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TI Precision Designs: Verified Design
Active Volume Control for Professional Audio

TI Precision Designs

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Circuit Description

This split-supply, high-performance volume control circuit attenuates a professional line-level audio signal with minimal distortion and noise. An input buffer preserves the behavior of the system independent of the audio input source impedance. A radio frequency (RF) filter on the circuit front end removes noise from outside the audio band, while a bidirectional transient voltage suppressor (TVS) diode protects against overvoltage spikes.

Design Resources

Design Archive	All Design files
TINA-TI™	SPICE Simulator
OPA1604	Product Folder

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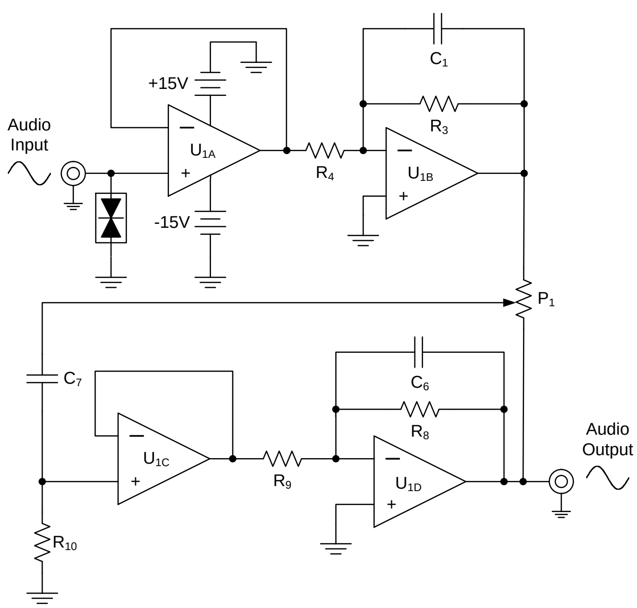

1 Design Summary

The design requirements are as follows:

- Supply Voltage: ±15 V
- Input: Professional line-level audio signal (+4 dBu / 1.228 V_{RMS})
- Input impedance: 20 Ω
- Output: Professional line-level audio signal (+4 dBu / 1.228 V_{RMS})
- Total harmonic distortion + noise (THD+N) ratio at 1 kHz: 0.0005%
- Ideal gain characteristic: -20dB over full potentiometer rotation
- Gain deviation (30% to 100% potentiometer rotation): ±1.5 dB
- “Off” gain: -100 dB

The design goals and performance are summarized in Table 1. Figure 1 depicts the measured transfer function of the design.

Table 1. Comparison of Design Goals, Simulation, and Measured Performance

	Goal	Simulated	Measured
THD+N ratio at 1kHz	0.0005%	0.000275%	0.000481%
Gain deviation (regulated region)	1.5 dB	1.32 dB	1.00 dB
“Off” gain	-100 dB	-134.4 dB	-103 dB

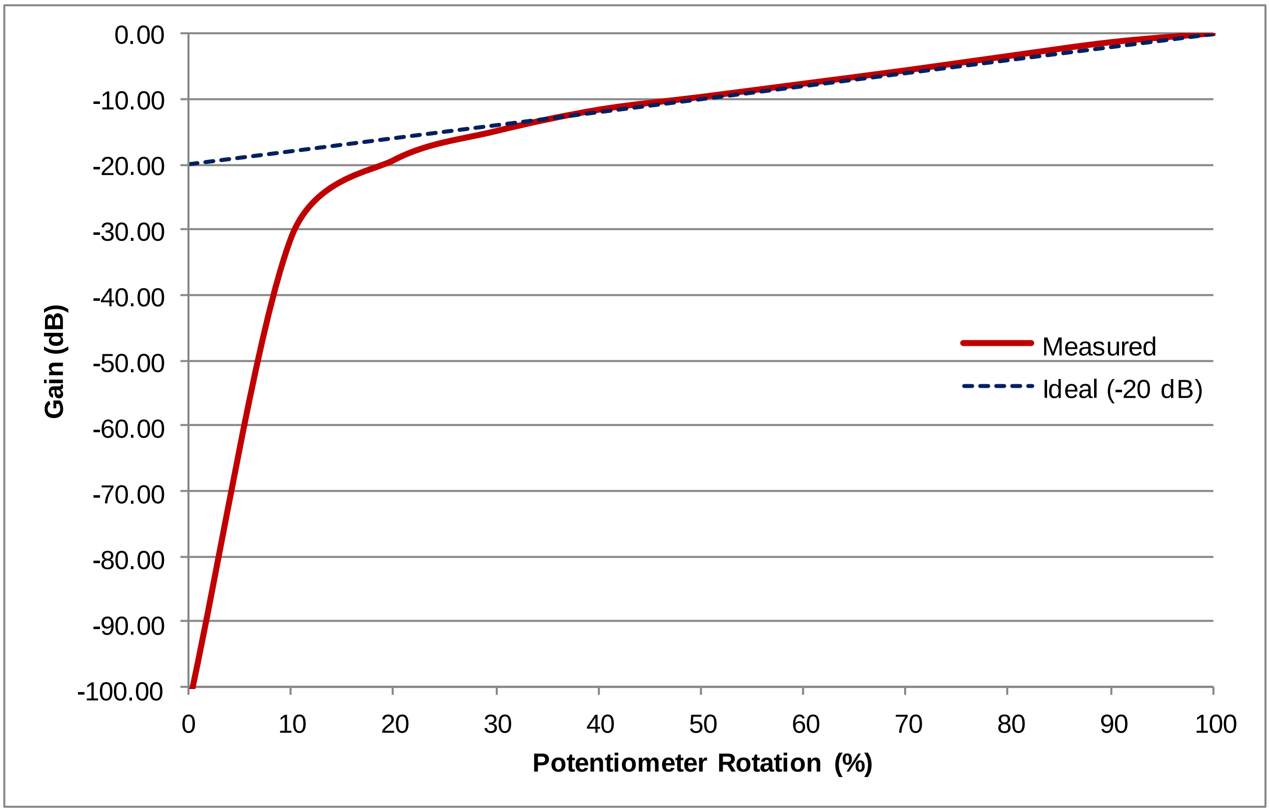

Figure 1: Measured Gain Characteristic

2 Theory of Operation

A more complete schematic for this design is shown in Figure 2. The transfer function of the circuit is based on the first stage gain (set by the ratio of R_3 and R_4), the rotation of potentiometer P_1 (expressed as a decimal), and the second stage gain (set by the ratio of R_8 and R_9). TVS diode D_1 protects the circuit from harmful transient energy. A second order low pass filter which attenuates energy in the RF frequencies is created by the audio signal source impedance, D_1's junction capacitance, R_5, and C_5. The remaining components are used for ac coupling, amplifier input biasing, stability compensation, and power supply decoupling.

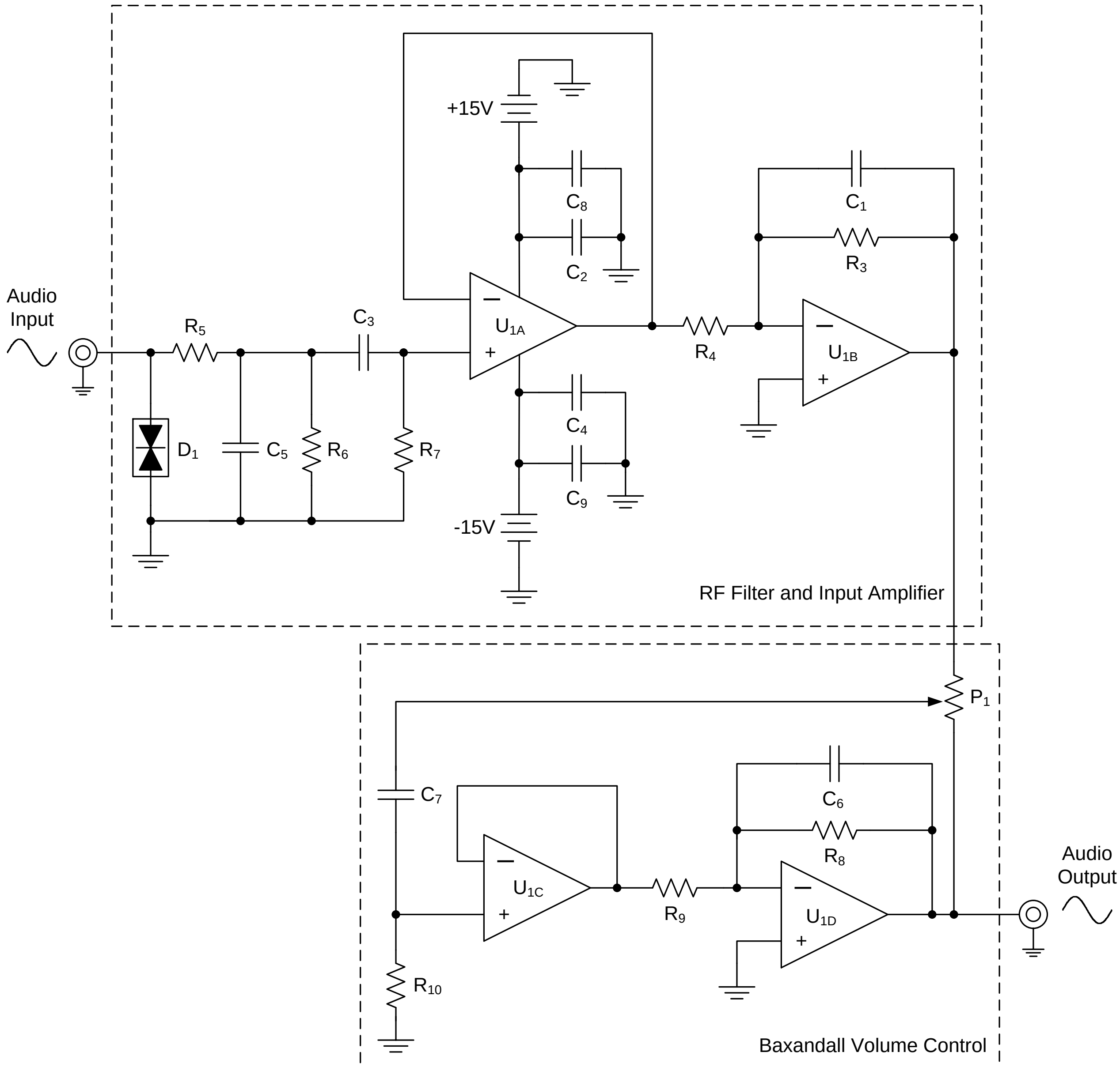

Figure 2: Complete Circuit Schematic

The transfer function for this design is defined by the following equation:

$$V_{OUT} = V_{IN} * \left(\frac{R_3}{R_4}\right) * \left[\frac{P_{1_{Rotation}}}{\left(1 - P_{1_{Rotation}}\right) + \frac{R_9}{R_8}}\right] \tag{1}$$

2.1 Volume Controls

The volume control is a critical component of any audio system. Because of the dynamic nature of audio, and the amount of variance in the output amplitudes of different signal sources, it is necessary for a user to have control over the amount of gain provided by an audio circuit. The volume control should contribute no significant distortion or noise in order to preserve the integrity of the source audio signal.

Human hearing spans a large dynamic range, so units of decibels (dB) are typically used to describe the power of audio signals. It is desirable for a volume control to have a gain characteristic which is linear in dB since the result is a very natural change in perceived volume as the user rotates the volume knob [1].

2.1.1 Potentiometer Characteristics

Potentiometers, often called pots, are by the far the most common component used to control volume, and several different types of pots exist for this purpose. The three most common types, also called tapers, are the linear taper, logarithmic (or audio) taper, and reverse logarithmic (or reverse audio) taper. Figure 3 shows an approximate resistance characteristic of these tapers.

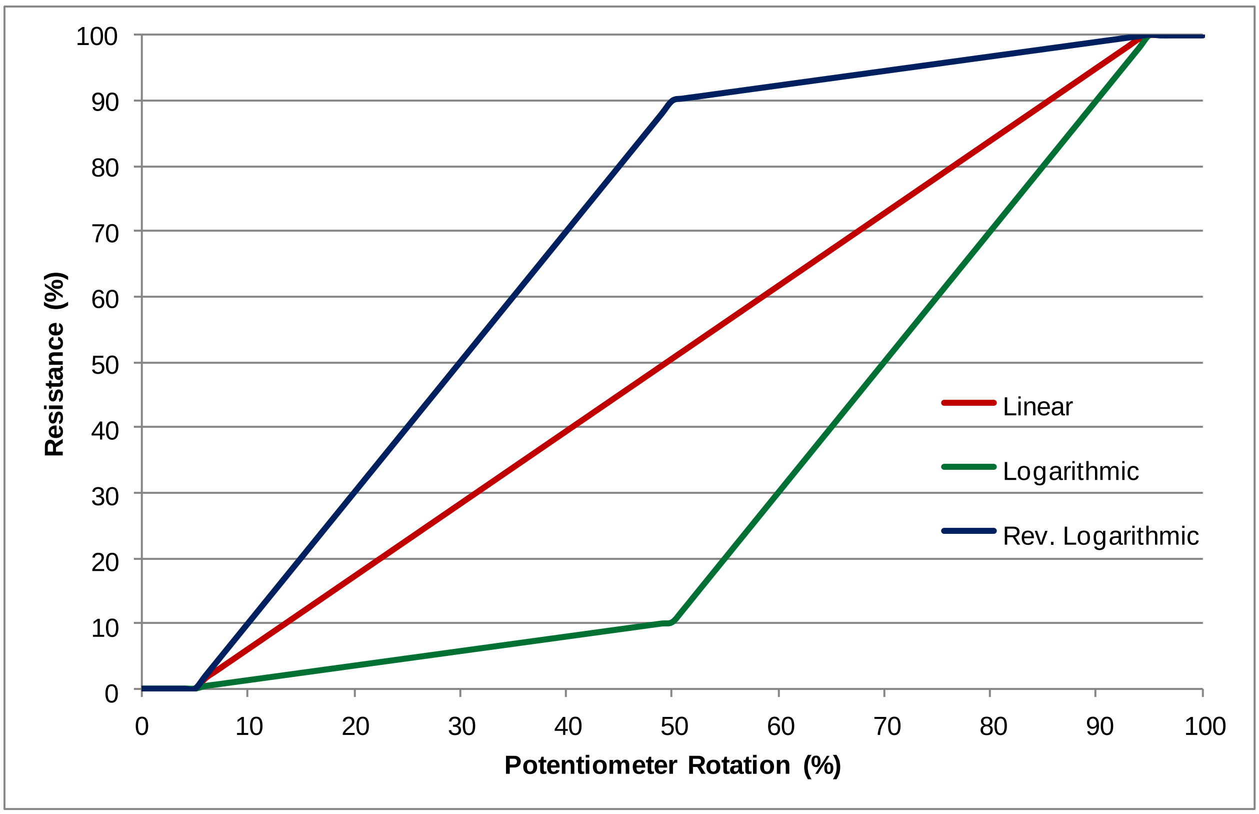

Figure 3: Common Potentiometer Characteristics

Linear pots, usually given the code letter ‘B,’ are simple devices where the amount of resistance is proportional to the amount of rotation. Logarithmic pots, usually given the code letter ‘A,’ roughly approximate a logarithmic response by combining two linear slopes. Reverse logarithmic pots, usually given the code letter ‘C,’ follow the same behavior as logarithmic pots but are constructed in reverse. As you can see, any of these potentiometers on their own do not create a very accurate approximation of a true logarithmic response, at least for professional audio applications [1].

2.2 Baxandall Active Volume Control

Several methods have been used in the attempt to better approximate a linear-in-dB response using pots. However, no solution provides the performance, flexibility, and simplicity of the circuit initially presented by Peter Baxandall in 1980 as part of an article in Wireless World magazine [1]. For this reason, a modified version of his circuit was chosen as the primary component of this reference design. Figure 4 shows the basic schematic of this circuit.

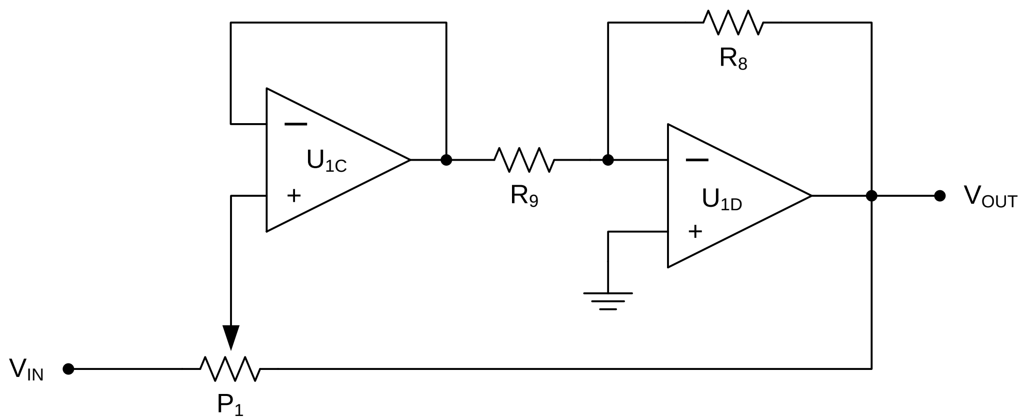

Figure 4: Baxandall Active Volume Control [1]

The Baxandall active volume control circuit is a type of shunt-feedback control with two main advantages over other solutions. First, it achieves excellent logarithmic behavior with a linear pot, and second, its transfer function is not a function of the pot track resistance or any other discrete resistances. Rather, the gain characteristic is only a function of the percentage of pot rotation and the maximum gain set by the ratio of two resistors. This allows a standard-tolerance pot to be used with excellent results, and a dual linear pot can give good matching between channels of a stereo system [1]. This design describes a single channel solution and therefore a single pot is used, but the same circuit can simply be copied for a stereo system.

Active volume controls in general have several other advantages over their passive counterparts. The use of amplifiers allows for gain early in the signal chain, improving noise performance. The current drive capabilities of the amplifiers allow low resistance values to be used, which minimizes Johnson noise and capacitive crosstalk. Finally, the high input impedance and low output impedance of the amplifiers ensures a robust design which, with some minor exceptions, maintains its performance independent of the source and load impedance [1].

2.2.1 Baxandall Active Volume Control Transfer Function

The simplicity of Baxandall's circuit allows for a straightforward transfer function analysis. For this analysis, potentiometer P_1 is replaced with two discrete resistors: R_X, which represents the percentage of pot resistance after the wiper, and R_{1-X}, which represents the percentage of pot resistance before the wiper. Together these two resistors represent the total possible span of pot rotation. Figure 5 shows the modified circuit schematic.

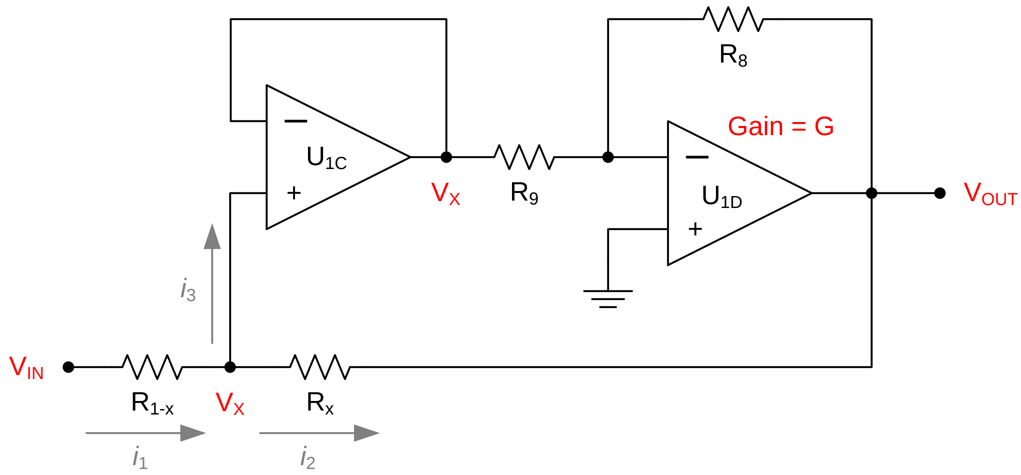

Figure 5: Modified Baxandall Volume Circuit for Transfer Function Analysis

To analyze the transfer function, first define the voltage at the wiper as V_X. Since amplifier U_{1C} is configured as a non-inverting buffer, the voltage at the output of U_{1C} is also equal to V_X. V_X is applied as the input to amplifier U_{1D}, which is configured as an inverting amplifier with gain G. Therefore, the output voltage V_{OUT} must equal the product of V_X and G. This relationship can be solved for V_X and written as shown in Equation 2. A negative sign is necessary to account for the inverting configuration.

$$V_X = -\frac{V_{OUT}}{G} \tag{2}$$

Next, Kirchoff's current law is used to analyze the current flow at the wiper. This law states that the sum of the currents flowing into a node equal the sum of the currents flowing out of a node, so these currents can be written as shown in Equation 3.

$$i_1 = i_2 + i_3 \tag{3}$$

Current i_3 is the current flow into the positive input of amplifier U_{1C}. Assuming that U_{1C} is an ideal amplifier, it has infinite input impedance and therefore no current can flow in that direction. Since i_3 must equal zero, Equation 3 can be simplified to Equation 4.

$$i_1 = i_2 \tag{4}$$

Ohm's Law can now be applied to currents i_1 and i_2, and Equation 4 can be rewritten in terms of V_{IN}, V_X, V_{OUT}, R_{1-x}, and R_x as shown in Equation 5.

$$\frac{V_{IN} - V_X}{R_{1-x}} = \frac{V_X - V_{OUT}}{R_x} \tag{5}$$

Using the relationship from Equation 2, V_X can be substituted for ($-V_{OUT}/G$). Equation 6 shows the new equation after making the substitution.

$$\frac{V_{IN} + \frac{V_{OUT}}{G}}{R_{1-x}} = \frac{-\frac{V_{OUT}}{G} - V_{OUT}}{R_x} \tag{6}$$

Equation 6 can be solved for V_{OUT}/V_{IN}, and the transfer function can be written as shown in Equation 7.

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_x}{R_{1-x} + \frac{1}{G}} \tag{7}$$

Amplifier U_{1D} is configured as an inverting amplifier, so its gain G is equal to R_8/R_9. After substituting in for G in Equation 7, the transfer function can be written as shown in Equation 8.

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_x}{R_{1-x} + \frac{R_9}{R_8}} \tag{8}$$

The transfer function versus pot rotation was plotted to verify proper circuit behavior, shown in Figure 6. The ideal (-20 dB) gain characteristic is overlaid for comparison.

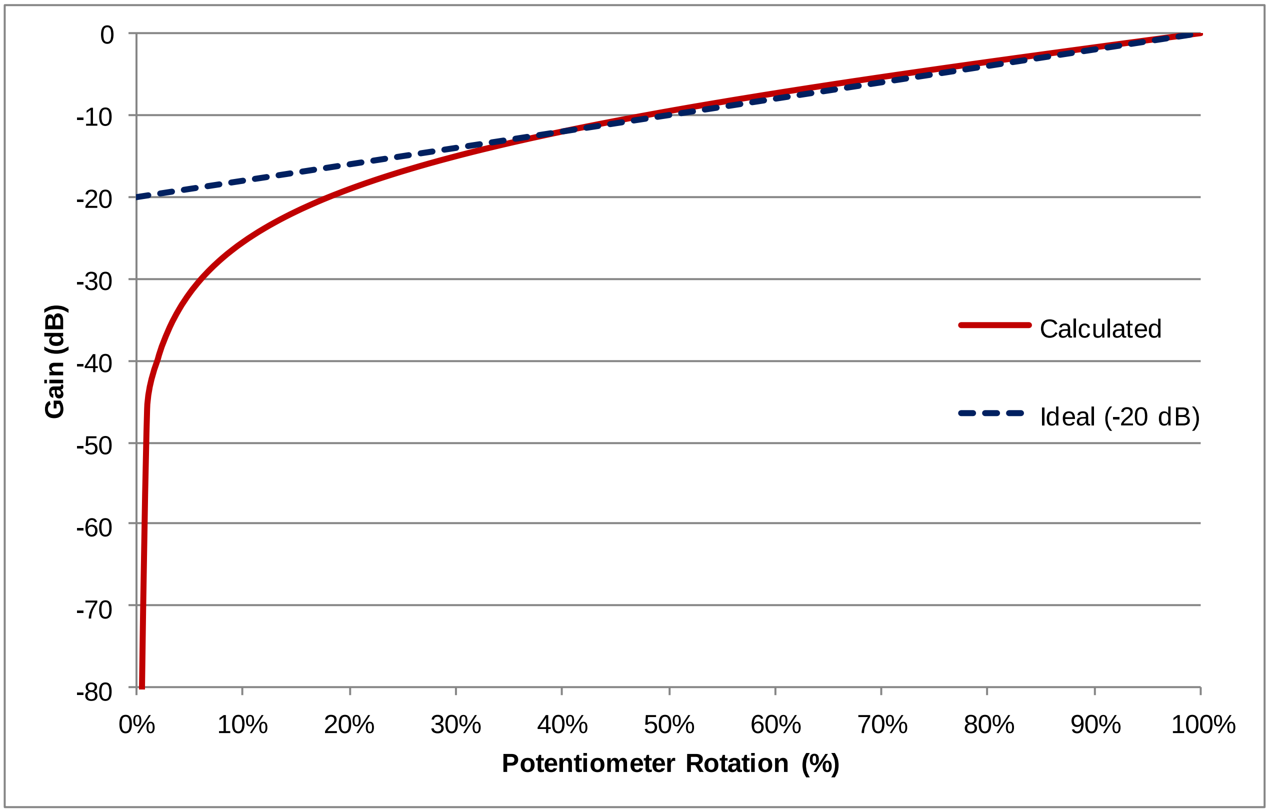

Figure 6: Calculated Baxandall Volume Control Response

2.3 RF Filter and Input Amplifier

A passive second-order low pass filter at the input of the circuit attenuates unwanted noise from outside the audio band. This filter is made up of the input source impedance R_{IN}, the junction capacitance of TVS diode D_1, as well as R_5 and C_5.

Next in the signal path is amplifier U_{1A}, configured as a non-inverting buffer. While the audio input source impedance in this design is well-defined, in the real world an audio system will have to interface with many different types of inputs. A buffer amplifier is necessary in order to preserve the behavior of the system independent of the audio input source impedance R_{IN}.

The last stage of the input circuit consists of amplifier U_{1B}, configured as an inverting amplifier with gain equal to R_3/R_4. This amplifier serves to counteract the inherent phase inversion of the Baxandall volume control stage and to provide additional gain if required. In this design, no additional gain is used.

Figure 7 shows the basic schematic of this circuit.

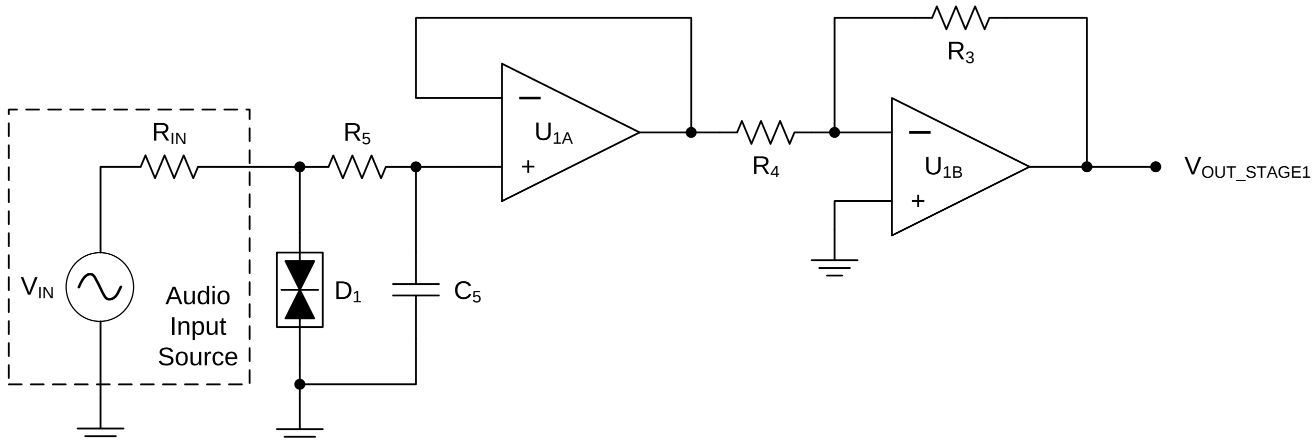

Figure 7: RF Filter and Input Amplifier

2.3.1 RF Filter Transfer Function

The RF filter at the input of the circuit should provide significant attenuation at frequencies outside the audio band while preserving the circuit's audio frequency gain and phase performance. 400 kHz is selected as the cutoff frequency for the filter. Figure 8 shows the RF filter schematic, including R_{IN} and the equivalent TVS diode junction capacitance C_{D1}.

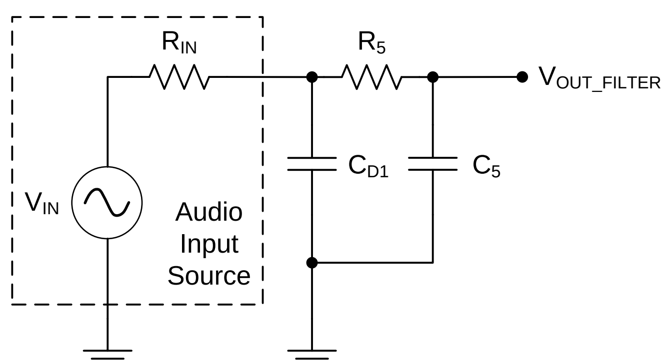

Figure 8: RF Filter Equivalent Schematic

The transfer function of the second-order low pass filter in the Laplace domain is given in Equation 9.

$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{1 + s * (R_{IN}C_{D1} + R_{IN}C_5 + R_5C_5) + s^2 * (R_{IN}C_{D1}R_5C_5)} \quad (9)$$

This function is not trivial to solve in order to find the required component values! Instead, a numerical approach was used in order to easily arrive at the correct result with minimal calculations. Fortunately, the values of R_{IN} and C_{D1} are given, and a reasonable value for R_5 can be chosen without calculation. This leaves only C_5 to calculate.

R_{IN} is specified at 20 Ω, and C_{D1} is listed in the TVS datasheet as equal to 1.476 nF. 100 Ω is chosen for the value of R_5, as the resistor is in the signal path and should be as low of a resistance as possible to minimize noise. Knowing these values, the filter gain at 400 kHz versus C_5 capacitance can be plotted to determine a suitable value for C_5. This response is shown in Figure 9.

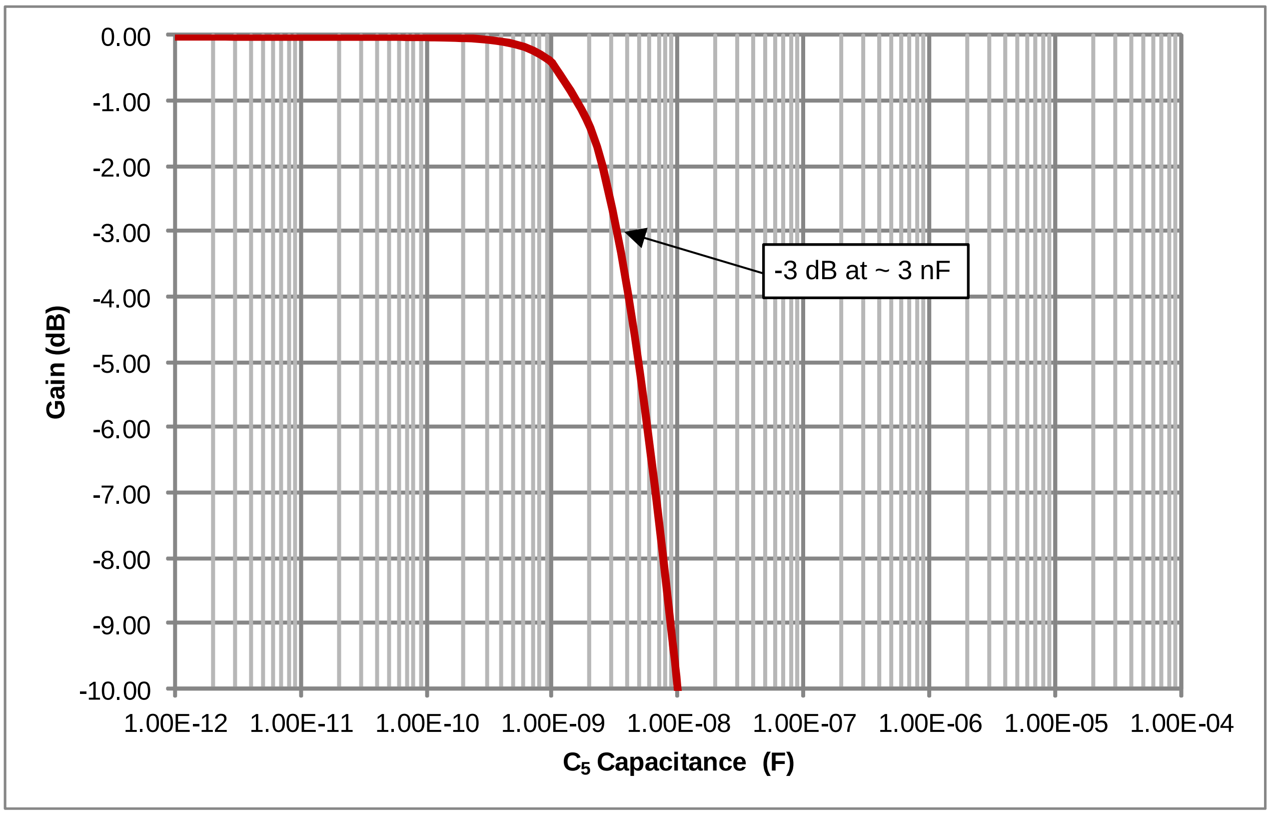

Figure 9: RF Filter Gain at 400 kHz versus C_5 Capacitance

The filter was found to have the correct response at 400 kHz when C_5 has a value of approximately 3 nF. The nearest standard capacitor value of 3.3 nF was selected as the real value. The full transfer function of the filter was then plotted to verify functionality, as shown in Figure 10.

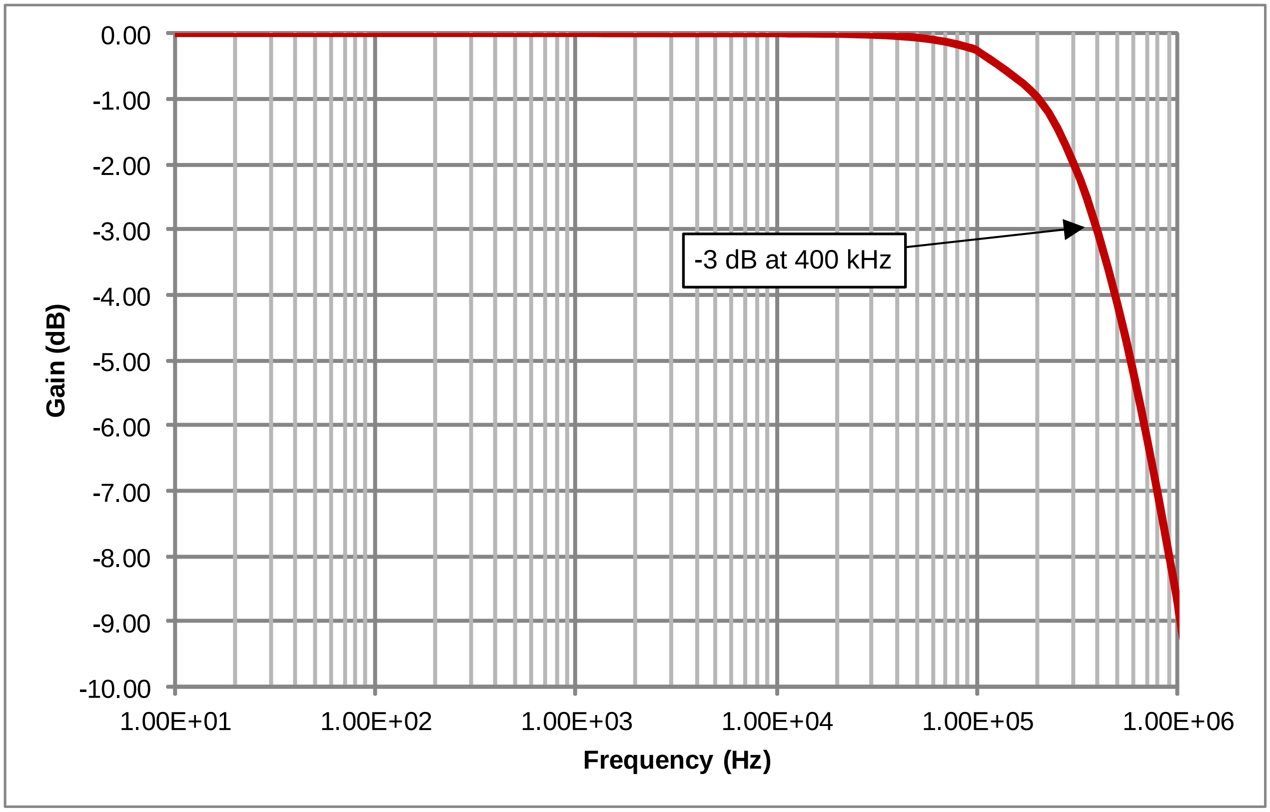

Figure 10: RF Filter Calculated Frequency Response

3 Component Selection

3.1 Amplifier Selection

This volume control circuit must provide accurate attenuation of the input audio signal while introducing as little distortion or noise as possible. Therefore, the amplifier selected must have very low distortion and noise performance in the audio frequency range. A wide supply voltage range is also required, as most professional audio circuits use large split supplies in order to avoid output clipping. Low quiescent current and relatively low cost are also desirable qualities which help to maintain an efficient design.

The OPA1604 is an excellent choice for this high-performance audio application, with total harmonic distortion + noise (THD+N) of only 0.00003% and input voltage noise density of 2.5 nV/√Hz. The amplifier can utilize power supply voltages up to ±18 V while consuming only 2.8 mA of quiescent current per channel, and its reasonable price point ensures that the total solution cost remains competitive.

3.2 Passive Component Selection

3.2.1 Resistor Selection

The type of resistors used in an ultra-low distortion audio circuit can have a significant impact on the circuit's overall performance. Real resistors have a certain amount of nonlinearity, which results in unwanted contributions to distortion and noise [2]. The most common sources of resistor nonlinearity are temperature coefficient of resistance (TC_R), which describes how the resistance changes as a function of temperature, and voltage coefficient of resistance (VC_R), which describes how the resistance changes as a function of applied voltage.

Two of the most common types of surface mount resistors are thick film and thin film. Thin film resistors typically perform better than thick film resistors, but thin film resistors also typically cost several times as much. When high-level audio signals are involved, the lower VC_R and TC_R of thin film resistors become critical to achieving ultra-low distortion performance.

This design, however, only deals with line-level signals with nominal amplitude of 1.228 V_{RMS}. At this signal level, thick film resistors are able to achieve excellent performance. All resistors on the board are thick film, ±1% tolerance, ¼ watt devices in a 1206 size. Packages smaller than 1206 are not recommended, as resistors of smaller physical size have higher dynamic thermal impedances and therefore have higher signal-dependent nonlinearity.

3.2.2 Capacitor Selection

Like resistors, capacitors also have a voltage coefficient (VC_C), which describes how the capacitance changes as a function of applied voltage. This change in capacitance results in unwanted distortion [3], so any capacitors in the audio signal path which can be subjected to significant voltages should have low VC_C. C_5, a capacitor in the input RF filter, is the only such device in this design, so an NP0-type capacitor is used. All other capacitors for ac coupling and power supply bypass are of type X7R.

3.2.3 Potentiometer Selection

Other than the linear taper, the characteristics of the potentiometer selected for this design are not critical as all of its electrical mismatches are canceled out by the design of the circuit. A linear taper, rotary potentiometer with ±20% tolerance and PCB mount termination was selected for this application.

4 Simulation

The TINA-TI™ schematic shown in Figure 11 includes the circuit values obtained in the design process. A load resistance of 100 kΩ is added to simulate the input resistance of the audio analyzer which will be used for real-world measurements. The source impedance of V_{IN}, the input signal, is set to 20 Ω.

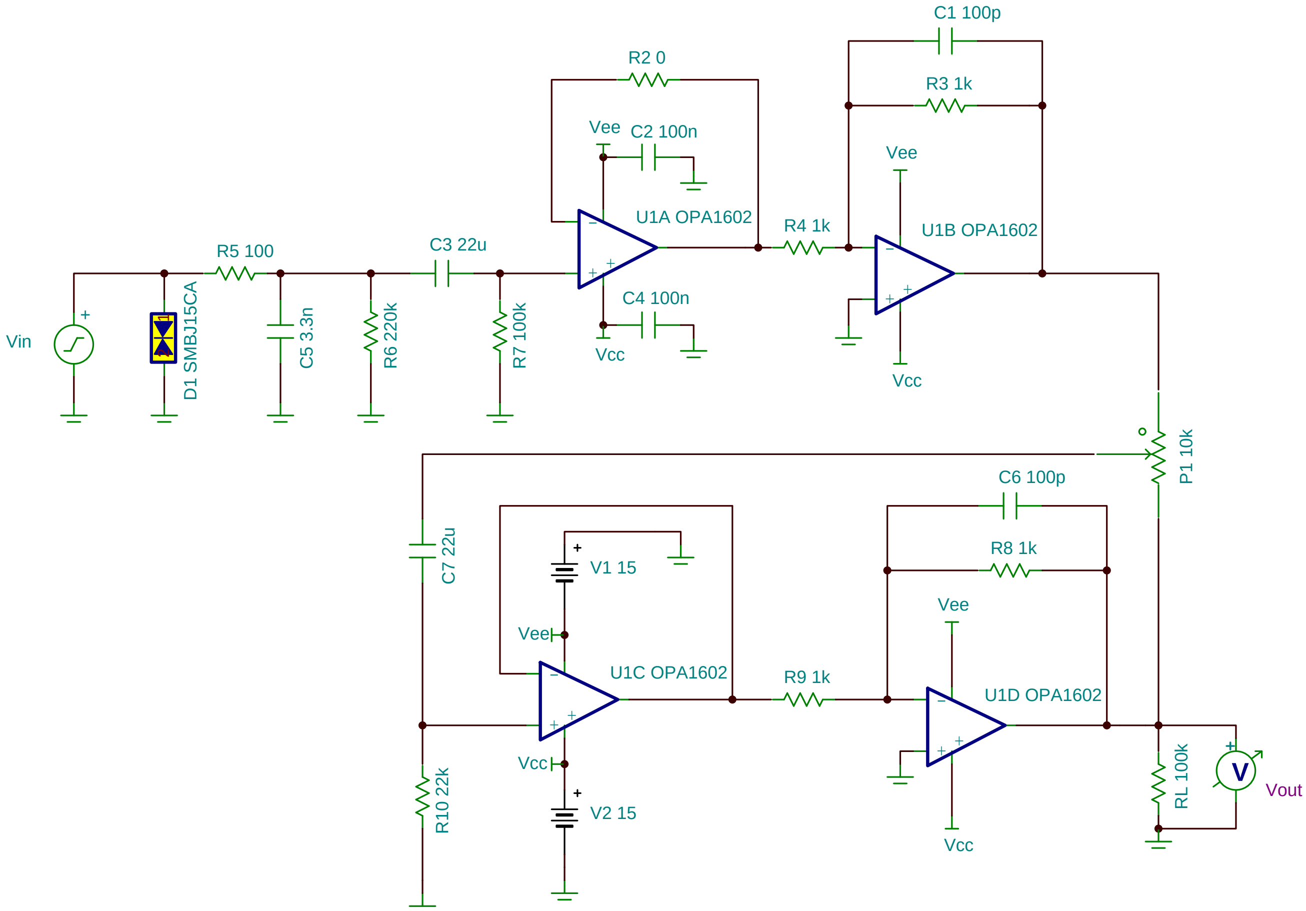

Figure 11: TINA-TI™ Schematic

4.1 Gain Characteristic

The result of the simulated gain characteristic as a function of potentiometer rotation is shown in Figure 12. The ideal (-20 dB) gain characteristic is overlaid for comparison.

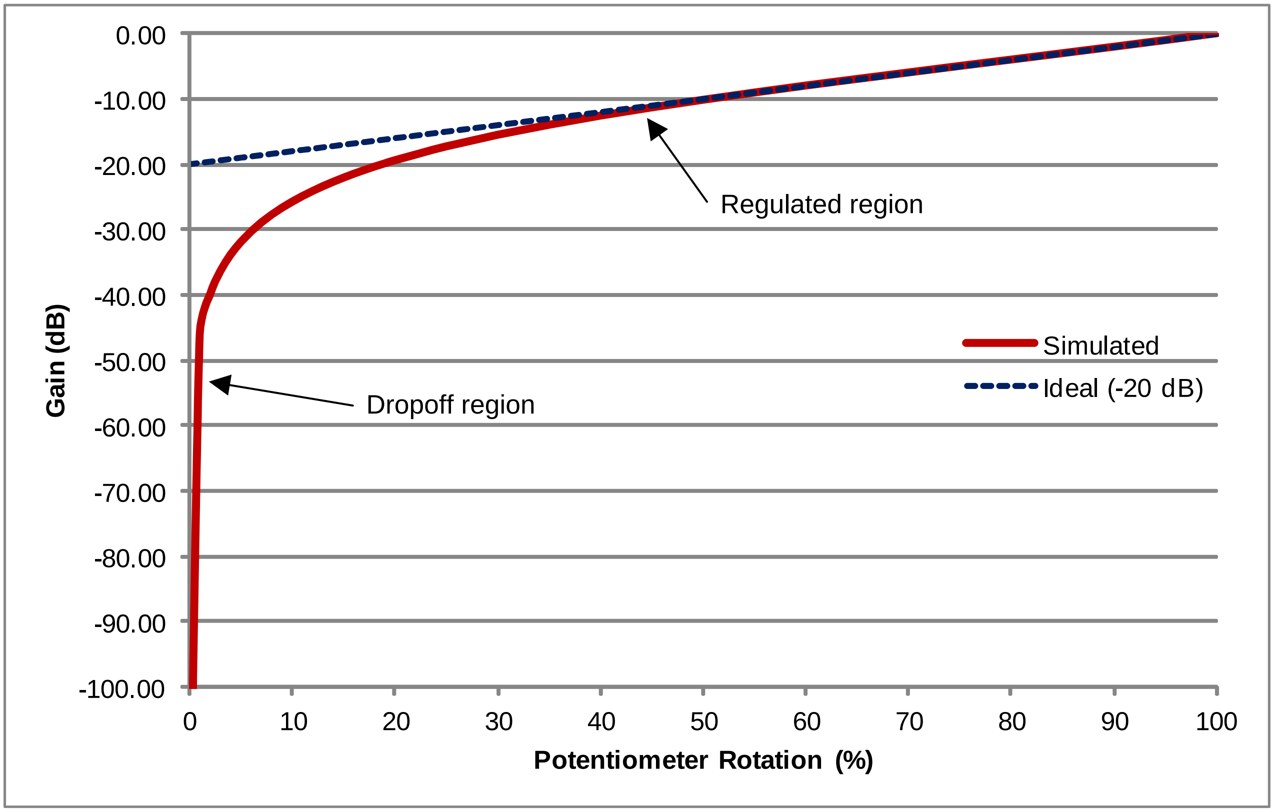

Figure 12: Simulated Gain Characteristic

4.1.1 Gain Deviation (Regulated Region)

The gain deviation from the ideal (-20dB) gain characteristic in the regulated region is shown in Table 2.

Table 2. Gain Deviation (Regulated Region)

Potentiometer Rotation (%)	Simulated Gain (dB)	Ideal Gain (dB)	Gain Deviation (dB)
100	-0.02	0	0.02
90	-2.08	-2	0.08
80	-4.05	-4	0.05
70	-6.01	-6	0.01
60	-8.03	-8	0.03
50	-10.19	-10	0.19
40	-12.63	-12	0.63
30	-15.32	-14	1.32

The maximum gain deviation in this region was found to be 1.32 dB, which meets the design requirement of 1.5 dB.

4.1.2 "Off" Gain

At potentiometer rotations less than 30%, the transfer function of the circuit causes the gain to rapidly approach negative infinity, resulting in a large deviation from the ideal "linear-in-dB" characteristic. However, this deviation is desired as it allows for enough attenuation such that the signal becomes inaudible. The simulated "off" gain, or gain with the potentiometer set to 0% rotation, was found to be -134 dB. This meets the design requirement of -100 dB.

4.2 Frequency Response

The result of the simulated ac analysis at unity gain is shown in Figure 13.

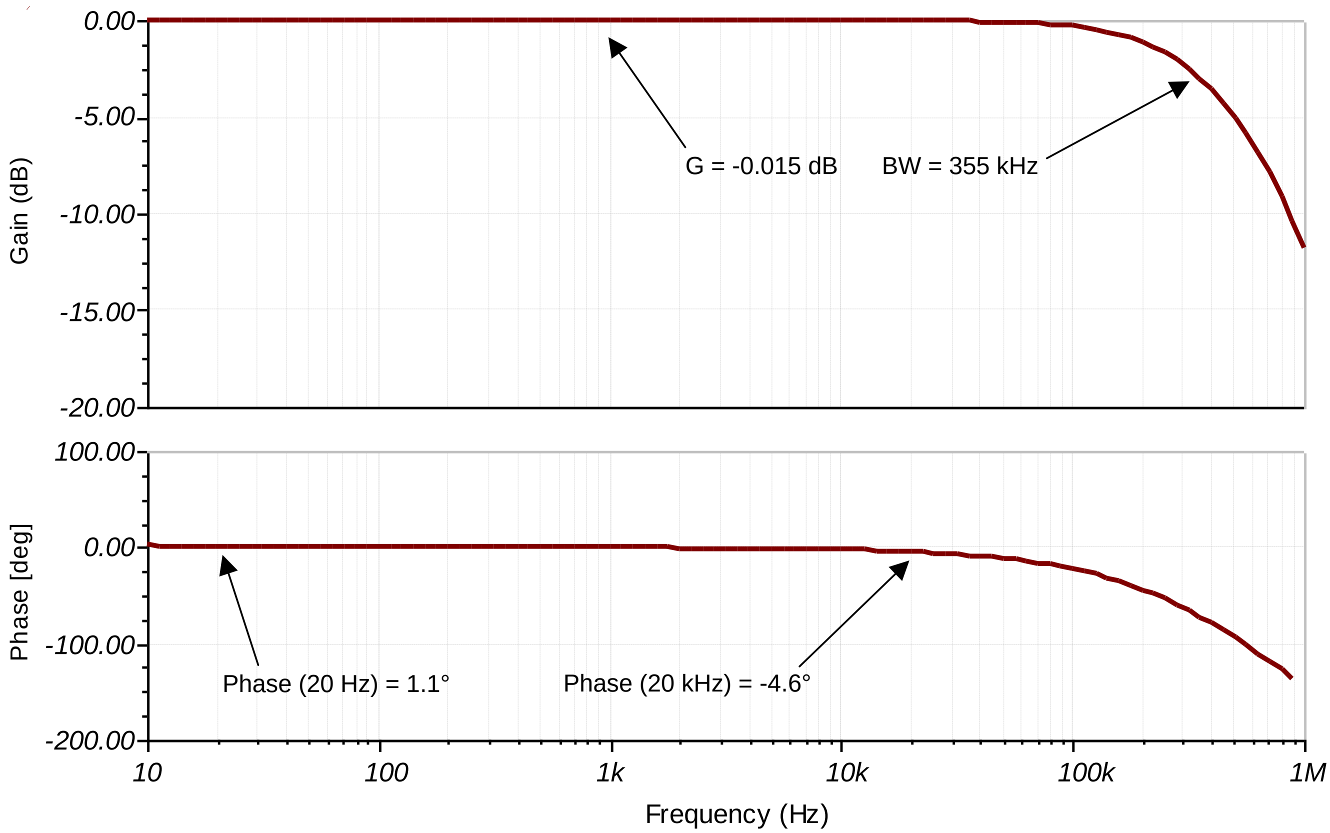

Figure 13: Simulated AC Analysis

The gain of the simulation at 1 kHz was found to be -0.015 dB. The -3dB bandwidth was 355 kHz. Please note that the audio analyzer used for the real-world measurements has a maximum bandwidth of 200 kHz, so for purposes of comparison the simulation gain at 200 kHz is measured and found to be -1.135 dB. The phase of the simulation was 1.1° at 20Hz and -4.6° at 20 kHz.

4.3 THD+N Performance

Unfortunately, TINA-TI™ does not currently support proper THD+N analysis. However, the THD+N ratio of a circuit can be predicted from the total noise by using Equation 10, where V_N is the total voltage noise in V_{RMS} over a specified bandwidth and V_F is the fundamental signal amplitude in V_{RMS}.

$$\mathrm{THD+N}(\%) = \sqrt{\frac{{V_N}^2}{{V_F}^2}} * 100 \quad (10)$$

The result of the simulated total noise analysis at unity gain is shown in Figure 14. The audio analyzer which will be used for real-world measurements will be set to a maximum bandwidth of 80 kHz, so this simulated analysis is performed to 80 kHz.

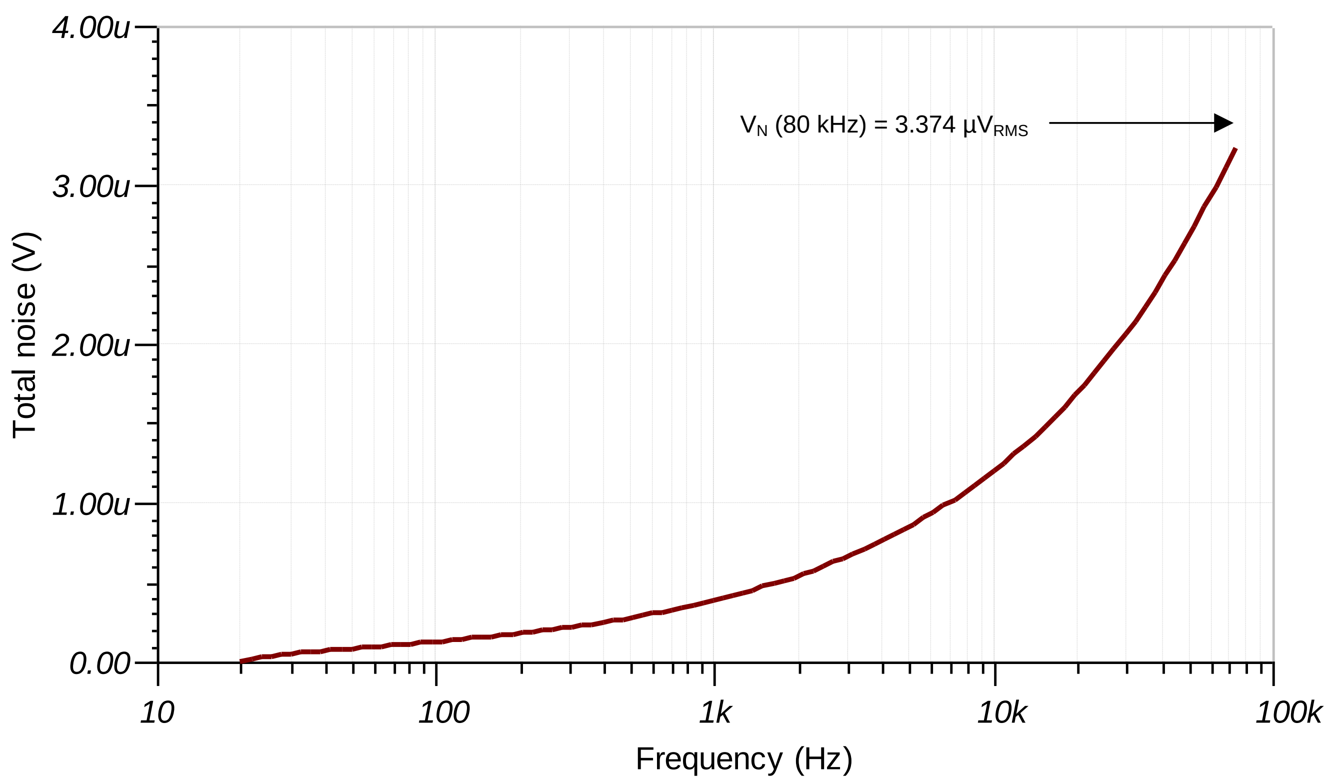

Figure 14: Simulated Total Noise Analysis

The total noise at 80 kHz was found to be 3.374 μV_{RMS}. Given our input signal amplitude of 1.228 V_{RMS}, the predicted THD+N ratio was calculated using Equation 11.

$$\mathrm{THD+N}(\%) = \sqrt{\frac{V_N^{\,2}}{V_F^{\,2}}} * 100 = \sqrt{\frac{(3.374\ \mu V_{RMS})^2}{(1.228\ V_{RMS})^2}} * 100 = 0.000275\% \tag{11}$$

The simulated THD+N ratio was found to be 0.000275%, which meets the design requirement of 0.0005%.

4.4 Simulated Results Summary

Table 3 summarizes the simulated performance of the design.

Table 3. Comparison of Design Goals and Simulated Performance

	Goal	Simulated
THD+N ratio at 1kHz	0.0005%	0.000275%
Gain deviation (regulated region)	1.5 dB	1.32 dB
“Off” gain	-100 dB	-134 dB

5 PCB Design

The PCB schematic and bill of materials can be found in the Appendix.

5.1 PCB Layout

The PCB used in this design is a 3” by 2.45” rectangle. This generous size allows for efficient routing of critical components and the use of larger RCA and banana plug connectors. The high-level approach to this layout was to place nearly all components on the top layer, with the op-amp in the center of the board, input connections on the left, output connections on the right, and the volume control potentiometer in the center. The power supply bulk capacitors were placed on the bottom layer close to the banana jacks.

Standard precision analog PCB layout practices are used in order to achieve the best possible performance. All passive components in the analog signal path are placed and routed very tightly in order to minimize parasitics, and all decoupling capacitors are located very close to their associated power pins. Solid copper planes on both layers provide an excellent low-impedance path for return currents to ground.

Connections to the split power supply are made at J2, J3, and J5. Connections to the unbalanced (single-ended) audio input and output are made at J1 and J4, respectively.

The PCB layout for both layers is shown in Figure 15.

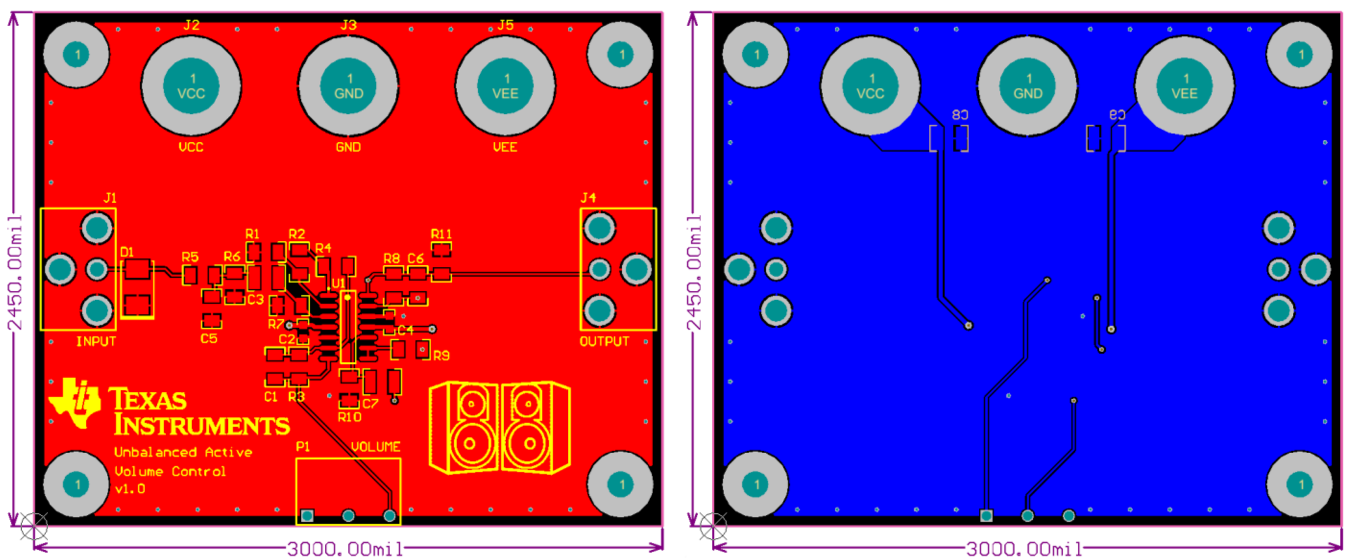

Figure 15: PCB Layout

6 Verification & Measured Performance

6.1 Bench Test Hardware Setup

The volume control circuit defined by this reference design is intended for use within a complete professional audio system. However, the circuit is also a standalone functional block whose real-world performance can be characterized. The convenient input, output and power connectors on the PCB allow the circuit to be easily tested on a bench using standard lab equipment. The test setup used consists of the components listed below. Figure 16 shows the bench test setup (computer not shown).

1. High performance audio analyzer: Provides the audio input and measures the audio output of the system.
2. Personal computer (PC): Communicates with and controls the audio analyzer through a digital interface. Software provided by the audio analyzer manufacturer allows the user to specify audio output signal characteristics and perform measurements.
3. Triple output power supply: Provides ±15 V power supply rails to the system.

Figure 16: Bench Test Setup

6.1.1 Angle Gauge

One of the key measurements required for this design is the gain characteristic as a function of potentiometer rotation. The potentiometer selected has a rotation span of 310°, so every 31° of rotation corresponds to 10% of the rotation span. In order to visually indicate these angles for the purpose of accurate measurements, an angle gauge was created as shown in Figure 17.

After installing the gauge over the potentiometer, a black knob with a white indicator line was also installed in order to easily mark the angle of rotation. Both the gauge and the knob can be seen in Figure 16.

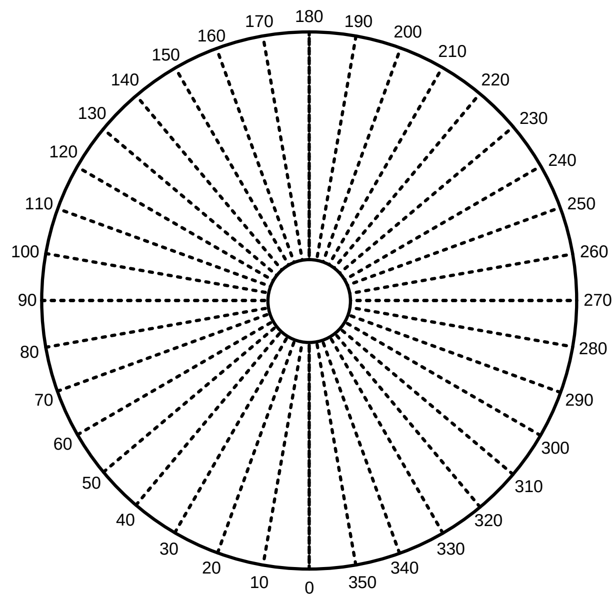

Figure 17: Angle Gauge

6.2 Gain Characteristic

The result of the measured gain characteristic as a function of potentiometer rotation is shown in Figure 18. The ideal (-20 dB) gain characteristic is overlaid for comparison.

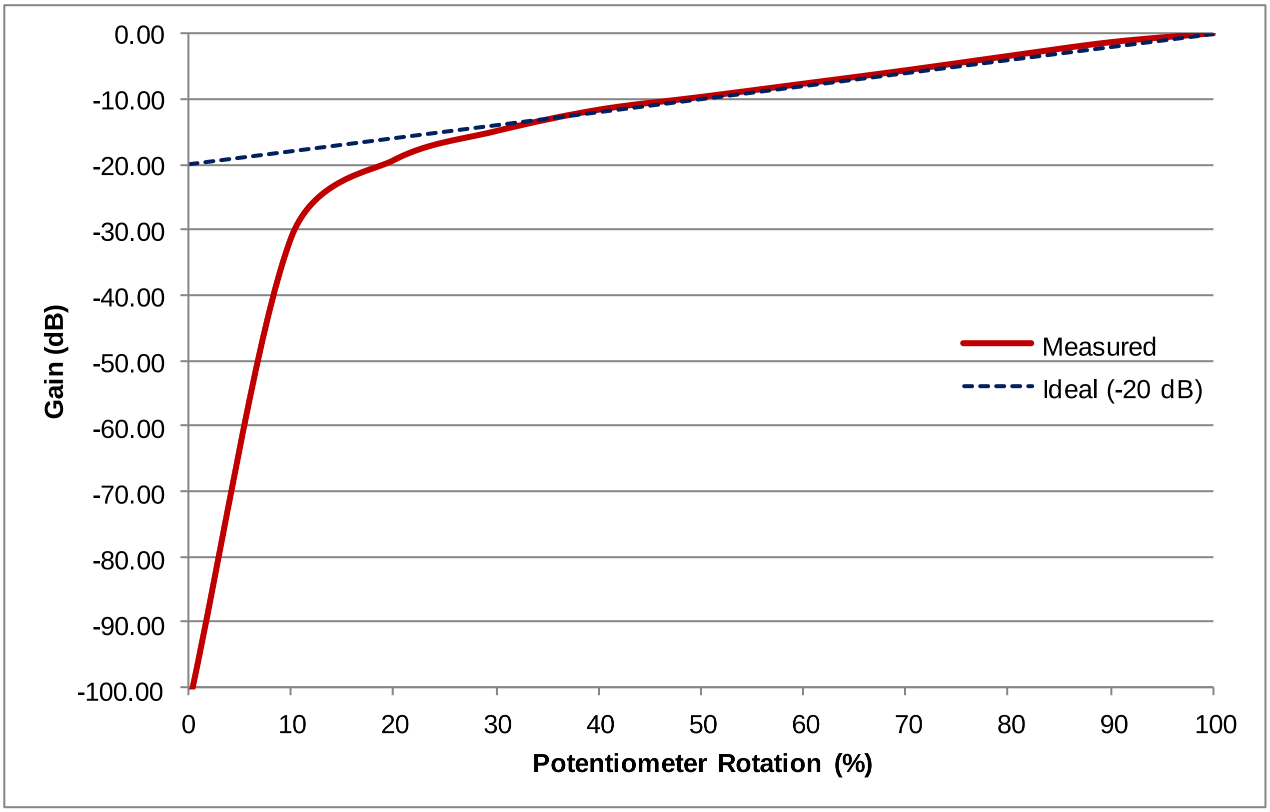

Figure 18: Measured Gain Characteristic

6.2.1 Gain Deviation (Regulated Region)

The gain deviation from the ideal (-20dB) gain characteristic in the regulated region is shown in Table 4.

Table 4. Gain Deviation (Regulated Region)

Potentiometer Rotation (%)	Measured Gain (dB)	Ideal Gain (dB)	Gain Deviation (dB)
100	-0.06	0	0.06
90	-1.43	-2	0.57
80	-3.54	-4	0.46
70	-5.72	-6	0.28
60	-7.76	-8	0.24
50	-9.79	-10	0.21
40	-11.74	-12	0.26
30	-15.00	-14	1.00

The maximum gain deviation in this region was found to be 1.00 dB, which meets the design requirement of 1.5 dB.

6.2.2 *"Off" Gain*

Recall from the simulation section that the transfer function goes to negative infinity as potentiometer rotation approaches zero. In the real circuit, the actual attenuation value is limited by the system's noise floor. The measured "off" gain, or gain with the potentiometer set to 0% rotation, was found to be -103 dB. This meets the design requirement of -100 dB.

6.3 *Frequency Response*

The results of the ac analysis at unity gain are shown in Figure 19: Measured AC Analysis.

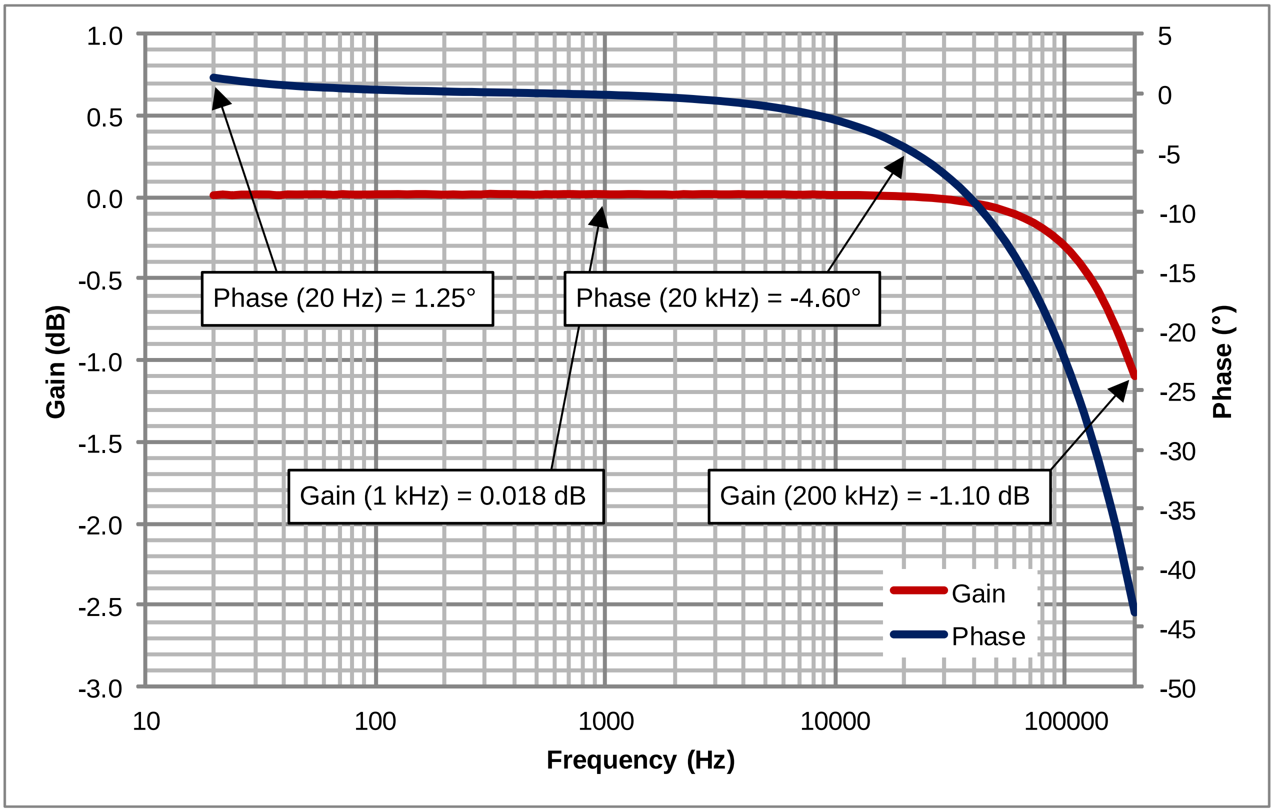

Figure 19: Measured AC Analysis

The gain at 1 kHz was found to be 0.018 dB. The -3dB bandwidth of the circuit was beyond the audio analyzer's maximum bandwidth of 200 kHz, however, the gain was measured to be -1.10 dB at 200 kHz. This correlates nicely to the simulated gain of -1.135 dB at 200 kHz, indicating that the measured bandwidth matches the simulation. The phase of the circuit was measured to be 1.25° at 20Hz and -4.6° at 20 kHz.

6.4 THD+N Performance

The result of the THD+N measurement at unity gain is shown in Figure 20. The audio analyzer was set to a maximum bandwidth of 80 kHz, and no additional filtering or weighting was applied.

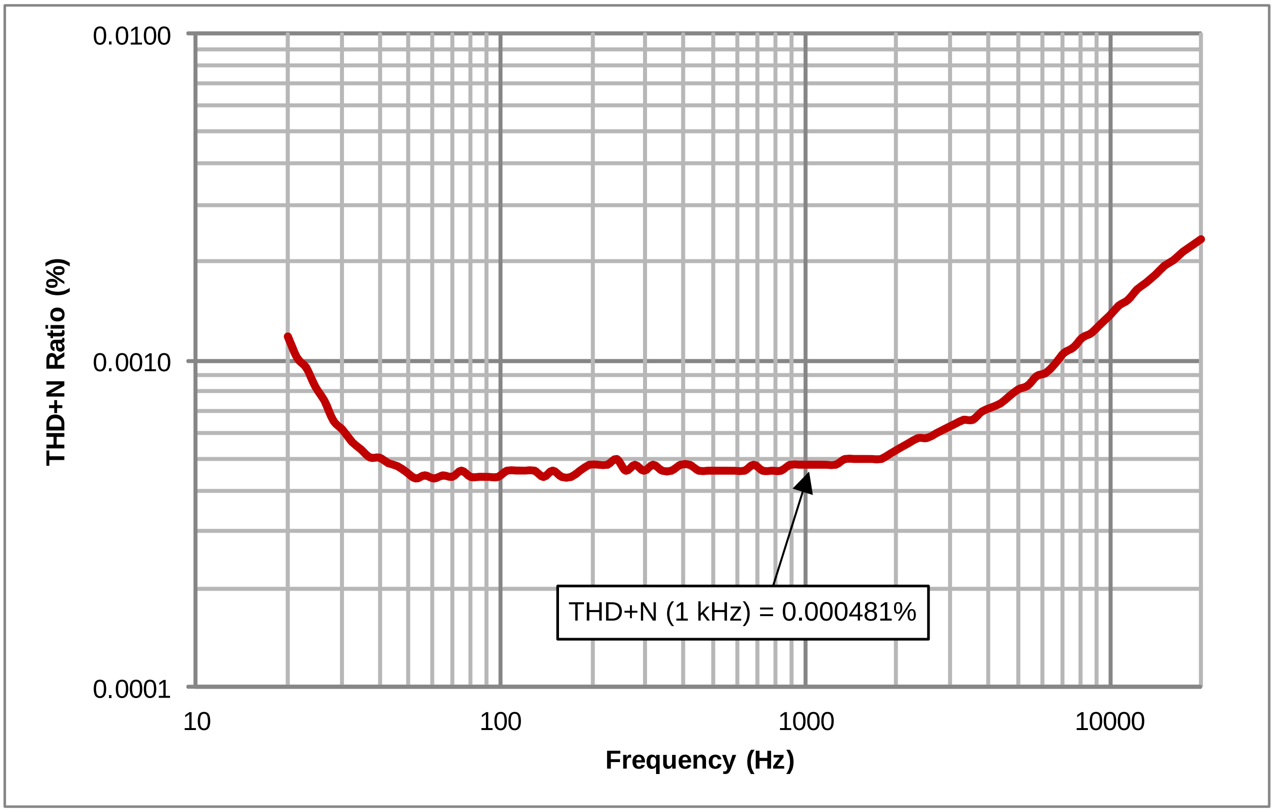

Figure 20: Measured THD+N Ratio

The measured THD+N ratio at 1 kHz was measured to be 0.000481%. This meets the design requirement of 0.0005%. The THD+N ratio at 20 Hz and 20 kHz was measured to be 0.0012% and 0.0023%, respectively.

6.5 Measured Results Summary

Table 5 summarizes the measured performance of the design.

Table 5. Comparison of Design Goals and Measured Performance

	Goal	Measured
THD+N ratio at 1kHz	0.0005%	0.000481%
Gain deviation (regulated region)	1.5 dB	1.00 dB
“Off” gain	-100 dB	-103 dB

7 Modifications

The components selected for this design were based on the design goals outlined at the beginning of the design process.

This reference design specifies a professional line-level audio input signal of +4dBu (1.228V_{RMS}) and focuses on cleanly and accurately attenuating that signal. However, other designs may have an input of lower amplitude, for example, a consumer audio line-level of -10 dBV (0.316V_{RMS}). In such cases it may be beneficial to add gain to the input stage, since gain is best added early in the signal chain in order to reduce total system noise.

The gain of the input stage can be modified by changing the values of R_3 and R_4 per Equation 12. For example, to provide 20 dB (10 V/V) of gain, simply increase R_3 to 10 kΩ:

$$G(dB) = 20 * \log_{10}\left(\frac{R_3}{R_4}\right) = 20 * \log_{10}\left(\frac{10\ k\Omega}{1\ k\Omega}\right) = 20\ dB \quad (12)$$

This design specifies an input impedance of 20 Ω. While this is a reasonable specification for a professional audio system, the actual value may vary across different signal sources. It may be necessary to adjust the values of R_5 and C_5 in the input filter in order to achieve the desired cutoff frequency.

The RF filter at the input of the system is set to a cutoff frequency of 400 kHz. However, this filter response causes nearly 5° of phase shift at 20 kHz. If less phase shift is required, the cutoff frequency of the RF filter can be increased.

Other audio operational amplifiers with excellent THD+N performance and low noise could also be used in a professional audio volume control application. The OPA1612, for example, has better audio performance than the OPA1604, but at nearly three times the cost per channel. The LME49740 has almost identical audio performance and cost compared to the OPA1604, but it consumes nearly twice the quiescent current per channel. Table 6 summarizes other potential audio operational amplifiers for this design as compared to the OPA1604.

Table 6. Brief Comparison of Audio Operational Amplifiers

Operational Amplifier	THD+N Ratio at 1kHz	e_N at 1 kHz	I_Q / Channel	Input Type	Approx. Cost / Channel
OPA1604	0.00003%	2.5 nV/√Hz	2.8 mA	Bipolar	$0.49 / 1ku
OPA1612	0.000015%	1.1 nV/√Hz	3.6 mA	Bipolar	$1.38 / 1ku
OPA1644	0.00005%	5.1 nV/√Hz	1.8 mA	JFET	$0.49 / 1ku
OPA1654	0.00005%	4.5 nV/√Hz	2.0 mA	CMOS	$0.24 / 1ku
OPA1664	0.00006%	3.3 nV/√Hz	1.5 mA	Bipolar	$0.36 / 1ku
LME49740	0.00003%	2.7 nV/√Hz	4.6 mA	Bipolar	$0.43 / 1ku
LME49743	0.0001%	3.5 nV/√Hz	2.5 mA	Bipolar	$0.29 / 1ku

8 About the Author

Ian Williams (ian@ti.com) is an applications engineer in the Precision Analog – Linear team at Texas Instruments where he supports industrial products and applications. Ian graduated from the University of Texas, Dallas, where he earned a Bachelor of Science in Electrical Engineering with a concentration in Microelectronics.

9 Acknowledgements & References

9.1 Acknowledgements

The author wishes to acknowledge John Caldwell for his guidance in the completion of this design.

9.2 References

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Appendix A.

A.1 Electrical Schematic

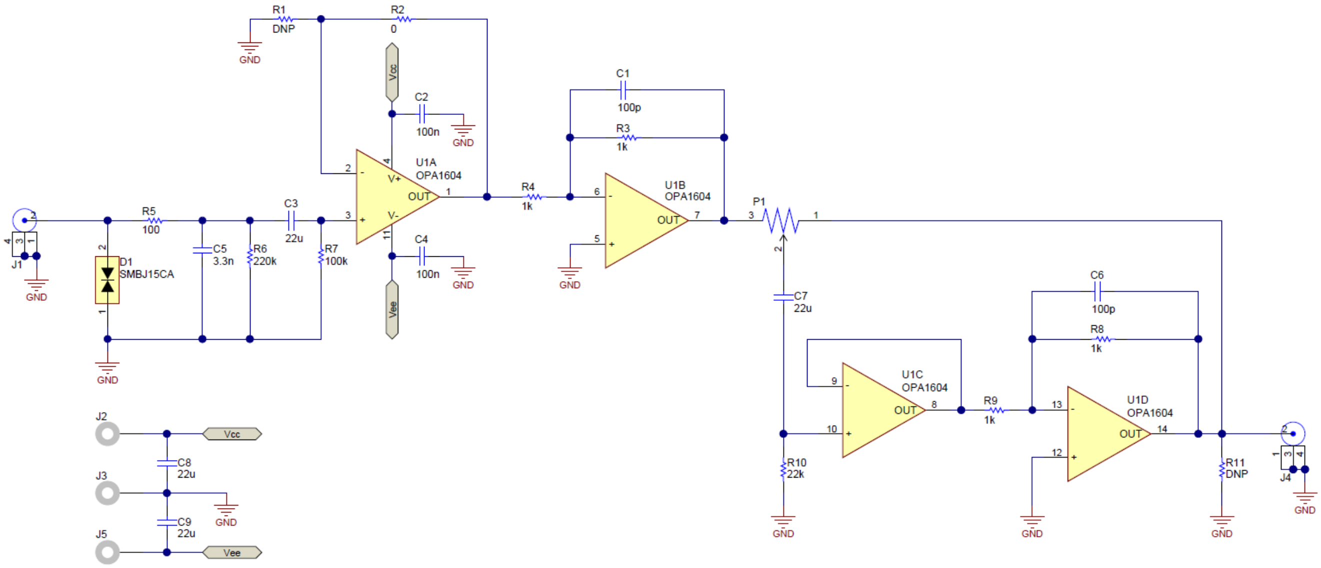

Figure A-1: Electrical Schematic

A.2 Bill of Materials

Item #	Quantity	Value	Designator	Description	Manufacturer	Part Number	Supplier Part Number
1	2	100pF	C1, C6	CAP CER 100PF 1KV 10% X7R 1206	Johanson Dielectrics Inc	102R18W101KV4E	709-1294-1-ND
2	2	0.1uF	C2, C4	CAP CER 0.1UF 50V 10% X7R 0603	TDK Corporation	C1608X7R1H104K080AA	445-1314-1-ND
3	4	22uF	C3, C7-C9	CAP CER 22UF 25V 10% X7R 1210	Samsung Electro-Mechanics	CL32B226KAJNNNE	1276-3392-1-ND
4	1	3.3nF	C5	CAP CER 0.033UF 50V 5% NP0 1206	Samsung Electro-Mechanics	CL31C333JBHNNWE	1276-3261-1-ND
5	1	TVS	D1	DIODE TVS 15V 600W BI 5% SMD	Bourns	SMBJ15CA	SMBJ15CABCT-ND
6	1	10kΩ	R2	RES 10K OHM 1/4W 1% 1206	Stackpole Electronics	RMCF1206FT10K0	RMCF1206FT10K0CT-ND
7	4	1kΩ	R3, R4, R8, R9	RES 1K OHM 1/4W 1% 1206	Stackpole Electronics	RMCF1206FT1K00	RMCF1206FT1K00CT-ND
8	1	100Ω	R5	RES 100 OHM 1/4W 1% 1206	Stackpole Electronics	RMCF1206FT100R	RMCF1206FT100RCT-ND
9	1	220kΩ	R6	RES 220K OHM 1/4W 1% 1206 SMD	Panasonic Electronic Components	ERJ-8ENF2203V	P220KFCT-ND
10	1	100kΩ	R7	RES 100K OHM 1/4W 1% 1206	Stackpole Electronics	RMCF1206FT100K	RMCF1206FT100KCT-ND
11	1	22kΩ	R10	RES 22K OHM 1/4W 1% 1206 SMD	Panasonic Electronic Components	ERJ-8ENF2202V	P22.0KFCT-ND
12	1	10kΩ POT	P1	10K LINEAR POT	Alpha	RV16AF-20-15R1-B10K-00H	RV16AF-20-15R1-B10K-00H4
13	1	OPA1604	U1	OPA1604 SOUND-PLUS OP AMP	Texas Instruments	OPA1604AID	N/A
14	2	RCA	J1, J4	CONN RCA JACK METAL R/A BLK PCB	CUI Inc	RCJ-011	CP-1400-ND
15	3	BANANA	J2, J3, J5	CONN JACK BANANA UNINS PANEL MOU	Emerson Network Power	108-0740-001	J147-ND
16	4	SCREW	Screws	SCREW MACHINE PHILLIPS 4-40X3/8	B&F Fastener Supply	PMS 440 0038 PH	H781-ND
17	4	STANDOFF	Standoffs	STANDOFF HEX 4-40THR ALUM .500"L	Keystone Electronics	2203	2203K-ND
18	2	DNP	R1, R11	DO NOT POPULATE	N/A	N/A	N/A

Figure A-2: Bill of Materials

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