reduces the total noise if the resistance thermal noise is a major contributor. However, the resistors used in this article are already low enough, so reducing the resistances is not helpful to reduce noise in this case. 0.1% precision and thin film resistors are recommended for the best common mode rejection and gain balance.
2. Ultra-low noise power supply is always helpful for this noise-sensitive application. Switching power supply cannot be used to directly drive the DAC and amplifiers because the supply has obvious switching noise, ripple and noise floor, instead, ultra-low noise LDO or amplifier is preferred. TI LDO TPS7A470x series are a cost-effective solution with RMS noise of only 2.47  $\mu\text{V}$  (20 Hz to 20 kHz) when the output is 5 V. However, even ultra-low noise LDO or amplifier must be carefully designed with low-ESR ceramic decoupling capacitors close to the power supply pins, the current loop areas as small as possible, and short and wide power supply traces.
3. Grounding is critical for noise-sensitive applications. All of the signals and noises on the board go through the common ground together, and each signal and noise component interfere with each other. this combined ground actually is noisy. Good grounding reduces the signal loop area and impedance, which minimizes interference.
4. Current generates magnetic field. Space radiation cannot be ignored even though the audio frequency is as low as 20 kHz. Keep the audio signal traces far away from the noise sources (switching power supplies, digital chips, digital traces, clocks, RF circuits, and so on).
5. OPA1612 is a verified, ultra-low noise, operational amplifier; however, sometimes the device's output noise is higher than expected. To get the normal noise floor, the device's input noise should be low, grounding should be good, power supply should be clean, decoupling capacitors should be close to its pins, and feedback circuit loop area should be small.
6. PCM1794A is also a verified, ultra-high, performance DAC; however, sometimes the device's output noise is higher than expected. To get the normal noise floor, the device's grounding should be good, power supply should be clean, decoupling capacitors should be close to its pins, and its clock should be clean.
7. Increase the gain of the I/V transimpedance amplifier, and decrease the gain of driver amplifier. However, these adjustments are only a little bit helpful because the adjustable range of output voltage swing is limited unless the power supply voltage for the amplifier could be increased.
8. The digital music file source should be very high quality and lossless. .wav, APE, and FLAC files are preferred while mp3 is not preferred because mp3 is compressed and very-low quality.
9. Correctly configure the audio analyzer and test cables.

## 4.2 THD+N Optimization

THD+N is a critical specification in HiFi circuit. Both total harmonic distortion and noise should be ultra-low. The noise optimization has been analyzed in [Section 4.1](#), so this section only analyzes the THD.

1. High THD might be caused by the DAC or amplifiers themselves. Ensure the DAC's and amplifier's external components and traces are well routed with clean power supplies. Switching power supplies are not recommended to directly drive the devices.
2. The THD is related with the output power and headphone impedance, and the output power and headphone impedance should be reasonable. The gain of each stage in the whole audio signal chain should be well distributed. If any one of the stages was too high, the output voltage might be too high, which will worsen THD.
3. C0G/NP0-type ceramic capacitors are recommended for the feedback circuits because these capacitors have better performance when the audio signal voltage across them is high. Other types of ceramic capacitors (X7R, X5R, and so on) will produce large amounts of distortion.
4. The digital music file source should be very high quality; mp3 is compressed and very-low quality.
5. Correctly configure the audio analyzer and test cables.

## 5 References

1. Texas Instruments, [OPA161x SoundPlus™ High-Performance, Bipolar-Input Audio Operational Amplifiers](#), OPA1611, OPA1612 Datasheet (SBOS450)
2. Texas Instruments, [OPA1622 SoundPlus™ High-Fidelity, Bipolar-Input, Audio Operational Amplifier](#), OPA1622 Datasheet (SBOS727)
3. Texas Instruments, [PCM1794A 24-Bit, 192-kHz Sampling, Advanced Segment, Audio Stereo Digital-to-Analog Converter](#), PCM1794A Datasheet (SLES117)
4. Texas Instruments, [Distortion and source impedance in JFET-input op amps](#), Technical Brief (SLYT595)

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