

A High-Power High-Fidelity Headphone Amplifier Design

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Abstract. This circuit is designed to convert the differential output current of an audio digital-to-analog converter (DAC) into a single-ended voltage capable of driving low impedance headphones. Two op amps are used as transimpedance amplifiers which convert the DAC output current to a differential voltage. A difference amplifier then converts the differential voltage to single-ended. A high-power, high-fidelity two-channel audio op amp was used in the difference amplifier to directly drive stereo headphone loads at output powers > 100 m W.

Theory of Operation

Many audio digital-to-analog converters (DACs) show improved linearity when used in the current output mode. These DACs provide a differential output current that varies with the input digital audio signal. A headphone output circuit must convert this differential current to a single-ended voltage signal capable of driving headphones at reasonable listening levels[1-3]. A simplified schematic of the circuit used to accomplish this function is shown in Fig. 1.

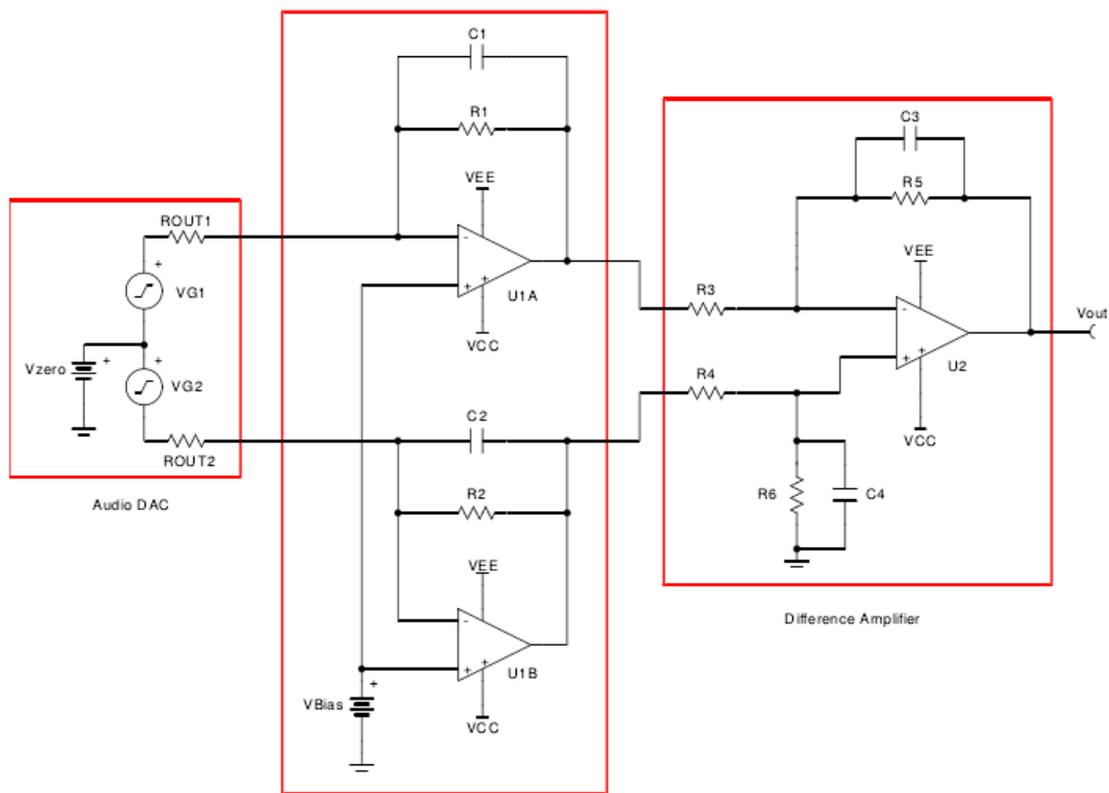


Figure 1. Simplified Schematic of DAC Output Circuit

Two transimpedance amplifiers are used to convert the differential output current from the audio DAC to a differential output voltage. Although the audio DAC has a current output, it is more accurately approximated by differential voltage sources with series resistances. There may also be an offset voltage when the DAC code is 0, represented by V_{zero} in Fig. 1.

Once the differential output current from the DAC has been converted to a differential voltage by the transimpedance amplifiers, the differential voltage is converted to a single-ended voltage by the difference amplifier. The amplifier must also be capable of driving the headphone impedance [4].

Transimpedance Amplifiers. From a noise standpoint, the total DAC output circuit consists of two amplifier stages in series in the signal path. Fig. 3 is a simplified block diagram of the signal path, with the two stages represented by amplifiers A_1 and A_2 . Each amplifier has two gains: the gain applied to the input signal, G_S , and a noise gain, G_N , which is the gain applied to the amplifier's intrinsic noise, en . The total signal gain of the circuit is the individual signal gains, G_{S1} and G_{S2} multiplied together[5].

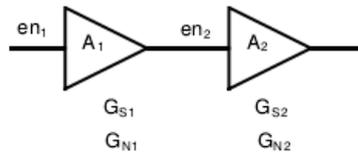


Figure 2. Symbolic Representation of Cascaded Amplifiers

Determining the total noise of the circuit is not quite as simple. The output noise of amplifier A_1 is multiplied by the noise gain of amplifier A_1 and the signal gain amplifier A_2 . Therefore, the total output noise is shown in Equation 1.

$$en_r = \sqrt{(en_1 G_{N1} G_{S2})^2 + (en_2 G_{N2})^2} \tag{1}$$

Although the noise gain will always be equal to or greater than 1, the signal gain of an amplifier can be made less than 1. This offers an interesting opportunity to reduce the overall noise of the circuit. If the signal gain of the second stage can be made much less than 1, the amount of gain in the first stage can be maximized and the noise of the first stage amplifier dominates the total noise[6]. For this reason, the gain of the transimpedance amplifiers should be as high as possible and the difference amplifier is configured for a signal gain less than one.

The appropriate gain of the transimpedance amplifiers is determined by the output current from the audio DAC and the output voltage swing capability of the op amp selected. Fig. 3 shows a simplified model of a popular audio DAC.

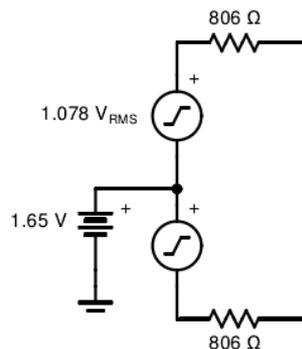


Figure 3. Simplified Model of a Popular Audio D/A Converter

In order to calculate the feedback resistors of the transimpedance amplifiers, the maximum ac output current from the DAC must be determined. For this analysis the contributions of the 1.65-V offset can be ignored. The peak single-ended output current is shown in Equation 2.

$$i_{ec(MAX)} = \frac{1.078 V_{RMS} \times \sqrt{2}}{806} = 1.891467mA_p \tag{2}$$

The output voltage of a transimpedance amplifier is given in Equation 3.

$$|V_{OUT}| = R_F |i_{IN}| \tag{3}$$

RF is the value of the feedback resistor of the transimpedance amplifier. The maximum value of RF is determined by the power supply voltages and the linear output swing of the op amp used.

Bias Voltage. When the DAC output code is zero, there is still an output current due to the offset of the DAC. In Fig. 2 a voltage, VBias, is applied to the non-inverting inputs of the transimpedance amplifiers to center their outputs at 0 V when the DAC code is zero. Fig. 4 shows the effective circuit when the DAC output code is zero.

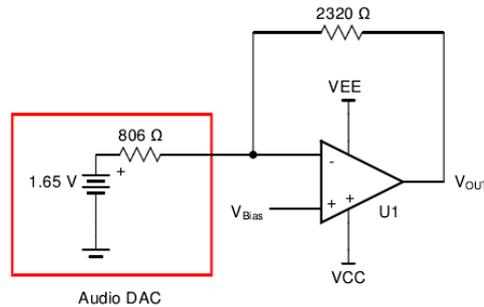


Figure 4. Simplified Schematic for Bias Voltage Calculation

The appropriate voltage for VBias may be calculated from Equation 4. As Equation 5 is show.

$$V_{OUT} = 0V = V_{BIAS} \left(1 + \frac{2320\Omega}{806\Omega} \right) - 1.65 \left(\frac{2320\Omega}{806\Omega} \right) \quad (4)$$

$$V_{Bias} = 1.225$$

(5)

A resistor divider may be used to provide the bias voltage to the non-inverting inputs of the transimpedance amplifiers, as shown in Fig. 5.

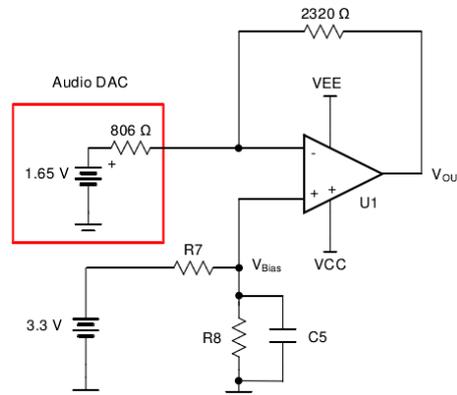


Figure 5. Bias Voltage Circuit for Transimpedance Amplifier

A 3.3-V supply is assumed for the resistor divider. R7 and R8 may be calculated to provide the desired bias voltage, as shown in Equation 6.

$$V_{Bias} = 1.225V = 3.3V \frac{R_8}{R_8 + R_7} \quad (6)$$

$$R_7 = 1.693878R_8$$

A capacitor must be placed in parallel with R8 to prevent noise from the 3.3-V supply from entering the signal path. The corner frequency produced by capacitor C5 is shown in Equation 7.

$$f_c = \frac{1}{2\pi(R_7 || R_8)C_5} \quad (7)$$

The corner frequency should be less than 20Hz to attenuate supply noise within the audio bandwidth. C5 is then calculated, as shown in Equation 8.

$$C_5 \geq \frac{1}{2\pi(R_7 || R_8)f_c} \geq \frac{1}{2\pi(9243.182k\Omega)(20\text{Hz})} \geq 0.861\mu\text{F} \tag{8}$$

2.2 μF is selected as the value for C5. Larger capacitors may be used but they may require larger PCB footprints and will extend the start-up time of the circuit.

Simulation

The simulation schematic shown in Fig. 6 is used for the noise and transfer function simulations. The audio DAC is represented on the left of the schematic in a blue rectangle. For many analyses in TINA-TI only a single input signal source can be accommodated, therefore a voltage controlled voltage source (VCVS) with a gain of 1 allows the DAC output voltage to be differential without requiring two voltage sources.

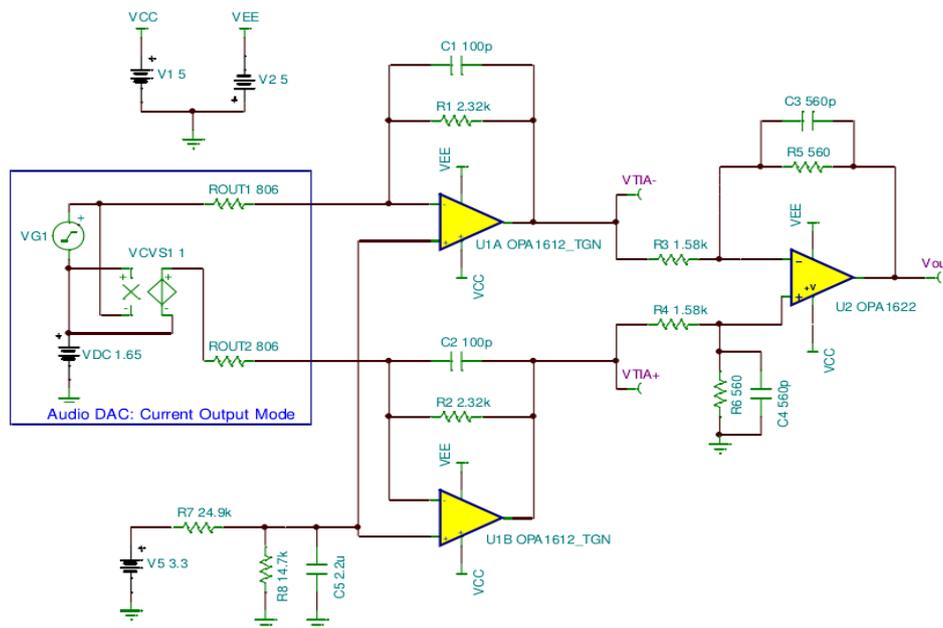


Figure 6. TINA-TI Simulation Schematic for Transfer Function, Transient, and Noise Analysis

Transfer Function. An AC transfer characteristic analysis was used to determine the magnitude and phase response of the circuit. At 20 k Hz, the magnitude response was down -0.0105d B and the phase had deviated -4.02 degrees. Fig. 7 shows the circuit magnitude and phase response plotted using an AC transfer characteristic simulation.

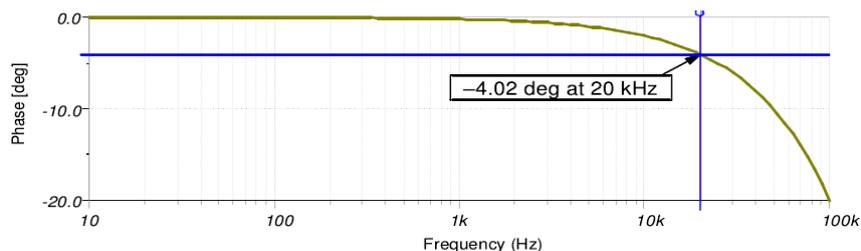


Figure 7. Circuit Magnitude and Phase Response Plotted

Transient Response. A transient simulation was run with a 1 k Hz full-scale sine-wave input of $\pm 1.078 \text{ VRMS}$ (1.525 VPP). As desired the transimpedance stages swing roughly 4.4 Vp and stay

0.6 V away from the supplies for best linearity performance. The output stage produces the desired 2.2 VRMS(3.111 VPP) output level. Fig. 8 shows the circuit magnitude and phase response plotted using an AC transfer characteristic simulation.

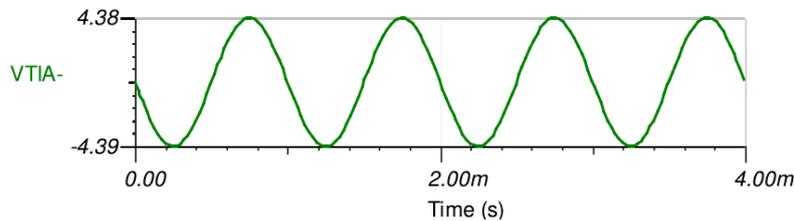


Figure 8. Circuit Magnitude and Phase Response Plotted

References

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