Introduction

The SMN Audio EQ board is designed to give users a platform to prototype active filters for use in audio electronics. The layout has been optimized for two-channel audio, with each channel going through two stages of analog signal processing. The Audio EQ Board can be configured with jumpers to accept single-ended or differential audio signals as inputs, and it can put out a signal that is single-ended or differential. Although audio signal conditioning is the primary use, this board is versatile enough to realize a variety of op-amp circuits including instrumentation amplifiers, signal mixers, RC oscillators, and headphone amplifiers.

Theory of Operation

The SMN Audio EQ consists of four dual op-amp IC’s that perform (for each channel) the input signal buffering, two stages of signal conditioning, and an optional signal inverter to produce an inverting or differential output. The use of a precision virtual ground IC provides a low-noise voltage bias for all signals that is half the supply voltage.

Power Entry

The SMN Audio EQ requires an external voltage supply. The supply voltage for the SMN Audio EQ can vary depending on application, but the virtual ground IC has an absolute maximum input voltage of 40V. A safe operating voltage can be anywhere between 10 and 15 VDC, such as those found in automotive applications. However, it is important to refer to the datasheet of the op-amps being used to avoid damaging them with too high a voltage.

Power is provided to the board through screw terminal block J5. The positive supply voltage should be applied to pin 1 (labeled B+) and pin 2 (GND) should be grounded. The input is protected from reverse-voltages and transient voltage spikes.

Input Signal Buffer

Signals enter the board through the RCA connectors J9 and J10, each corresponding to a different channel. The center pin of each RCA connector provides the + input to the differential buffers. Pin headers J2 and J4 are used to select between differential and single-ended input. This is accomplished by either shorting the barrel of the RCA connector to the – input of the buffer for differential operation, or shorting the barrel of the RCA connector and – input of the buffer to ground for single-ended, non-inverting operation. Refer to the connection diagrams on the bottom side of the board to see the proper jumper configurations.

The default setup for the input buffer is a unity-gain differential amplifier that removes the input signal bias and re-biases it to half the supply voltage of the Audio EQ. The input buffer has a DC blocking capacitor, and capacitors in the feedback path and output to mitigate high-frequency noise. It should be noted that R28 and R4 could be used on their respective channels to divide down the output signal amplitude of the input buffers. For applications where the input signals need to be summed, a jumper can be installed on the 2-pin header, J8, to sum the buffered inputs from both channels together.

EQ Stages

The two EQ stages per channel are where the signal conditioning takes place. It is here that the user can choose the circuit design to produce a desired gain level and frequency response. Pad placement for many components have been provided so that different filters in the Sallen-Key topology can be realized on this board. All of the resistor pads (prefix R) are of 0603 size, while the pads for the capacitors (prefix C) can accommodate 0603, 0805, and 1206-sized capacitors. The first capacitor in the EQ stages (C11 and C31) has a pad that can fit 2220 and through-hole parts if a high-pass filter with a very low cutoff is desired. A test point has been placed at the output of the first EQ stage of each channel (TP12 and TP10) so that the second EQ stage can be bypassed in single stage designs.

Different Output Conversion / Signal Inverter

The last part of the signal chain is an op-amp configured for signal inversion. Since the output of the last EQ stage is connected directly to the center pin of the RCA output connectors (J6 and J7), the signal inverter can be omitted in single-ended designs. For applications requiring increased dynamic range, such as ADC inputs, the signal inverter can be used in conjunction with the output of the last EQ stage to produce a differential signal.

The pin headers, J11 and J1, are used to configure the board for single-ended or differential output. This is accomplished through the different connections that can be made to the output RCA connectors with jumpers. Shorting the output of the last EQ stage to the center pin of the RCA connector, and shorting the inverted signal to the barrel of the RCA connector achieves differential output. Single-ended operation occurs with the last EQ stage output shorted to the center pin of the RCA connector, and the barrel connected to ground. Lastly, shorting the inverted output to the center pin of the RCA connector, and connecting the barrel to ground obtains a single-ended inverted signal. Refer to the connection diagrams on the bottom side of the board for proper jumper settings.

Virtual Ground

The Audio EQ board uses a TLE2426 IC to provide a signal bias that is one half the input supply voltage. C18, connected to pin 8 on the TLE2426, may be left open, but installing a 1 uF capacitor here will provide some noise reduction on the signal ground.

Design Examples

The following designs use equal component value circuits in the feedback loop. This design allows for easy tuning of the damping (flatness) and bandwidth of the frequency response. It should be noted that the gain resistors R21 and R49 adjust flatness, but can also have a profound effect on the cutoff frequency. Therefore, it is best to adjust signal gain outside of these filter circuits, possibly at the input buffer. Notice that the high-pass filter is just a mirrored component version of the low-pass filter. This symmetry can only be used in equal component value circuits, where the filter resistors (R11 and R15 of Figure 1 and the filter capacitors (C23 and C26 of Figure 1) match each other.

Fourth-Order Low-Pass Filter with 1 kHz Cutoff (Gain of 2.6 V/V)

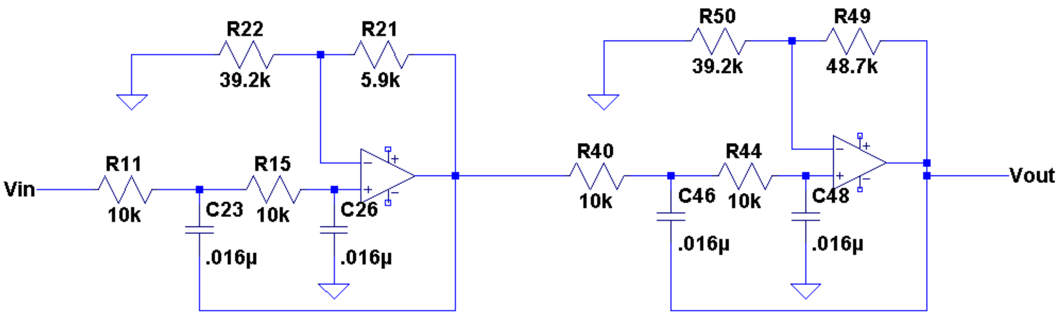

Figure 1: Circuit Schematic for One Channel

EQ1A Equivalent	EQ1B Equivalent	Value	EQ2A Equivalent	EQ2B Equivalent	Value
R11	R26	10K	R40	R54	10K
R9	R25		R39	R53	
R12	R27		R41	R55	
R14	R29		R42	R56	
R15	R30	10K	R44	R57	10K
R19	R33	SHORT	R47	R60	SHORT

R21	R35	5.9K	R49	R62	48.7K
R22	R36	39.2K	R50	R63	39.2K
R18	R32	SHORT	R46	R59	SHORT
R17	R31		R45	R58	
R23	R37		R51	R64	
R73	R76		R70	R69	
C11	C31	SHORT	N/A	N/A	
C22	C33		C45	C55	
C21	C32		C44	C54	
C23	C34	.016 uF	C46	C56	.016 uF
C24	C35		C47	C57	
C26	C36	.016 uF	C48	C58	.016 uF
C29	C38		C50	C60	
C30	C39		C51	C61	
C28	C37	SHORT	C49	C59	SHORT

*Entries left blank should not be populated. Cutoff frequency scales with capacitors. Doubling the capacitances will half the cutoff frequency.

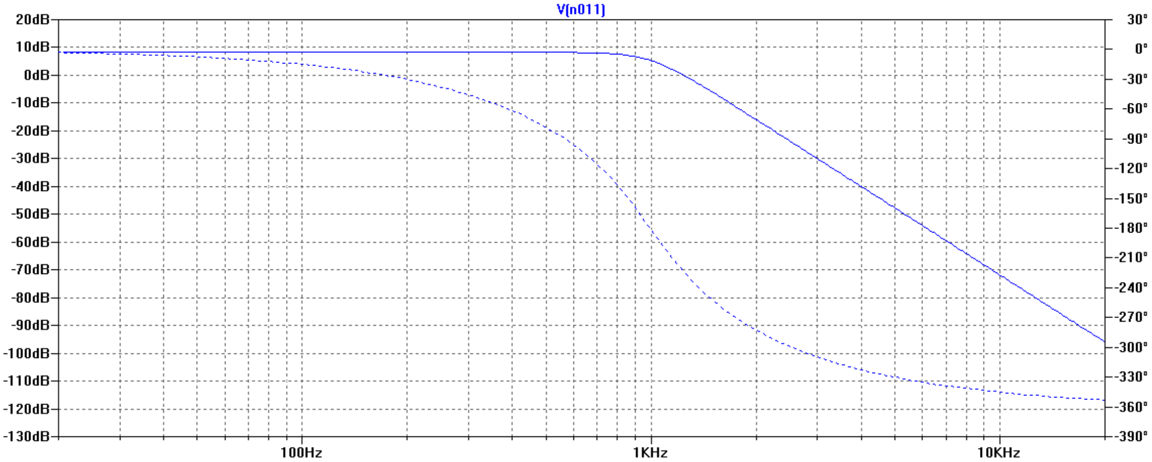

Figure 2: Frequency Response of Fourth-Order Low-Pass Filter with 1 kHz Cutoff

Fourth-Order High-Pass Filter with 1 kHz Cutoff (Gain of 2.6 V/V)

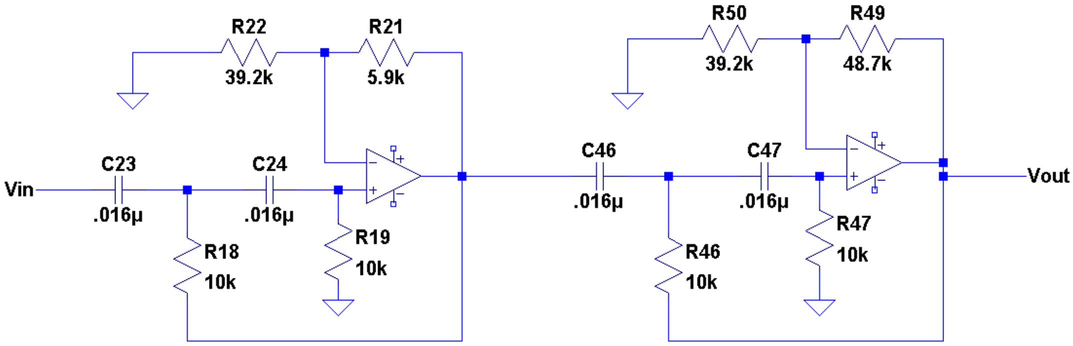

Figure 3: Circuit Schematic for One Channel

EQ1A Equivalent	EQ1B Equivalent	Value	EQ2A Equivalent	EQ2B Equivalent	Value
R11	R26	SHORT	R40	R54	SHORT
R9	R25		R39	R53	
R12	R27		R41	R55	
R14	R29		R42	R56	
R15	R30		R44	R57	
R19	R33	10K	R47	R60	10K
R21	R35	5.9K	R49	R62	48.7K
R22	R36	39.2K	R50	R63	39.2K
R18	R32	10K	R46	R59	10K
R17	R31		R45	R58	
R23	R37		R51	R64	
R73	R76		R70	R69	
C11	C31	SHORT	N/A	N/A	
C22	C33		C45	C55	
C21	C32		C44	C54	
C23	C34	.016 uF	C46	C56	.016 uF
C24	C35	.016 uF	C47	C57	.016 uF
C26	C36	SHORT	C48	C58	SHORT
C29	C38		C50	C60	
C30	C39		C51	C61	
C28	C37	SHORT	C49	C59	SHORT

*Entries left blank should not be populated. Cutoff frequency scales with capacitors. Doubling the capacitances will half the cutoff frequency.

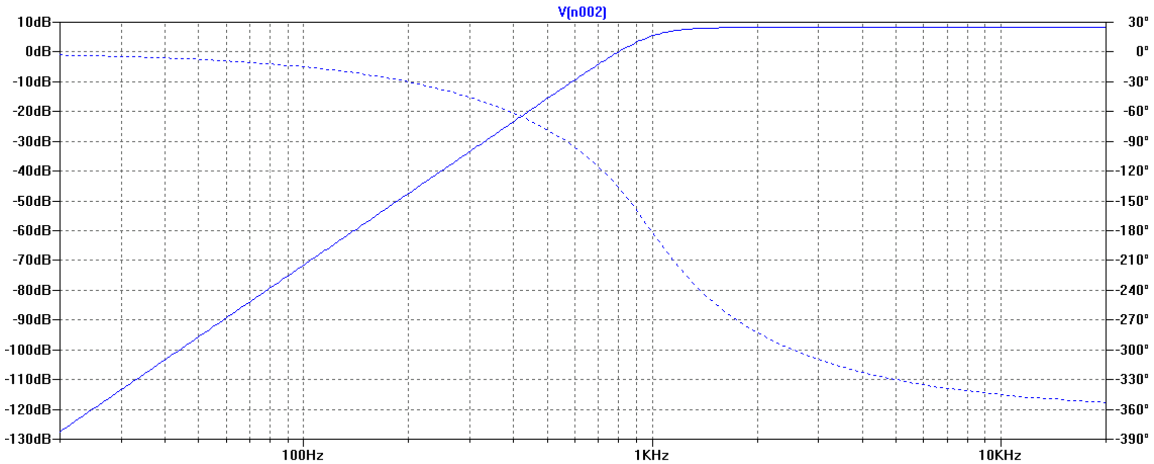

Figure 4: Frequency Response of Fourth-Order High-Pass Filter with 1 kHz Cutoff

Butterworth Filter Design

Butterworth filters are a class of filters designed for maximal flatness in the pass band, and can be constructed with RC networks and op amps. Without getting into controls theory, the following tutorial presents a simplified method to calculate component values to obtain the desired frequency cutoff. The following designs are unity gain.

Firstly, we demonstrate a design of a low-pass filter that will have unity gain in the pass band and 80dB/decade of attenuation in the stop band.

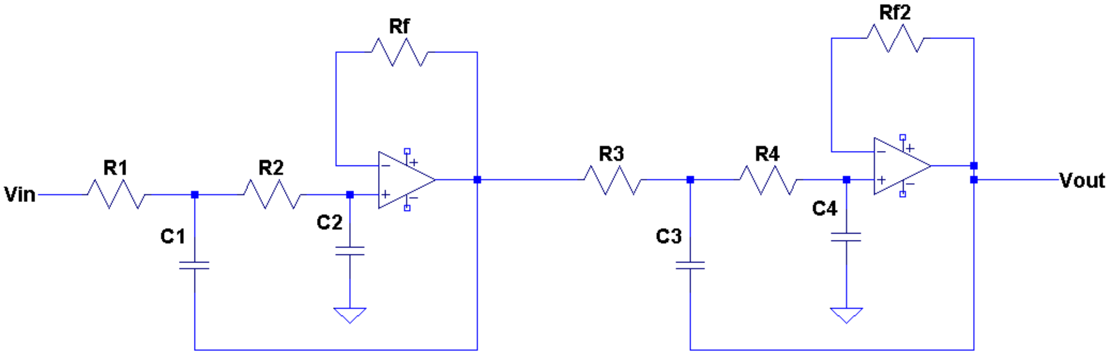

Figure 5: Schematic of a Unity Gain Fourth-Order Butterworth Low-Pass Filter

1. Select a cutoff frequency. For this example, we will choose 1 kHz.

2. Calculate the capacitor values for the first stage (C1 and C2). A Butterworth filter has its s-plane poles on a semi-circle in the left half plane. Thus, we choose two angles for our four-pole design that space out the poles evenly on the semi-circle. Here, we will use

35° and 70°, where each angle represents a double pole on the semi-circle. To calculate the first set of capacitor values, use the formula:

$$\tan(35°) = \sqrt{\frac{C1}{C2} - 1}$$

$$C1 = 1.49 * C2$$

We can choose C1 = .01 μF and C2 = .015 μF.

3. Calculate the Value of R1=R2 using the formula:

$$2\pi(1000Hz) = \frac{1}{\sqrt{C1 * C2} * (R1)}$$

$$2\pi(1000Hz) = \frac{1}{1.22 * 10^{-8} * (R1)}$$

R1 =R2 ≅ 13K

4. Calculating Rf is optional, but installing a resistor here will reduce DC offset. Rf is simply the sum of the resistors in the DC path of the + input, which is 13K + 13K = 26K.

5. Repeat this process for the second stage of the filter, using 70° for the angle in the capacitor formula, and C3 and C4 for the necessary resistor. Also, Rf2 shall be the sum of R3 and R4.

Next, we present a high-pass design in a similar topology. This filter is also unity gain with 80dB/decade of attenuation in the stop band. The high-pass filter design is like the low-pass design, except that the capacitors and resistors have switch places.

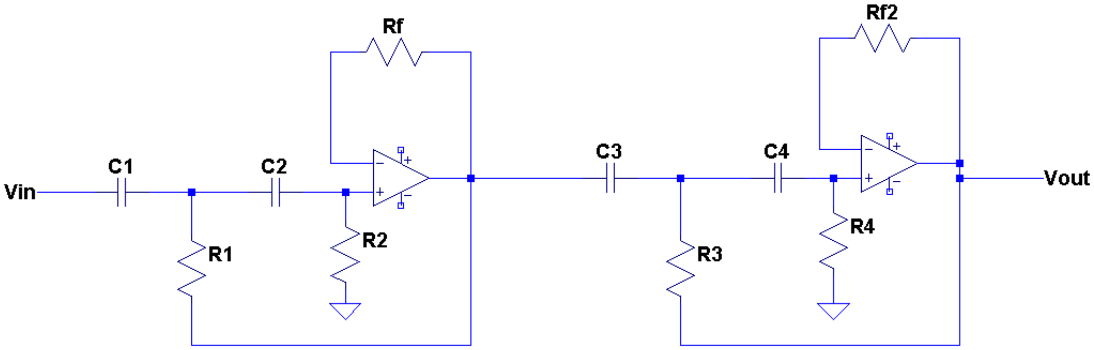

Figure 6: Schematic of a Unity Gain Fourth-Order Butterworth High-Pass Filter

1. Select a cutoff frequency. We'll use 1 kHz, again.

2. Calculate values for R1 and R2 using the angles 35° and 70°.

$$\tan(35°) = \sqrt{\frac{R2}{R1} - 1}$$

$$R2 = 1.49 * R1$$

We can choose R1 = 10K and R2 = 15K.

3. Calculate the value of C1 = C2.

$$2\pi(1000Hz) = \frac{1}{\sqrt{R1 * R2} * (C1)}$$

$$2\pi(1000Hz) = \frac{1}{1.5 * 10^{8} * (C1)}$$

C1 = C2 ≅ .013 µF

4. Rf is 15K, since R2 is the only DC path to the + input.

5. Repeat this process for the second stage of the filter, using 70° for the angle in the resistor formula and R3 and R4 for the necessary capacitor. Also, Rf2 shall be equal to R4.

Designs from the Lab

The following component designations are for unity-gain audio crossovers that have been tested and verified on an audio analyzer.

	100 Hz		250 Hz		Notes
	Low-Pass	High-Pass	Low-Pass	High-Pass	
C11, C31	SHORT	SHORT	Open	SHORT	
R11, R12, R26, R27, R40, R41 ,R54, R55	1K	1K	1K	1K	Divider resistors
C21,C32, C44, C54	Open	.01u	Open	.01u	Noise filter
C23, C24, C34, C35, C46, C47, C56, C57	34.8K	.047u	34.8K	4.7n	Install resistors for LP
C26, C36, C48, C58	.047u	SHORT	.022u	SHORT	
R19, R33, R47, R60	SHORT	32.4K	SHORT	1M	
R18, R32, R46, R59	.047u	39.2K	.022u	47.5K	Install caps for LP
R17, R31, R45, R58	Open	Open	Open	34.8K	Reduces Feedback Sensitivity
R21, R35, R49, R62	22.1K	60.4K	22.1k	22.1K	Controls gain
R22, R36, R50, R63	22.1K	60.4K	60.4K	22.1K	Controls gain
C28, C37, C49, C59	SHORT	SHORT	SHORT	1u	Short C49 and C59 on 250Hz HP
C29, C38, C50, C60	Open	18p	Open	Open	Helps with stability
C30, C39, C51, C61	Open	SHORT	Open	Open	

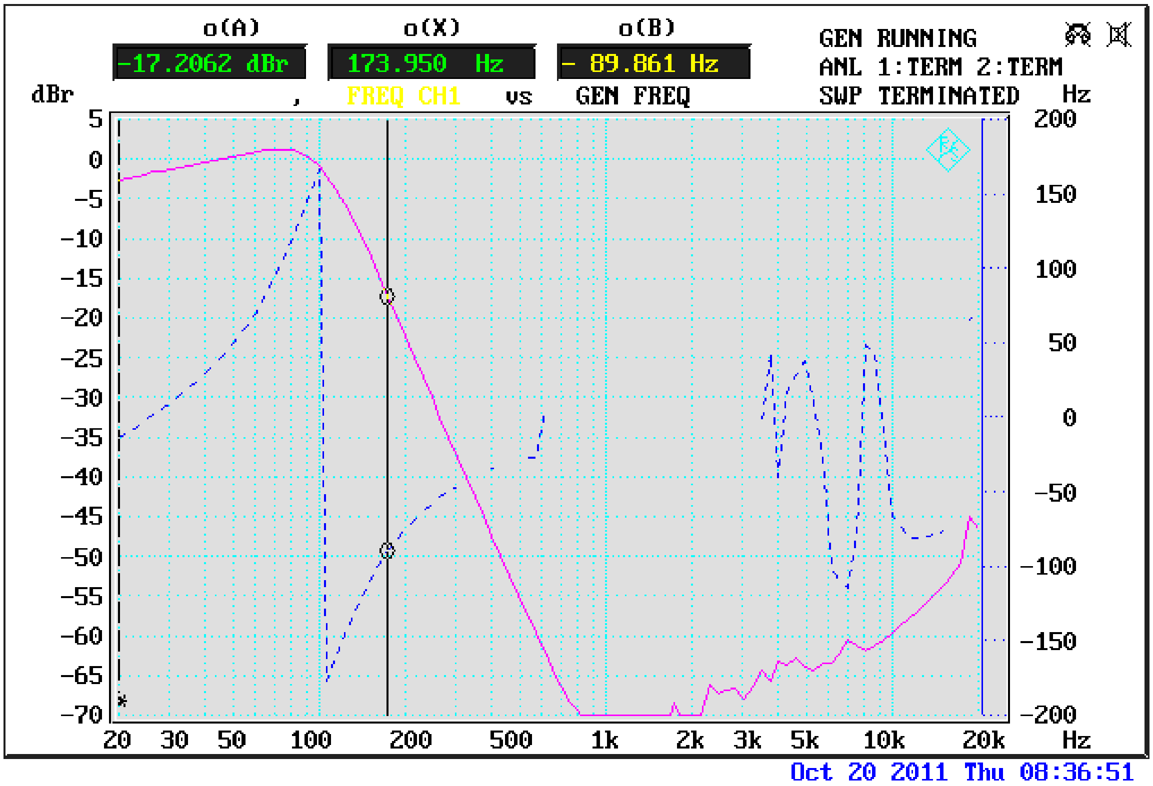

Figure 7: Frequency Response of 100 Hz Low-Pass Filter

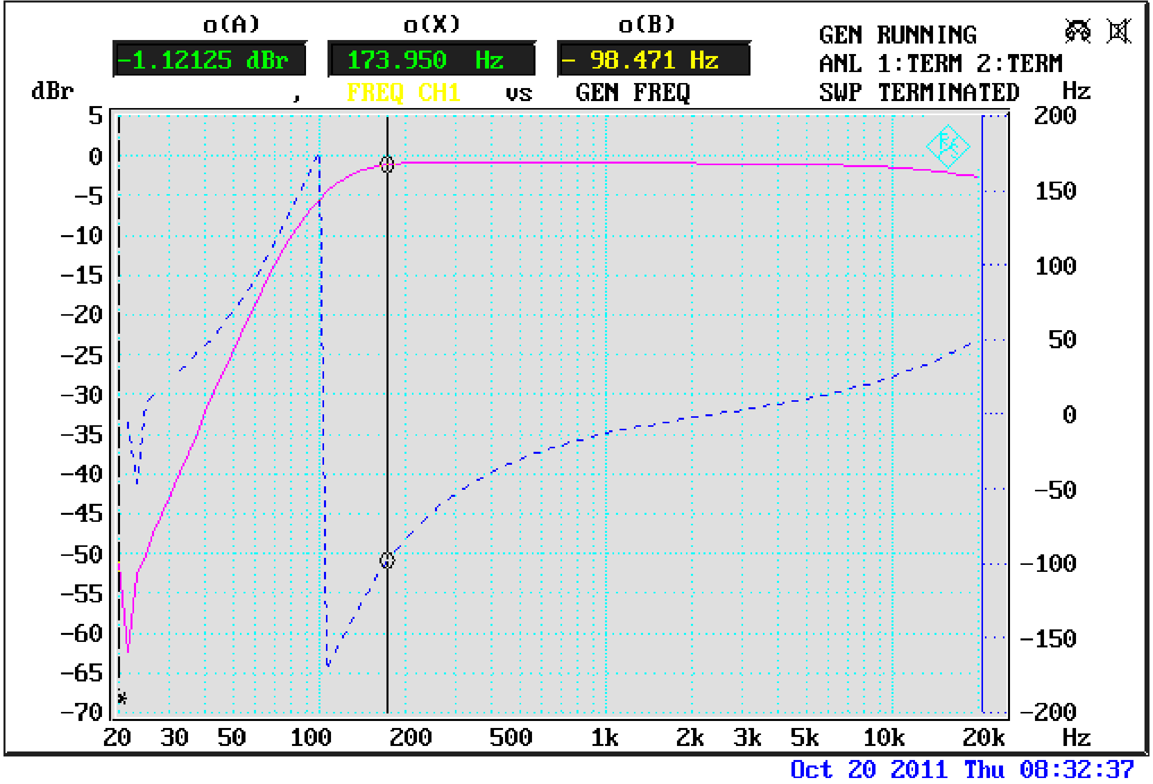

Figure 8: Frequency Response of 100 Hz High-Pass Filter

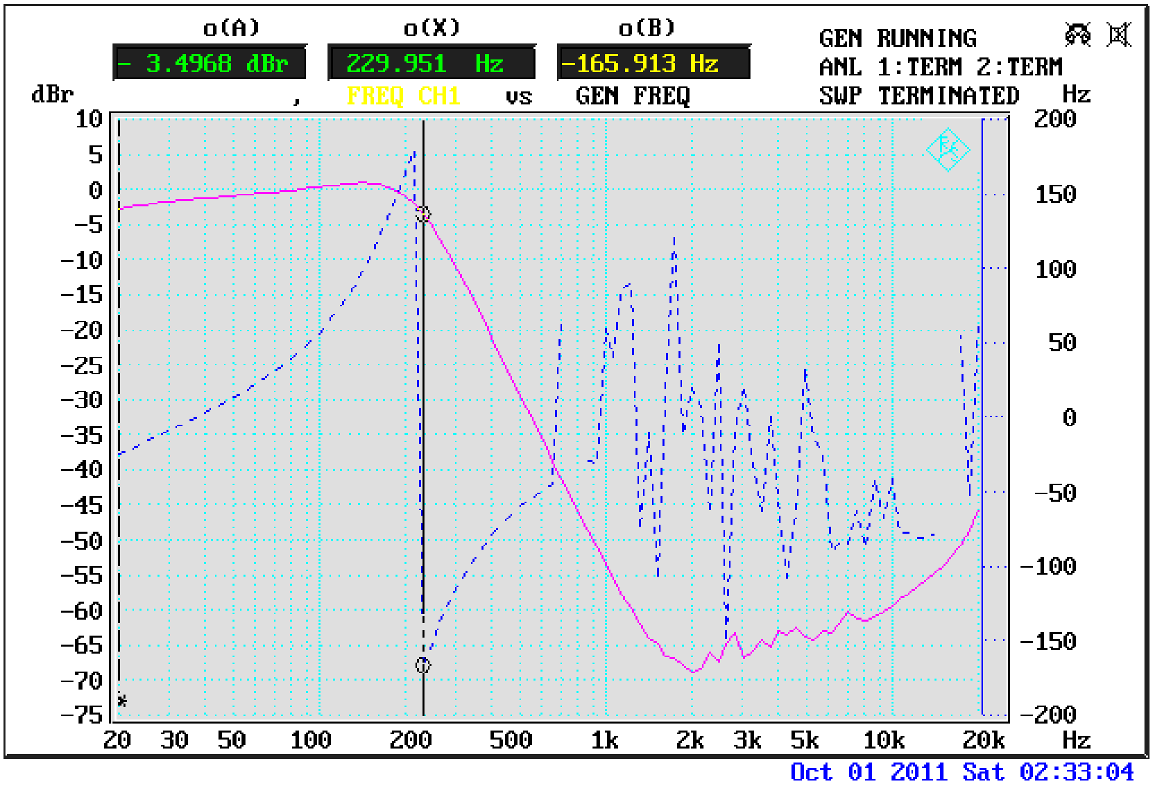

Figure 9: Frequency Response of 250 Hz Low-Pass Filter

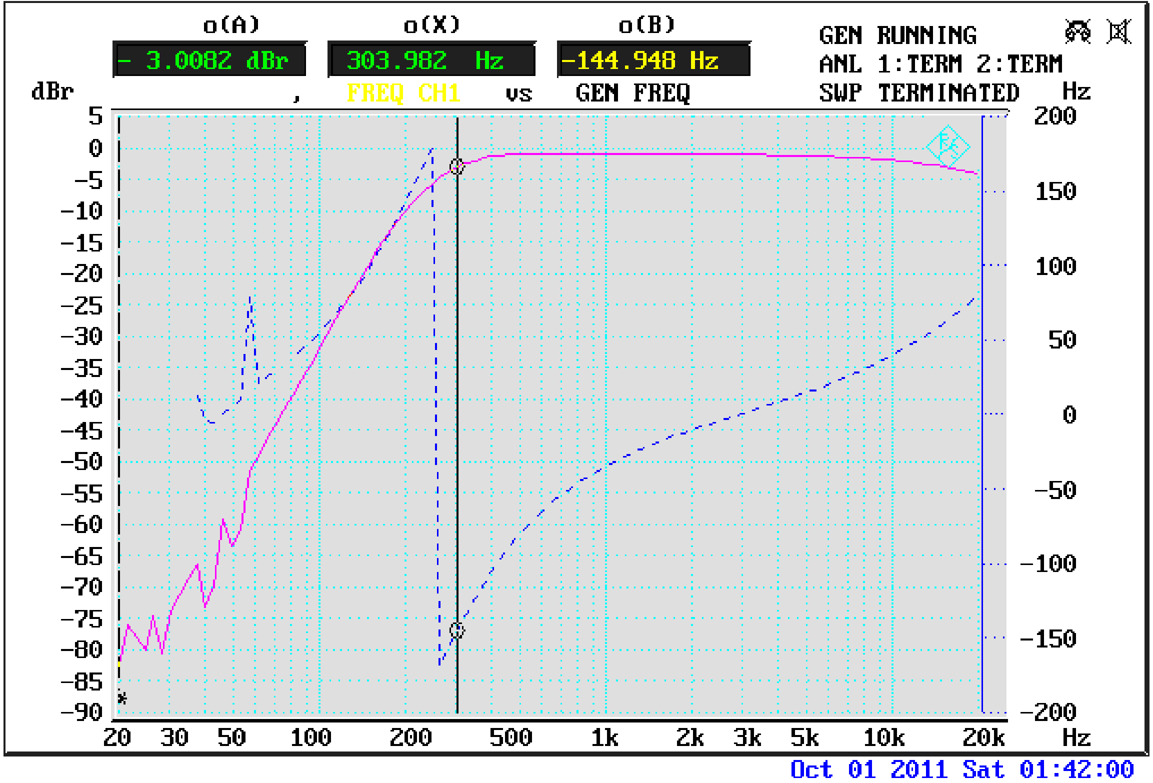

Figure 10: Frequency Response of 250 Hz High-Pass Filter

Troubleshooting

Oscillating Op-Amps

Op amps will oscillate when enough phase-lag is introduced into the feedback path by either the feedback components or by stray electrical properties caused by circuit layout. Although the SMN Audio EQ has been designed with short trace length in mind and proper power supply bypassing, all materials have capacitance, inductance, and resistance that are not accounted for in design schematics.

There are several ways to curtail oscillations in op amps, depending on the supposed problem. Op amps are not good at driving capacitive loads, and the ability to drive a 100 pF load is considered very good in terms of op amp ability. By putting a small resistance (10-100Ω) in series with the load, any load capacitance is isolated from the op-amp.

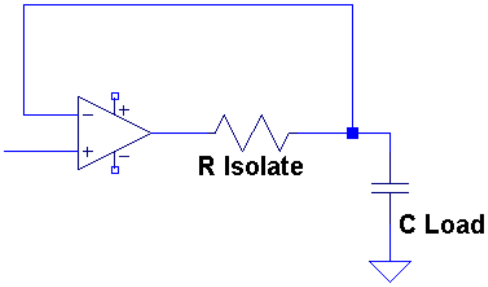

Figure 11: Isolating Capacitive Loads

Another cause of oscillations excessive phase lag in wide bandwidth op amps. Although audio frequencies are low compared to op amp performance capability, this does not mean that high frequency noise cannot be randomly introduced into an op-amp circuit. Depending on the frequency of noise and the phase margin available to the op amp, negative feedback may not be enough to reject the noise. Limiting the bandwidth of the op amp with a capacitor in the negative feedback path can solve this problem. Doing so will roll off gain towards unity before the op amp has too much phase lag. The pole introduced by this feedback cap is calculated by:

$\frac{1}{2\pi * R * C}$, where C is the added capacitor and R is the resistor in parallel with it.

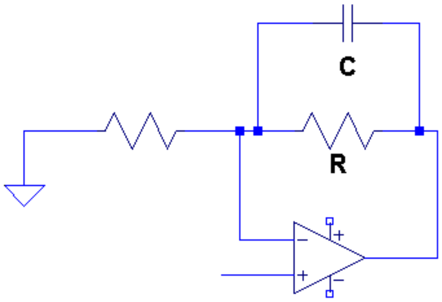

Figure 12: Bandwidth Limiting Capacitor

Lastly, an op amp circuit may oscillate because there is not enough gain. The gain and bandwidth of an op amp are related by a figure called the gain bandwidth product (GBW). Basically, if there is not enough gain, the bandwidth will be enough so that the op amp can operate in a region of excessive phase lag. Some op amps have versions that are not unity-gain stable, meaning that the internal compensation is not enough to make the op-amp stable as a unity gain buffer. Thus, stability must be achieved with the external feedback network in the form of more gain.

Signal Ground is Not Half the Supply Voltage

The most likely reason for this is a short somewhere in the circuit. If signal ground (the TLE2426 output) is 0 volts, there is a short to ground on the signal ground. If the signal ground deviates significantly from half the supply voltage, and it is not 0 volts, then the TLE2426 is sinking or sourcing too much current to remain in normal operation. This could be due to a short that is not ground, or if too much of a load is put on the TLE2426. Driving low-impedance headphones requiring more than +/- 20 mA would cause the TLE2426 to drop out of regulation.

There is a Significant DC Offset Between the Signal Ground and Output

All op amps have an inherent DC offset that is usually small and they also have an input bias current. Although the input bias current is usually small, forcing it across resistors that vary greatly in value at the inputs of the op amp will create a voltage difference to be amplified by the op amp. The solution is to make the resistance seen from the inputs equal along any DC path. Another possible solution is to choose an op amp with lower DC bias and lower input bias current.

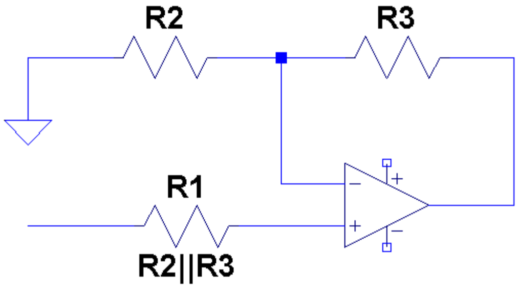

Figure 13: Making the Resistance Seen at Both Inputs Equal

The Output is Significantly Attenuated

Check the jumpers for the correct settings. Setting the output for inverting operation when the output is single-ended will result in no output signal. Grounding the – input on a differential signal will reduce the voltage swing by half. Check the gain resistors for their proper values, and that the op amp pins are not solder-bridged. Lastly, make sure the output current limits of the op amps and virtual ground are not exceeded.

Reference:

Lancaster, Don. Active Filter Cookbook, Second Edition. Great Britain: Newnes, 2002. Print.

Bill of Materials

Item	Qty	Reference	Value	Description	Manufacturer	Part Number	Package
0	21	R4 R28 R69 R70 R73 R76 R80 R81 TP1 TP2 TP3 TP4 TP5 TP6 TP7 TP8 TP9 TP10 TP11 TP12 TP13	DNI	Do Not Insert	N/A	DNI	N/A
1	4	C1 C9 C10 C15	0.47UF	CAP, 0.47UF, X7R, 1812, 50V, 10%	KEMET	C1812C474K5RAC	CSN_1206
2	2	C2 C3	1000pF	CAP, 1000pF, X7R, 1206, 50V, 10%	KEMET	C1206C102K5RAC	CSN_0603
3	12	C4 C5 C6 C7 C8 C12 C20 C65 C66 C67 C70 C75	100pF	CAP, 100PF, NPO, 0603, 50V, 10%	Panasonic	C0603C100p	CSN_0603
4	2	C11 C31		CAP 0603-2220, 200mil Through-Hole			OMNI-200MILTH
5	2	C13 C69	10uF	CAP, 10uF, 35V, AE, Case C	Panasonic	EEE-FK1V100R	CAPAE-C
6	8	C14 C40 C41 C42 C43 C52 C63 C64	0.1uF	CAP, 0.1UF, X7R, 0805, 50V, 10%	KEMET	C0805C104K5RAC	CSN_0805
7	1	C16	100uF	CAP, 100uF, 35V, AE, 8x10mm	Panasonic	EEEFP1V101AP	CAPAE-F
8	7	C17 C25 C68 C71 C72 C73 C74	1000pF	CAP, 1000PF, X7R, 0603, 50V, 10%	KEMET	C0603C102K5RAC	CSN_0603
9	2	C18 C62	1uF	CAP, 1uF, 25V, X7R, 0805	Murata	GCM21BR71E105K	CSN_0805
10	32	C21 C22 C23 C24 C26 C28 C29 C30 C32 C33 C34 C35 C36 C37 C38 C39 C44 C45 C46 C47 C48 C49 C50 C51 C54 C55 C56		CAP 0603-1206SMT			OMNI-SMT

		C57 C58 C59 C60 C61					
11	1	C27	10uF	CAP, 10uF, 25v, X7R, 1210	Murata	GCM32ER71E106K	CSN_1210
12	1	C53	0.1uF	CAP, 0.1UF, X7R, 0603, 16V, 10%	KEMET	C0603C104K4RAC	CSN_0603
13	1	D1	24V-TVS	TVS ZENER UNIDIRECT 600W 24V SMB	ON Semiconductor	1SMB24AT3G	DO-214AA
14	1	D2	MBRX160	DIODE, SCHOTTKY RECT, Low Vf, 1A, 60V, SOD-123	Micro Commercial	MBRX160-TP	SOD123
15	4	H1 H2 H3 H4		PCB Feature - 030 Target	N/A	DNI	TARGET-030
16	2	J1 J11	HDR4X2	STAKE HEADER, 4X2, 0.1" CTR, GOLD	SAMTEC	TSW-104-07-G-D	HDR4X2
17	2	J2 J4	HDR2X2	STAKE HEADER, 2X2, 0.1" CTR, GOLD	SAMTEC	TSW-102-07-G-D	HDR2X2
18	1	J5		2-Pin Screw Terminal Block	Kobiconn	158-P02EK381V2-E	SCREWTERMINAL150-2PIN
19	2	J6 J9	Red	CON RCA 1x1 RIght Angle	CUI Stack	RCJ-012	RCJ-012
20	2	J7 J10	White	CON RCA 1x1 RIght Angle	CUI Stack	RCJ-013	RCJ-012
21	1	J8	HDR2X1	STAKE HEADER, 2X1, 0.1"CTR, GOLD	SAMTEC	TSW-102-07-G-S	HDR2X1
22	1	L12	FB 0805	FBEAD,0805,600@100MHz,0.5AMPS	Steward	HZ0805E601R-10	IND_0805
23	12	R1 R2 R5 R6 R7 R8 R13 R43 R66 R71 R72 R86	22K1	RES, 22.1K , 0603, 1/16W, 1%, 200ppm	Phycomp	R0603V22K1	RES_0603
24	6	R3 R10 R74 R75 R90 R91	221	RES, 221 , 0603, 1/16W, 1%, 200ppm	Phycomp	R0603V221	RES_0603

25	44	R9 R11 R12 R14 R15 R17 R18 R19 R21 R22 R23 R25 R26 R27 R29 R30 R31 R32 R33 R35 R36 R37 R39 R40 R41 R42 R44 R45 R46 R47 R49 R50 R51 R53 R54 R55 R56 R57 R58 R59 R60 R62 R63 R64		RES 0603, 1/16W, 1%, 200ppm			RES_0603
26	1	R16	0 Ohm	RES, 0Ohm , 0603, 1/10W, 1%, 200ppm	Yageo	R0603V000	RES_0603
27	2	R67 R68	10K0	RES, 10K0 , 0603, 1/16W, 1%, 200ppm	Phycomp	R0603V10K0	RES_0603
28	1	U1	TLE2426	The 'Rail Splitter' Precision Virtual Ground	Texas Instruments	TLE2426CD	SO8-150
29	4	U2 U3 U4 U5	TL072	Dual JFET Op Amp	Texas Instruments	TL072CDR	SOIC-8
Total	**161**						

Simple Media Networks, Inc