Dual Method Headphone Amplifier

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Abstract

Many high impedance headphones underperform their full potential when directly connected to the audio source. Amplifiers boost the audio signal and provide the headphones with sufficient power to ensure their maximum performance. The invention of transistors caused vacuum tube implementation to decline, leaving many audiophiles unsatisfied with the transistor's sound signature. Vacuum tubes and transistors both amplify signals, however the distinct "tube sound" has vanished.

We have designed and created a product where the user selectively switches between solid-state transistor and tube amplification to compare the sound signatures of each amplification method. The ability to switch between the solid-state and tube amplifiers creates the ability to achieve a more customized sound for individual songs and improve the user's listening experience. This requires the design of two separate amplifiers and circuitry to switch back and forth between amplification methods without pausing the music or unplugging any device.

CHAPTER 1:

Introduction

High fidelity audio is slowly disappearing. High quality headphones are becoming scarce due to a rise in popularity of ear buds, fashionable headphones, and inability to properly interface to most audio sources. High-fi headphones often have large impedances and require more power than a common mp3 or laptop can output. To remedy this issue, headphone amplifiers take in an audio signal, amplify it with more power, and output it to the headphones. This allows any audio source to drive large impedance headphones.

Three main methods of audio amplification exist: vacuum triodes, solid-state transistors, and solid-state op-amps. All provide viable means of audio signal amplification, but provide very different sound signatures. Op-amps provide odd harmonics (3rd, 5th, 7th) [1]. Solid-state transistors provide a large 3rd harmonic, which gives a limited, metallic sound. Tubes provide whole spectrum distortion (2nd, 3rd, 4th, 5th harmonics) [1], giving a fuller sound. Even harmonics, innately, present more musical tones than odd harmonics. Many describe this as the "tube sound". In addition, tubes present smooth clipping, as they can run even in overload. Transistors do not run in overload, resulting in sharp clipping.

These distortion differences may be hard to audibly notice, but a device that actively switches between tube and solid-state amplification offers a direct comparison between sound signatures. Our dual-method amplifier provides a direct medium through which a user can compare the sound of each amplification method. In addition, we provide a 2-in-1 product: the user can choose which method they prefer at any given moment and can switch without the hassle of unplugging headphones or sources.

Many solid-state headphone amplifiers exist on the market, including the Rupert Neve RNHP [2], JDS Labs Objective2 [3], and Schiit Magni2 [4]. Although less frequent, tube headphone amplifiers also exist on the market, including the Schiit Vali 2 [5] and Hifiman EF2C [6]. However, through our Internet searches, we could not find a product that achieves active switching between amplification devices.

This dual method amplifier intends to create an easy comparison between sound signatures of tube and solid-state amplification. The intention of this report, is to explain the rationale and thoughts of the entire design and testing process.

Before design work begins, customer needs must be identified and used to create technical specifications and requirements.

CHAPTER 2:
Customer Needs, Requirements, and Specifications

Chapter 2 contains the criteria in which the amplifier should meet. By identifying customer needs and amplifier technical requirements, the project now has concrete goals that must be met.

Customer Needs Assessment

The Dual Headphone Amplifier targets audiophiles and high impedance headphones owners. We have concluded, through online forums and personal experience, that these groups require their audio equipment to precisely replicate the original audio signal. These assumptions helped to determine customer needs. Many users have multiple pairs of headphones and, thus, this amplifier must properly drive many different headphones. Distortion over the full audible (20Hz-20kHz) range and system noise must be kept at a minimum. The amplifier must have stereo output, volume controls, and an aesthetically pleasing design.

Requirements and Specifications

This project's number one priority is to create distortion-less audio amplification along the full audible range. Most high impedance headphones replicate the incoming audio signal very accurately; therefore, the incoming signal must possess noise-free and distortion-less characteristics. To achieve this, three characteristics must occur: the signal-to-noise ratio must remain above 70dB, the total harmonic distortion must remain below 0.1%, and crosstalk distortion must remain below -50dB. We also require volume control and stereo output. The amplifier must integrate with many different headphones at different impedances. By reducing the output resistance of the amplifier to fewer than 15 Ohms, most headphone models interface with this amplifier without worry of loading [7]. Cost must also remain relatively low to remain appealing to both audiophiles and poor college students with audio hobbyists. By comparing the technical specifications of other desktop headphone amplifiers near this price point [2,3,4,5,6], we obtained specific values for these requirements. These values give us achievable goals and allow us to stay competitive with other headphone amplifiers on the market. Table I tabulates the marketing requirements and engineering specifications identified for this amplifier project.

TABLE I
Dual Method Headphone Amplifier Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1, 2	Input impedance >100k Ohms at 1kHz Output impedance <15 Ohms at 1kHz	An input impedance of 100k Ohms provides high enough impedance to accept most audio inputs. Output impedance under 15 Ohms follows the 1/8 rule presented by NwAvGuy [7]
2, 6, 9	Total Harmonic distortion under 0.1% at 1kHz and 1VRMS	Based on other amplifier spec sheets [2,3,4], this presents an achievable value while maintaining a true-to-source audio signal.
3	SNR > 90dB at 1kHz	A large SNR ensures minimal audible noise. [2,3,4]
4, 8	Ability to adjust amplifier's volume between -∞dB and 32dB via external knob	Volume control on the amp itself prevents the need to directly change volume on the source. Contributes to ease of use.
5, 8	Smaller than 6"x6"x4"	Able to comfortably sit on a desk without impeding on desk space. Comparable size to other desktop headphone amplifiers
7	Visible tube	Everyone loves the tube glow!
2, 6, 9	Bandpass with <-0.5db points at 20Hz and 20kHz	Provides full audible range
2, 9	Left and Right channels with < -50dB crosstalk and <1dB balance at half volume from 20Hz-20kHz	Signals from left and right should not affect each other throughout full audible range. Left and Right channels balanced.
1,5,8	120V AC power input from typical wall plug	AC-DC converter to give the amplifier its proper power source (likely 12V or 24V)
1	Capable of supplying 100mW to a 250 Ohm load	Ensures maximum power for a common set of high impedance headphones, the Beyerdynamic DT 770 250 Ohms [8].
10	All live and conducting wires enclosed in chassis. All power connections properly shielded and protected from exposure.	No external "hot" wires, limits the risk of injury and shock. Any power circuitry must be contained within project and not exposed in accordance with NFPA 70 mains connection safety standards.
1	3.5mm input audio jack (female)	3.5mm audio connector, allows use with multiple sources
1	1/4" output audio jack (female)	High end headphones often have 1/4" male audio connector
2	1% tolerance resistors	Provides accurate simulations and ensures left and right channels behave similarly
2,3	Internal Temperature of amplifier unit cannot exceed 200 degrees F	The solid state and tube amplifiers within the project unit generate a substantial amount of heat. Adequate airflow and heat dissipating elements required. Temperatures beyond 200℉ affect electronics performance [9].

Marketing Requirements
1. Versatile (usable with many different headphones)
2. Low distortion
3. Low noise
4. Volume control
5. Relatively small
6. Full audio range
7. Aesthetically pleasing
8. Cost per unit <$250
9. Stereo output
10. Safe for use

With these requirements and specifications, top level design may begin, as shown in chapter 3.

Chapter 3
Functional Decomposition
Chapter 3 gives insight into the inner workings of the amplifier. It provides level 0 and level 1 block diagrams as well as lists of inputs and outputs.

This chapter displays the level 0 and level 1 block diagrams for the Dual Method Headphone Amplifier. Figure 1 displays the top-level block diagram for the Dual Method Headphone Amplifier. It identifies inputs, outputs, power, and user controls. Figure 2 displays the level 1 block diagram for the Dual Method Headphone Amplifier. It shows the power circuitry and the signal chain. Power derives from a 120 VAC source and converted to a 12VDC source for the amplifier components. The audio signal is input to the system from an mp3, laptop, or similar device, sent through a volume control potentiometer, and sent either to the tube amplifier or the solid-state amplifier. The functionality switch is a user input. The amplified signal then gets sent to an output stage with low output impedance, and out of the system into the headphones. Table II breaks down the inputs and outputs of the Level 0 block diagram. User inputs include volume control, functionality switch, and power switch. Table III identifies the inputs and outputs of each component in the level 1 block diagram.

Figure 1: Level 0 Block Diagram of the Dual Method Headphone Amplifier
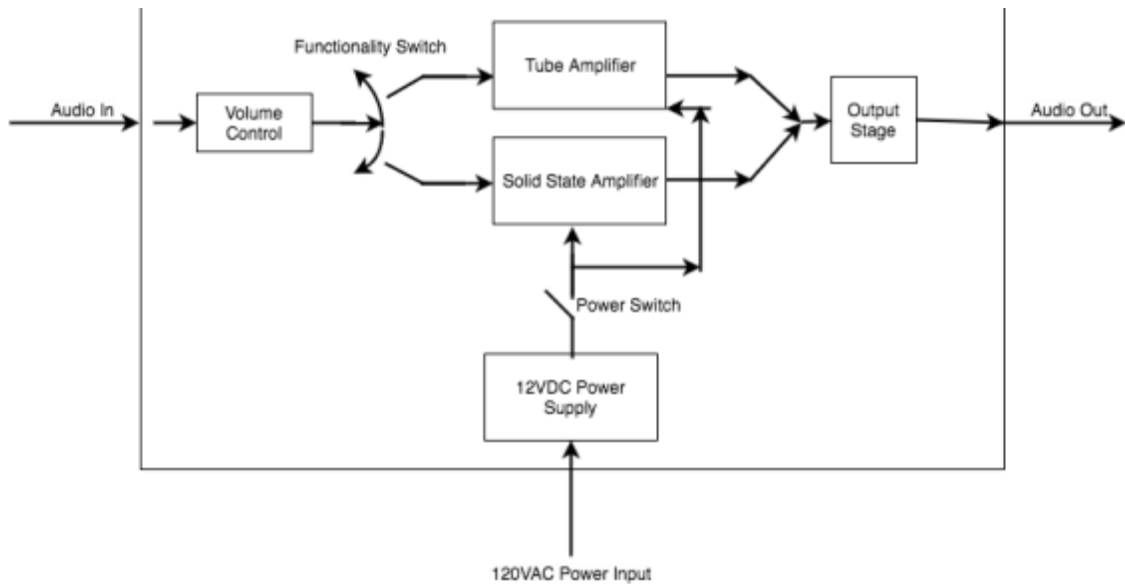
Figure 2: Level 1 Block Diagram of the Dual Method Amplification

TABLE II
Level 0 Block Diagram Functionality Table

Module	Dual Headphone Amplifier
Inputs	-Audio In: Input audio signal from source .5V DC -Volume Control: Knob controls potentiometer to attenuate audio signal -120V AC Power: 120 VRMS, 60Hz -Functionality Switch: binary switch to swap between tube amplifier and solid state -Power Switch: Binary switch to turn amplifier on or off
Outputs	-Audio Output: 5V
Functionality	Amplifies the audio in signal using either tube or solid-state amplification.

TABLE III
Level 1 Block Diagram Functionality Table

Module	Dual Headphone Amplifier
System Inputs	- Input: audio signal from source - Input: 120V AC Power: 120 VRMS, 60Hz
Volume Control	-Input: Manual knob controls potentiometer to attenuate audio signal -Output: Volume-adjusted audio signal Provides user volume control between -∞dB and 32dB
Functionality Switch	-Input: Manual switch or button (binary) to switch between tube amplification and solid state amplification -Output: Unchanged, volume-adjusted audio signal Provides user control for amplification method
12VDC Power Supply	-Input: 120VAC -Output: 12VDC provides power source for all components Supplies 12VDC for all components
Power Switch	-Input: Manual switch or button to provide DC power to the system -Output: 12VDC supply Controls power to system
Tube Amplifier	-Input: Volume adjusted audio signal -Input: 12VDC supply -Output: Large audio signal Amplifies audio signal with little noise and distortion
Solid State Amplifier	-Input: Small audio signal input -Input: 12VDC supply -Output: Large audio signal Amplifies audio signal with little noise and distortion
Output Stage	-Input: Large audio signal -Output: Equivalent large audio signal Low Rout to prevent loading from low impedance headphones
System Outputs	-Output large audio signal output

To ensure this project can be completed within the 3 quarters expected for a senior project, important dates are identified, and a Gantt chart are presented in chapter 4. In addition, project cost is estimated.

Chapter 4
Project Planning (Gantt Chart and Cost Estimates)
Chapter 4 presents project planning estimates. This includes key dates, Gantt Charts, and cost estimates.

Table IV lists project deliverables throughout the entire design and build process. It provides deadlines for reports and demos. Table V displays an estimate of total project cost. By listing each component and their estimated cost, it becomes clear where money needs to be allocated. Labor cost is included and listed as $30/hour as this presents a reasonable salary for an entry-level engineer.

TABLE IV
Dual Method Headphone Amplifier Deliverables

Delivery Date	Deliverable Description
April 28, 2017	Design Review
May 12, 2017	Prototype solid state amplifier
May 19, 2017	EE 461 demo
May 31, 2017	Prototype Tube amplifier
June 9, 2017	EE 461 report
Sept. 1, 2017	PCB design finalized
Nov. 28, 2017	EE 462 demo
Nov. 30 2017	Sr. Project Expo Poster
Dec. 4, 2017	EE 462 Report

TABLE V
Dual Method Headphone Amplifier Cost Estimation

Item	Cost Type (Labor/ Component)	Cost Estimate	Cost Justification
Audio Grade Vacuum Tube	Component	$22.50	An audio optimized vacuum tube provides best sound quality. Worth the investment
1% tolerant resistors	Component	$10	1% resistors can be costly. 1% required to obtain consistent gain and frequency responses
Audio Grade Capacitors	Components	$10	Capacitors must remain small and introduce minimal distortion on the circuitry
Vacuum Tube Amplifier Support Circuitry (includes knobs and jacks	Component	$10	Support circuitry enables amplifier operation, a non-negotiable expense. Cheap components easily obtainable on sites like Digikey or Mouser
Audio Grade Op-Amp	Component	$5	Like the vacuum tube, an audio optimized op-amp allows best sound quality for our solid state amplifier

PCB Fabrication (x2 custom boards)	Component	$106	PCB's allow better project integration. A large expenditure because market rates vary on PCB fab and project size.
Amplifier Chassis with machined holes	Component	$40	The project needs enclosure for protection safeguard against any power discharge due to the high power requirements of the amplifier.
Circuitry for Amplifier Switching	Component	$3	Project operation requires the ability to switch between the solid state and tube amplifier.
Shipping Costs	Labor/ Component	$35	Shipping costs inevitably incur. May vary.
Design/Assembly Costs (Assuming a $30/hour wage)	Labor	$4500 per person (based on 150 hours of design and assembly activity)	In a hypothetical production situation, $30/hour represents a reasonable entry-level engineer pay.
Troubleshooting and Testing (Assuming a $20/hour wage)	Labor	$1500 per person (based on 50 hours of testing and troubleshoots)	Same justification as above.

Estimated Overall Cost Based on Labor	$12,000
Estimated Overall Cost Neglecting Labor and Custom PCB's (most realistic estimate)	$241.50

*Costs estimates based on PERT:

$$\$ = \frac{costa + 4*costb + costc}{6}$$

Where cost a=most optimistic cost, cost b=most realistic cost, and cost c=worst-case cost.
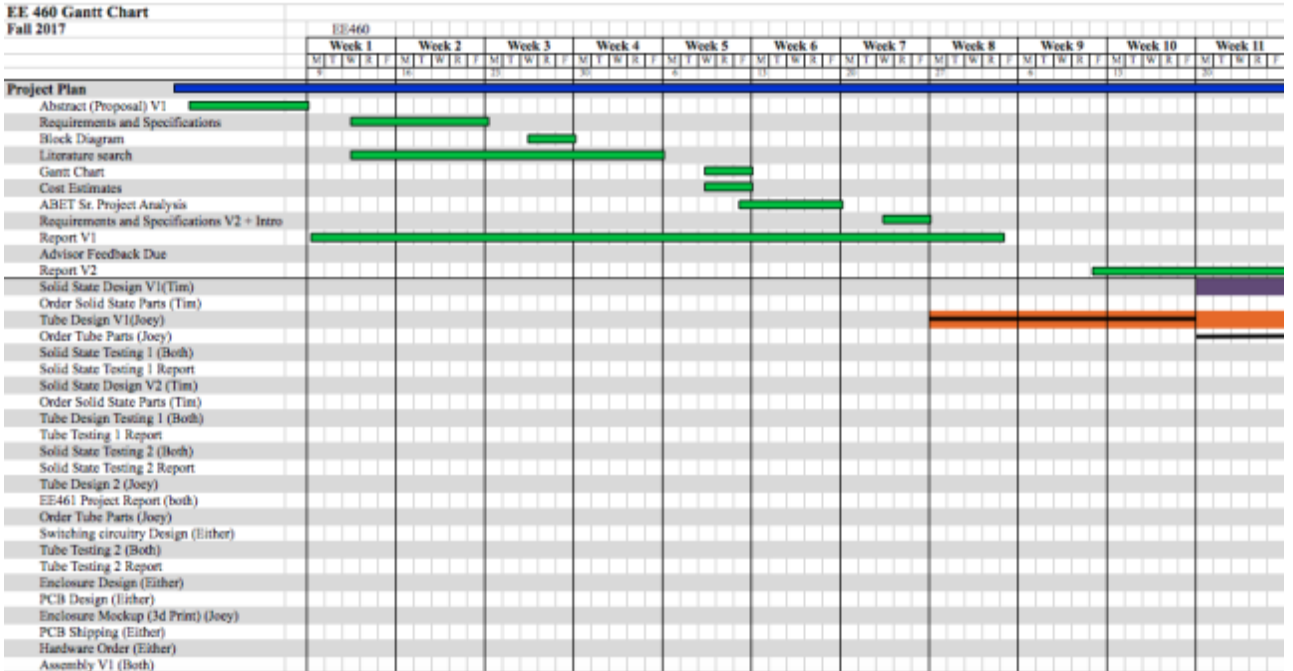
Figure 3: EE460 Gantt Chart

*Time estimates based on PERT:

$$Estimated = \frac{time_a + 4*time_b + time_c}{6}$$

Where time a represents the most optimistic amount of time, time b represents the most realistic time estimate, and time c represents the worst-case time estimate.
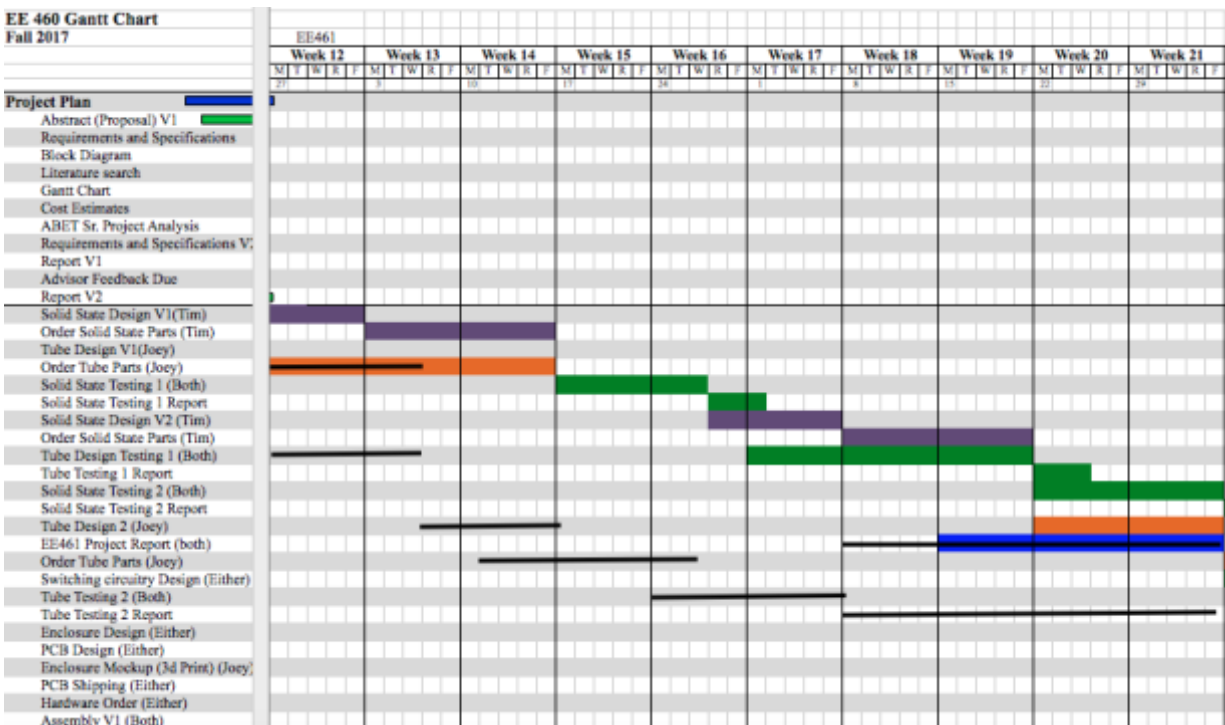
Figure 4: EE461 Gantt Chart (see page 12)
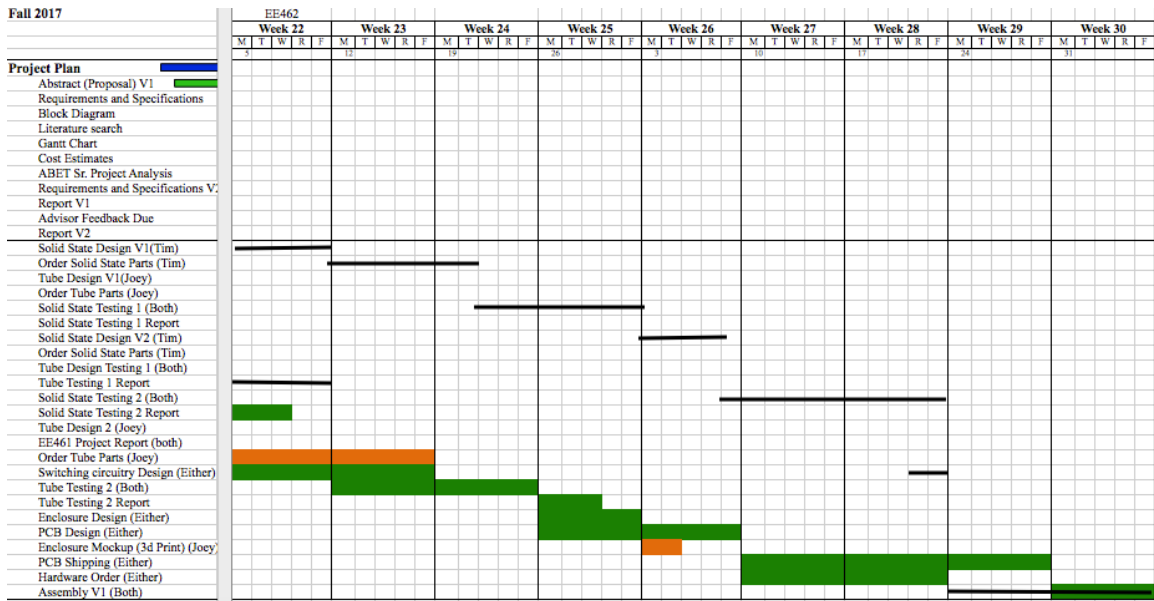
Figure 5: EE462 Gantt Chart

Figures 3, 4, and 5 provide a reasonable timeline for project completion. It lists various benchmarks and design iterations throughout the design and building process

Once the Gantt chart is completed with our estimated timing, physical building and testing can begin. This process is documented in chapters 5-10.

Chapter 5:

Phase I: Initial Triode Vacuum Tube Amplifier Prototyping

Chapter 5 contains a narrative of the design process in regard to initial prototyping of the triode amplifier. Thought processes are outlined along with data from testing and issues that may have occurred.

Design and construction of the vacuum tube amplifier portion of the project began on April 7, 2017, the beginning of Spring Quarter. Coming into the initial phase of the project, we, as a group, had an initial idea of what type of vacuum tube amplifier the project should base itself on. Hoping to save time on design, an existing triode vacuum tube amplifier design was chosen from a DIY audio enthusiast website as pictured in Figure 6 [41].
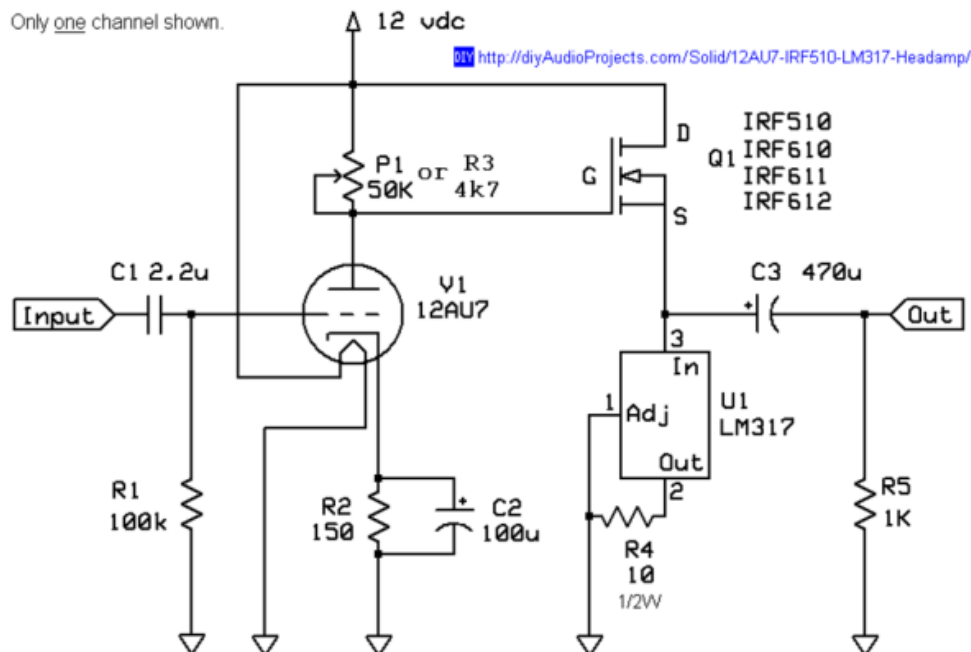
Figure 6: Initial Vacuum Tube Amplifier design [41]

However, given lack of collective experience with vacuum tube electronics, there was no certainty on how the circuit worked. Dr. Braun, the project advisor, gave a name of a fellow student, Justin Jee, who had project experience working with vacuum tubes. We managed to meet with Justin Jee, and got information on how vacuum tube electronics work as well as an understanding of the proposed triode amplifier circuit. Based on what Justin said, the circuit in Figure 6 used the triode vacuum tube as a "tone conditioning" stage rather than an actual amplifier. The MOSFET pictured as Q1 in Figure VI does most the amplification. Using the triode as the main source of amplification requires the plate voltage (pictured as 12 VDC in Figure 6) to sit at something higher than 12 Volts DC, elimination of the MOSFET and utilization of an output stage circuit. Such a scheme provides a viable gain stage solely driven by the triode vacuum tube. Armed with this information, the initial design work began on a triode gain stage.

Modifying the amplifier in Figure 6 to a pure triode gain stage required hands on vacuum tube experience, which was we as a group lacked. Gaining this experience merited building a basic triode amplifier layout like the "common cathode" configuration seen in Figure 7. Surprisingly, the common cathode configuration looks very similar to common source BJT amplifier. As it turns out common contemporary transistor circuits derive from previous vacuum tube circuits. A common cathode triode amplifier was constructed using a 12AT7 triode donated from the EE department. It took some adjustment to get used to the pinout of a vacuum tube as pictured in Figure 8. Six of the tube pins go to two triodes while the other 3 pins belong to the heating circuit that makes the vacuum tube work. Once a basic amplifier circuit was wired, experimentation with different gain values began by adjusting resistor values and using a 30 Volt plate voltage (HT+ in Figure 7). Varying the resistor Ra in the common cathode circuit with 4.7 kΩ, 10 kΩ, and 220 kΩ, produced gains of about 8.5, 9, and 11 V/V. These results indicated that looking at a vacuum tube characterization was required.
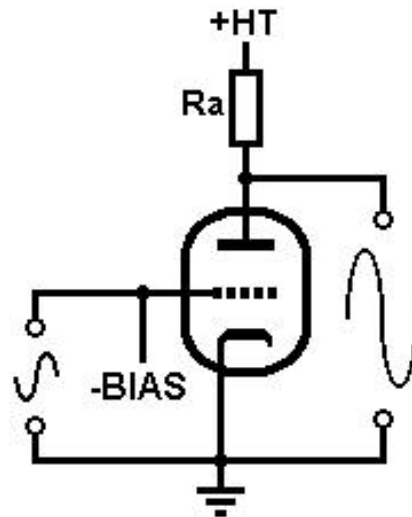
Figure 7: Common Cathode Amplifier Test Circuit [39]
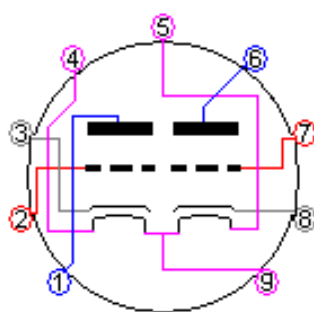
Figure 8: Generic Dual Triode Vacuum Tube Pinout [40]

Biasing the triode vacuum tube in a suitable region was paramount to design direction. Having characterization data on a triode tube would help discern what constitutes a suitable bias region. Unfortunately, there was no technical documentation for most of the

tubes that were donated by the EE department. Because of this, device characterization now relied on running voltage sweeps on a singular tube. An old Westinghouse 12AT7 triode served as the first characterization test bed. Figure 9a displays the results of this test while Figure 9b shows characterization setup.
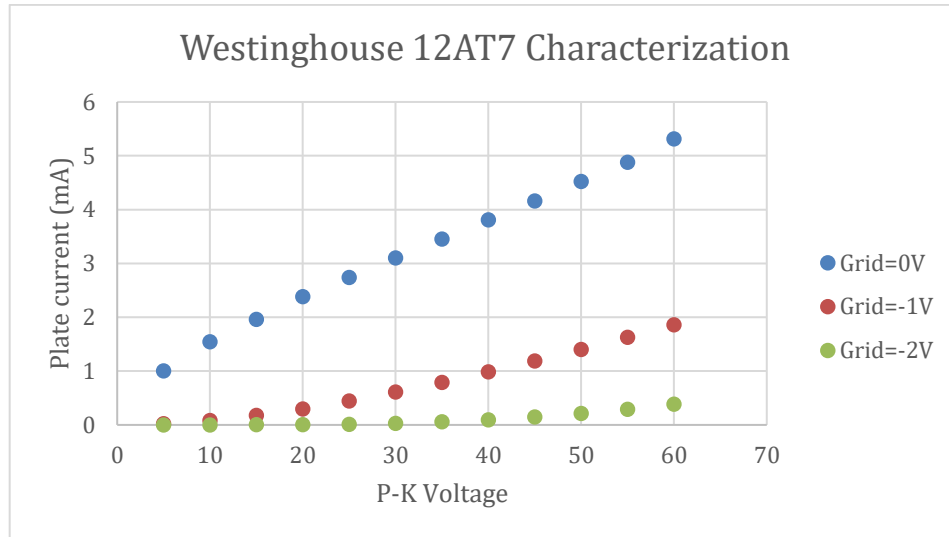
Figure 9a: Westinghouse 12AT7 Tube Characterization
*Note P-K stands for voltage between plate and cathode. Grid numbers indicate voltage applied at Grid.
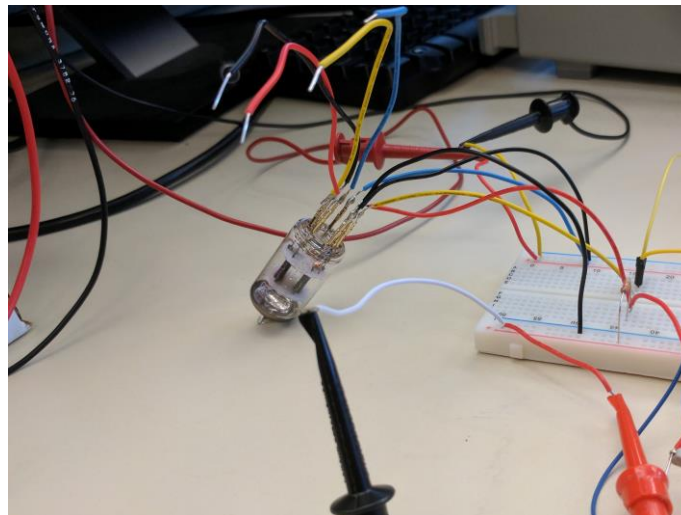
Figure 9b: Westinghouse 12AT7 Characterization Setup

By inspection of the figure 9a data, increasing the PK voltage produces more gain. A search of online datasheets indicated that 12AX7 type triodes produce a higher gain compared to a 12AT7 when driving the PK voltage higher. Aiming for better amplifier gain, a new production JJ Electronic ECC803S (12AX7) triode was purchased [21]. It was decided that to test the new triode in a basic amplifier setting, a version of the Figure 6 circuit should be utilized. However, the MOSFET was omitted and the value of R5 adjusted to 220 kΩ. The idea was to get the amp set up as a common cathode

amplifier since the goal was to make the amplifier purely triode driven. Testing the JJ ECC803S triode at a 60V plate voltage in this new circuit configuration only produced a gain in the 10-12 V/V range. At the time, this did not seem like much. Interestingly, when we compared the ECC803 and to the old 12AT7 in the modified circuit, the 12AT7 produced a larger gain than the 12AX7. It still did not produce gain as large as desired. The initial goal called for gain of around 30 V/V not the 20 V/V produced by the modified circuit using the 12AX7 triode. The 12AT7 triode produced a gain close to 30 V/V in the modified Figure 6 circuit configuration, which was close to the initial gain goal. The 12AT7 tube appeared the better triode for driving the amplifier circuit. However, a newer 12AT7 was required to ensure more accurate gain measurements because the old Westinghouse 12AT7 tube possessed unknown wear. A new production 12AT7 was procured from JJ Electronic. But, before any further testing could begin on the new 12AT7 tube, a 1 MΩ potentiometer was added to the input modified circuit 6 input to allow volume control. See Figure 10 for the modified Figure 6 design.
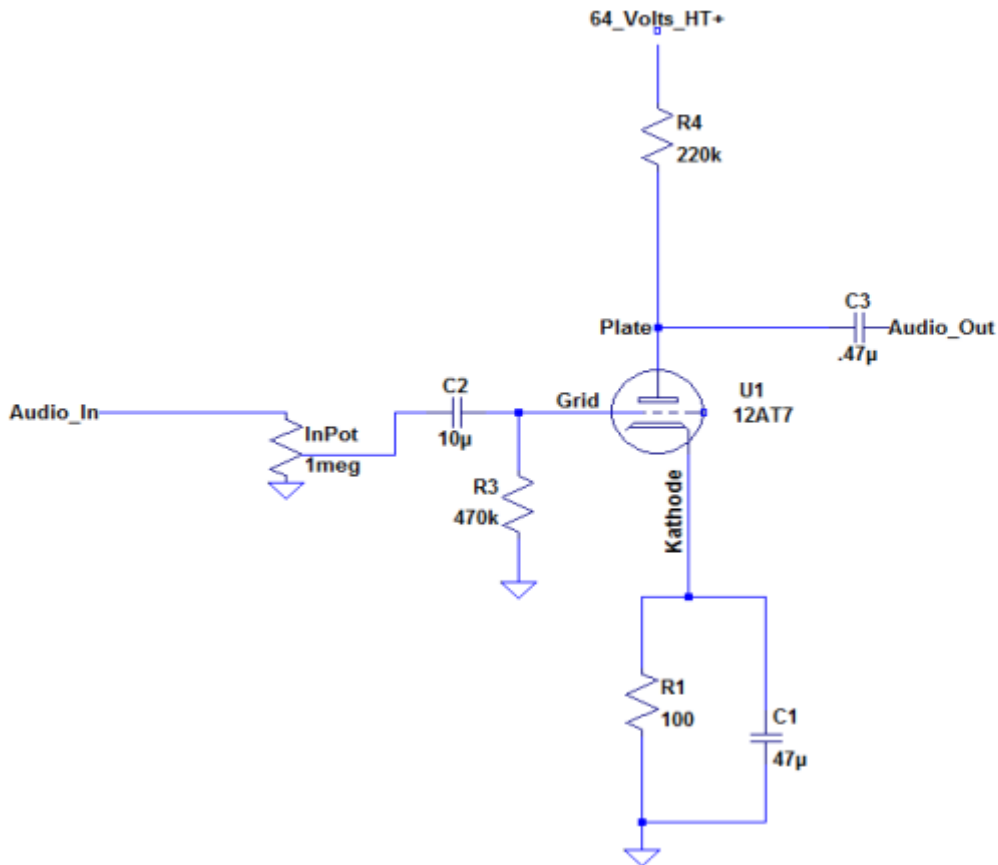
Figure 10: Modified Figure 6 Triode Amplifier Circuit

The new JJ Electronic 12AT7 triode tube worked flawlessly with the Figure 10 circuit. Gain remained the same from when the Westinghouse 12AT7 tube was in the circuit. For a gain comparison over audible frequencies (20 Hz to 20 kHz), frequency response

measurements were performed on the new JJ 12AT7 and 12AX7 tubes. Tests were conducted at a plate voltage of 64 VDC (refer to Figure 11).
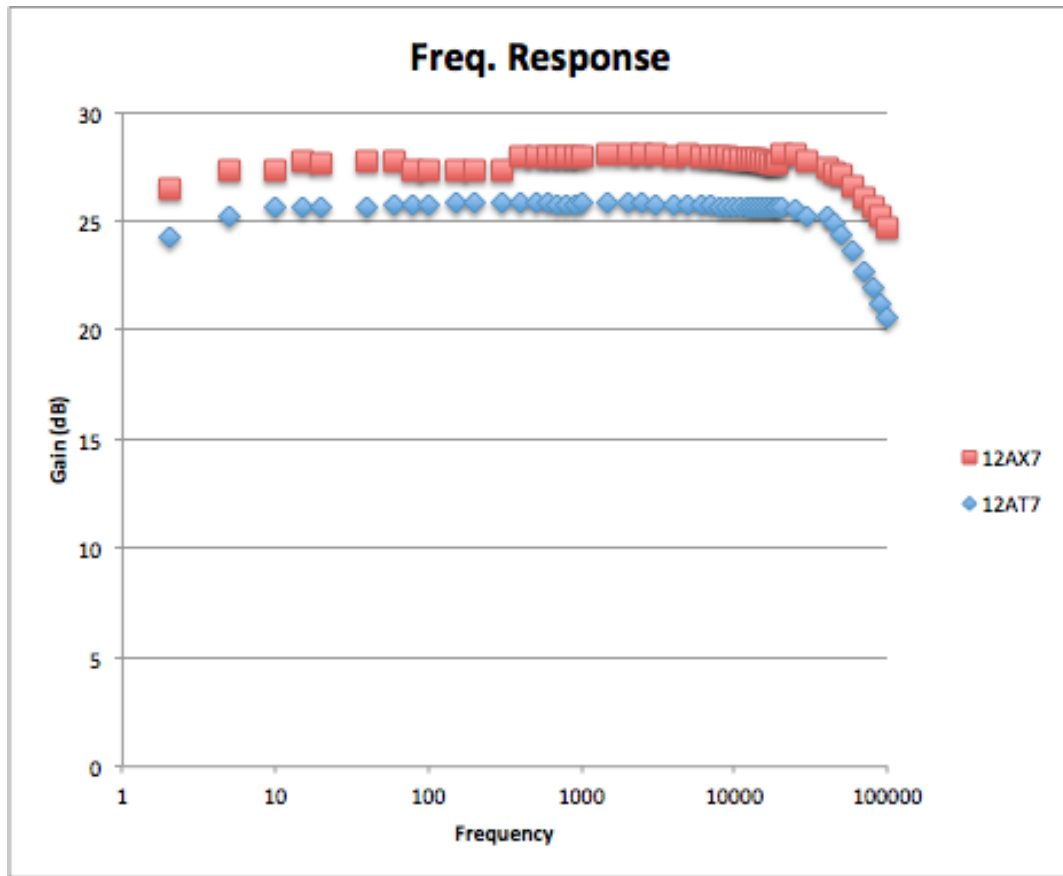
Figure 11: Single Channel Frequency response of 12AT7 and 12AX7 with Plate Voltage = 64 VDC

The frequency response test using the new circuit layout confirmed datasheet suggestions rather than our empirical observations. Initial observations pegged the 12AT7 having a higher gain the 12AX7. Using the updated Figure 6 circuit, the 12AX7 produced a higher gain. This matches what vacuum tube datasheets suggest: 12AX7 tubes produce larger gains than 12AT7 type tubes. The frequency response test clearly indicated that the 12AX7 should serve the primary tube in the amplifier circuit. Increasing R4 (in reference to Figure 6) to 220 kΩ and putting in a 1 MΩ parallel input pot, most likely changed the DC biasing of the triode. Such a bias change mostly likely put the 12AT7 in a region where it could not produce as much gain as the 12AX7.

With basic amplifier configuration solidified, two issues needed addressing: power and output staging. In terms of power, the circuit required two operating voltages: 64 VDC for the triode plate and 12 VDC to run the triode heating circuit and output stages. Given such specific operating voltages, design started to turn toward the use of a linear power supply. The main problem was that most transformer taps in linear power supply circuits lacked the specific voltages the design merits. Most transformers step down 120 VRMS to voltages like 70 VRMS, 50 VRMS, 20 VRMS etc. Finding a transformer that could

give a 12 Volt tap along with a 64 Volt tap while keeping costs low was difficult. Bearing costs and available voltage taps in mind, a transformer was found online that could step down 120 Volts to 50 VRMS and 12 VRMS for around $43. This specific transformer provided roughly the voltages the desired voltages for the design while not blowing budget out on components. However, we now had to increase the plate voltage to 70 VDC, which would increase our gain. Aside from the power, we needed to develop an output stage for our amplifier. The circuit pictured in Figure 10 couldn't drive a low ohmic load like a 30Ω headphone. Our tube amplifier, like most single end amp designs, has too high of a output impedance to drive low resistive loads. We needed an output stage to ensure the amplifier load stays consistent despite different headphone impedances. Rather than spend the time and energy on developing an output stage from components, we decided to buy an integrated audio buffer IC. Luckily, we found just what we needed on the Texas Instruments catalog, the LME49600 headphone buffer pictured in Figure 12. TI specifically optimized this buffer for headphone applications. The data sheet shows low total harmonic distortion margins (THD) as well as high max output current ratings (250mA) [38]. However, we neglected to check on the power dissipation and input voltage limit of the buffer. Later, this neglect would come back to hurt us. The buffer seemed like a ideal fit for our project so we proceeded to order a set of buffer IC's.
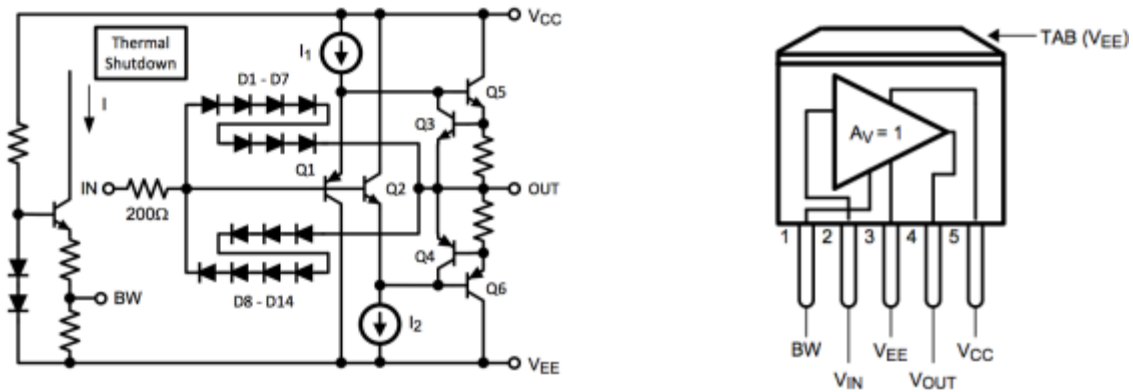
Figure 12: LME49600 Output Buffer Circuit [38]

With the vacuum tube amplifier fully configured and our output stage sorted out, we began the last round of frequency response tests and audio tests using the tube amplifier circuit and output buffer. We decided to test one buffer by itself to see if it worked. We passed in a 4.5Vpp signal and got a 4.3Vpp signal at the unloaded output of the buffer. The buffer gave us a gain of .95 v/v, very close to the datasheet specification of .98 v/v. With confirmation that the buffer worked, we proceeded to wire in one buffer with a 32Ω load on triode #2 to simulate a complete singular stereo channel with simulated headphone load in our audio amp. Refer to figure 13 for complete stereo channel circuit. Testing the output of the buffer with the 32Ω load we got a clean amplified signal. We next tried loading the buffer with 100Ω load we saw another clean amplified signal. The results of these loaded tests indicated our buffer performed as expected with low impedance loads. The convenience of the LME49600 buffer as a output stage came at a cost: ease of prototyping. The buffer came in a TO-263 surface mount package [38],

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which has no connection ability in a breadboard setting. Wires were soldered onto the leads of the buffer IC. However, these buffer-wire connections proved very delicate and broke often. When working on our amp, we would often have to re-solder the wires. We now needed to find a way to better integrate our buffers into our project. Luckily on DigiKey.com, DIP package adapters for TO-263 surface mount packages were found and ordered to make our buffer setup manageable.
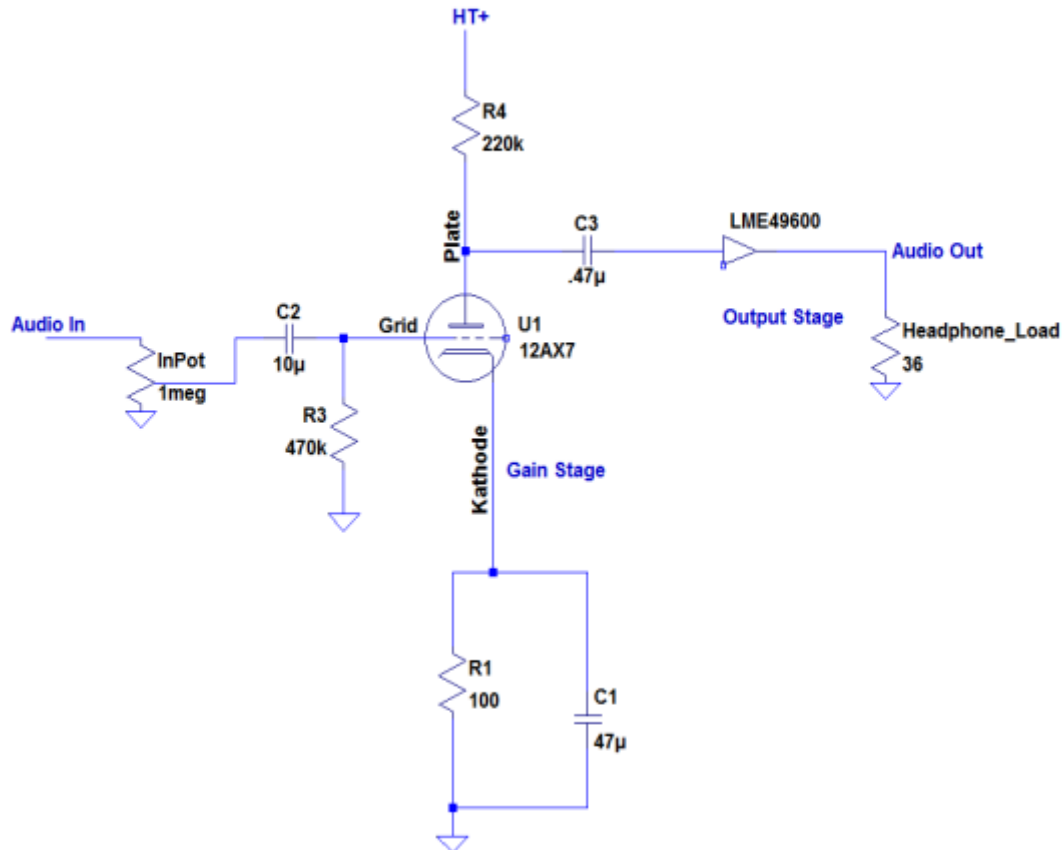
Figure 13: Complete triode audio amplifier for a singular stereo channel
*HT+ is our plate voltage of 64 Volts in this figure
**LME49600 utilizes supply voltages of + and - 12VDC

With confirmation that the amplifier and the buffer worked well together, we initiated more frequency response tests. Using only one channel, we tested the amplifier using a 100 mVpp input sine wave and varied the frequency between 5 Hz and 50 kHz while loading the output with 32 ohms. The results in figure 14 look promising. Throughout the audible range, the amplifier successfully drove a 32Ω load with a consistent gain of about 28 dB (26.94 v/v) (volume pot turned all the way up).
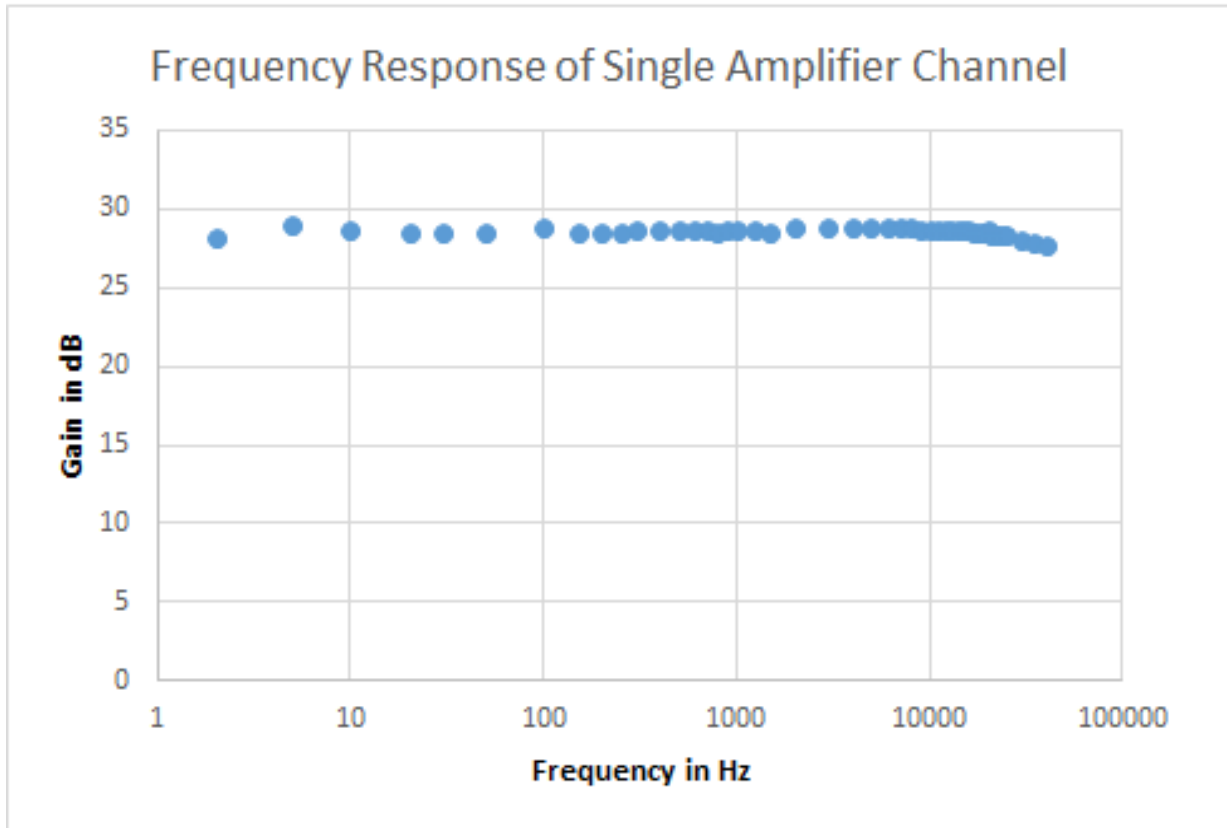
Figure 14: Frequency Response of Triode Amplifier's Right Channel
*This setup includes amplifier and LME49600 buffer with a 32Ω load

With the right channel of the amplifier working, the left channel was constructed using the same circuit design. Initial testing of the amplifier's left channel sans the output buffer looked good. Gain roughly matched the right channel, and no distortion manifested. However, as soon as the output buffer was connected with a 32Ω load, issues became present. On the oscilloscope, distortion became evident on both amplifier channels. The initial thought was that crosstalk was the cause, buffers were isolated to see if that would fix the issue. It did not. Instead distortion remained, and the buffer IC's became scorching hot. The buffer IC's were never given heatsinks because excessive heat was never considered a issue. Distortion got worse, eventually load resistors got burning hot, and our amplified signal terminated. After some probing with the oscilloscope, it was determined the buffers were fried, luckily the tube amplifier remained intact. Unsure what went wrong with the buffers, senior project advisor Dr. Braun was consulted. Dr. Braun believed that the buffers fried most likely due to the combination of heat and high input voltage. He suggested that the LME49600 buffer datasheet may contain input voltage limit information as well as power dissipation. Now that heat rejection represents a major issue for the project, heatsinks became absolutely necessary for the buffer IC's.

Figuring out heatsinking for the LME49600 required rough thermal calculations for how much heat is dissipated when the buffer runs. The LME49600 datasheet [38] provided equations and graphs to help predict heat dissipation. Assuming 25°C ambient temperature and max temperature of 85°C, the max power dissipation calculated out to

.923W. Using ±12 Volts supply and quiescent current of 10.5mA, and an output current of .03mA, the total power dissipation is .2817 Watts. This shows that under normal operation (input voltage <3 Volts), the heat of the buffer should not present any issues. However, the triode tube amplifier produces output voltages larger than 3 Volts, at this point heatsinks were required to prevent further damage. Additionally, keeping the volume pot at a low setting, ensures the input threshold voltage of the buffer stays below its maximum. Addressing the heating issue, a copper heatsink with a 1 in^2 surface area allows enough heat dissipation for the buffers. The Aavid Thermalloy TO-263 was chosen as the necessary heat dissipating element

Aside from figuring out the heat dissipation, thoughts began to shift was to what represents a necessary gain of the triode amplifier. The initial goal involved a gain greater than 24 v/v, however we realized that in audio applications current gain represents an equally important factor as voltage gain. Because the output buffer amplifies current, not much voltage gain from the tube is required to supply sufficient power to the headphones. When the load resistors began heating up, this indicated that too much power was supplied to the load. As a solution, the plate voltage was dropped to a much more manageable 24 VDC. Gain expectedly decreased and load resistors no longer got hot. Once new buffers and heatsinks arrived more frequency response tests were performed on both tube amplifier channels amplifier using a 24 VDC supply (Figures 15 and 16). Gain remained stable throughout 5-10 KHz with only slight falloff at higher frequencies. Overall, this frequency response provides gain within 1dB of max over the full audible range. Although our goal was to be within 0.5dB of max over audible range, the results pleased.

The gain differential between left and right channels was also slightly troublesome, most likely an artifact of vacuum tubes in general. A new production balanced triode tube solves this issue.
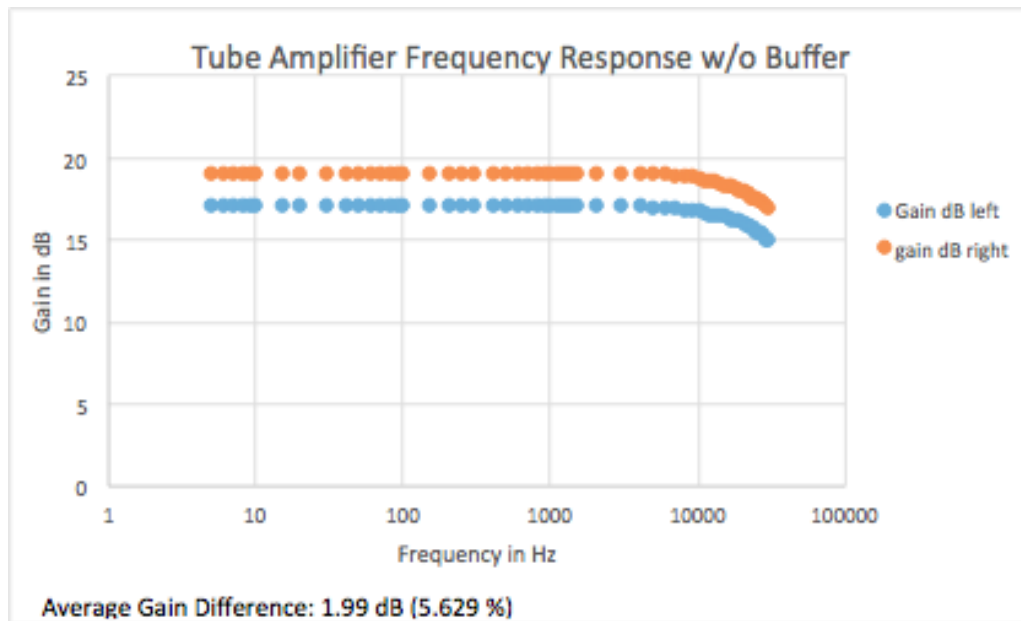
Figure 15: Frequency Response (without buffer) of Triode Amplifier with HT+ at 24V

*Load of 6.8MΩ used to simulate the input resistance of the buffer

Tube Amplifier Frequency Response With Buffer
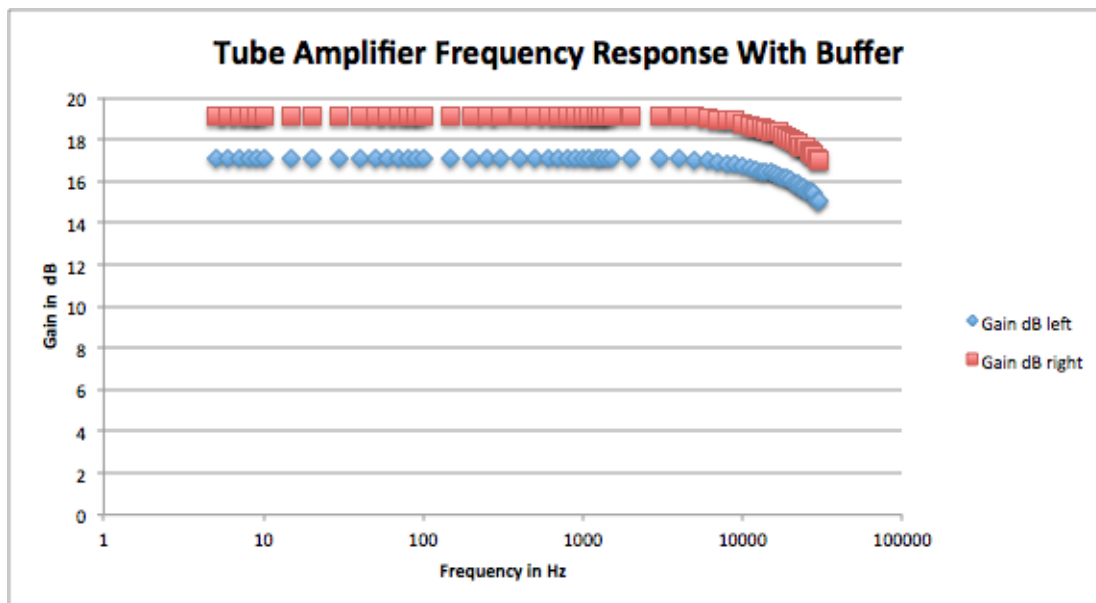
Figure 16: Frequency Response (with buffer) of Triode Amplifier with HT+ at 24V
*Load of 32Ω used

Using the 24V plate voltage (HT+) and heatsinked buffers seemed to solve the heating issues. Both buffer IC's and the load resistors remained cool throughout all tests, even when input voltage spiked slightly above 3V. These results gave confidence to try plugging in headphones and testing to see if the amplifier outputs a proper audio signal. Testing the full amplifier setup, a pair of Beats by Dre Solo 45Ω impedance headphones were hooked into a stereo jack at buffer output. Audio was successfully outputted over both left and right channels. For the most part, audio seemed clear, undistorted, and had the nice "organic" tube noise. However, with the volume turned all the way down, power supply noise was audible. Besides power noise, AM signal interference was present. An official enclosure for our amplifier, in theory, resolves much of the outside EM noise.

With our triode vacuum tube amplifier fully operational (see Figure 17 below) we can now prepare for Phase II of our senior project, the solid-state audio amplifier. The only remaining task for the triode tube headphone amp is to finalize our source of power for the setup. With the plate voltage lowered to 24V, the setup can run off a 24V wall adapter instead of a large linear power supply with diode bridges and transformers. Additionally, adding voltage regulators to the 24V power input from the adapter ensures a steady 24 VDC and 12 VDC supply to our triode amplifier. With a plan in place for power, we stand in a good position now to commence Phase II over the summer and by Fall quarter the two amplifiers should be ready for integration into one enclosure.

Figure 17: Complete Triode Stereo Headphone Amplifier
*HT+ = 24 VDC and VCC = +12VDC and VEE = -12VDC

Chapter 6:

Phase II: Adapting the Triode Amplifier to a Split 12 VDC Supply
Chapter 6 outlines the process of fine tuning the triode amplifier alongside developing a split rail supply for the amplifier.

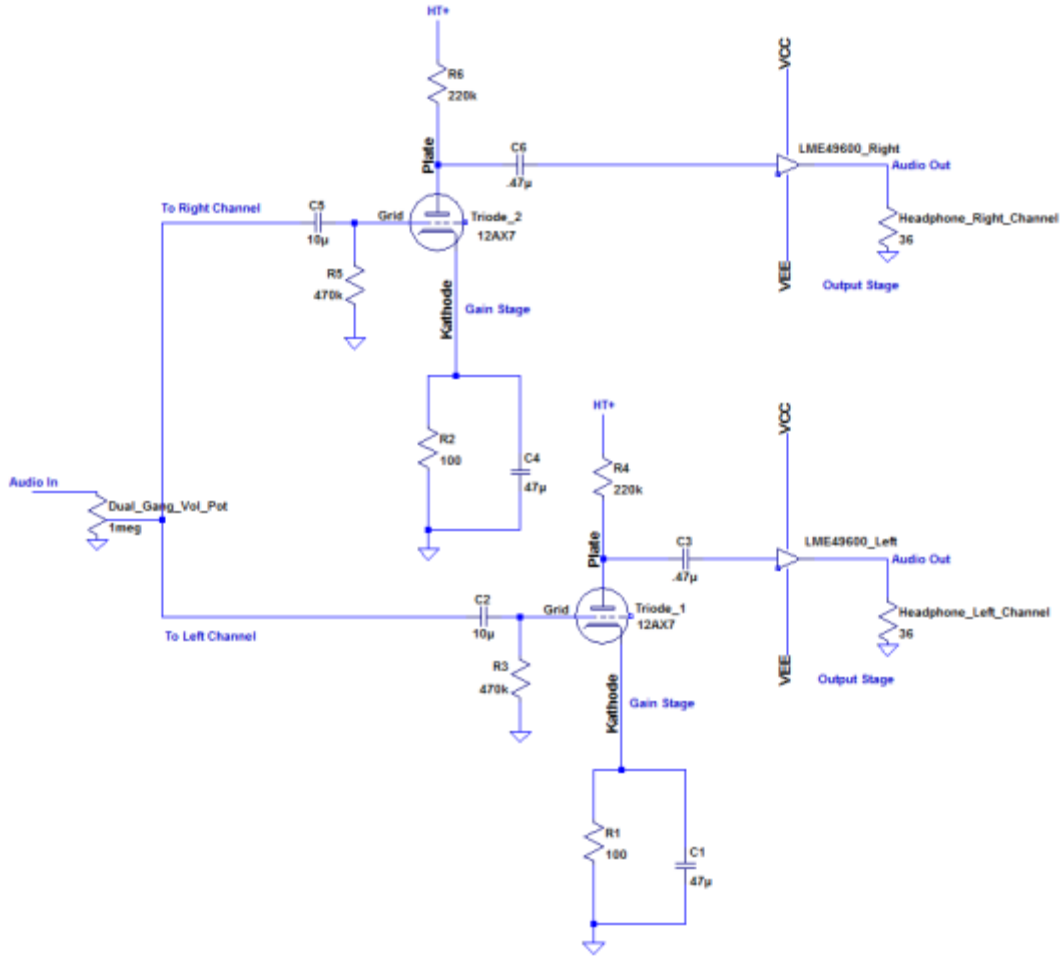Following the initial completion of the triode amplifier at the end of spring quarter, the next phase of the project began work on finalizing the power supply of the amplifier. Given the output buffers required a +/- 12 Volt supply and our triode amplifier biased at a 0 to 24 Volt potential, the project demanded a split rail supply. Due to the time remaining, we decided against designing and building our own power supply. The collective lack of experience in sizing transformers along with working with the uncertainty of handling high voltage electronics would only hinder progress on the project. As a group, we chose a switched mode power supply, a 24 Volt wall adapter coupled with a voltage regulator to split the 24Volts and regulate it to +/- 12 Volts. This option seemed like an easier implementation since it did not require the use of a complex rectifier circuit coupled with a heavy transformer. The Mean Well SGA60U24 24 Volt wall adapter seemed well suited for the power requirements primarily because it possessed a 500mA current rating. A 500 mA rating gives a "cushion," so to speak, in terms of current draw. Based on previous measurements the triode amplifier coupled with the buffers at max drew about 158.66 mA, which leaves about 341.34 mA of safe current draw from the 24V wall adapter. The amount of leftover available current was more than enough to accommodate any loading from our solid-state amplifier. With a 24 Volt wall adapter selected, we next determined an appropriate regulation circuit to split the 24 Volts into +/- 12 Volts rails. The Microchip Technologies MIC29300 proved an ideal candidate for the job [42]. The MIC29300 has a high current carrying capability of 1A as well as the ability to split and regulate input voltage to a specified level (see Figure 18 Below) [42]. The MIC29300's characteristics shows it comfortably handles any current draw the 24 V adapter might throw at it while maintaining the desired +/-12 rail supply to the buffers and triode amplifier.
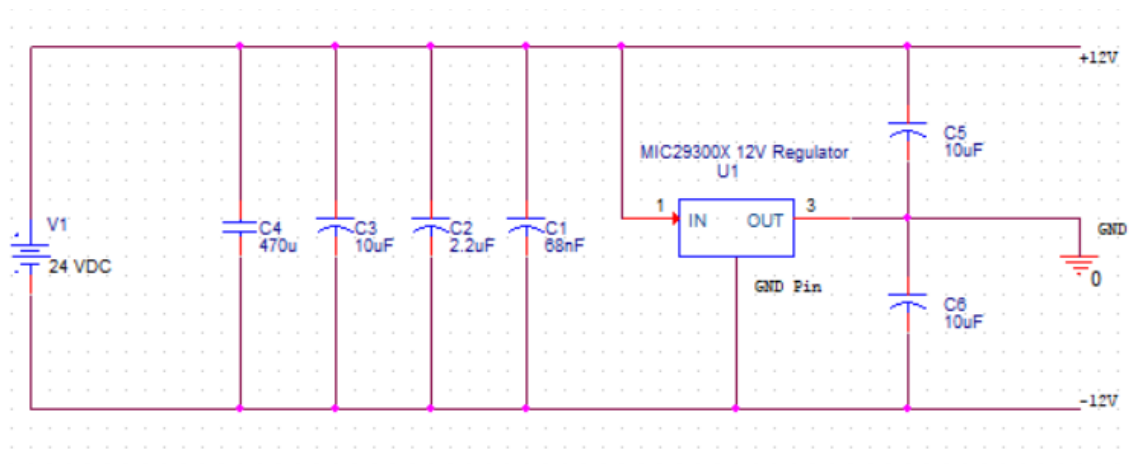

Figure 18: +24V to +/- 12V Spilt Rail Power Supply
*note V1 is a switched mode 24 VDC wall adapter input

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With the power supply figured out, next came the challenge of adapting the triode amplifier from a 0 – 24 Volt supply to a +/-12 Volt supply.

Adjusting our triode amplifier to operate with a split rail proved to be straightforward. The only change that needed to be made was supplying the cathode with -12V instead of 0V. The input bias resistor (R2) remains connected to ground in order to bias the grid at 0V. Because the PK voltage remained 24V, circuit operation was unchanged. However, to lower gain, the plate resistor R3 was lowered to 100kOhms. This did not reduce gain as much as we had wished, and lowering the resistor further began to raise gain. As a solution, we inserted an attenuation resistor (R_atten) on the input. Although this doesn't directly affect the gain of the triode, it lowers the input signal and thus lowers the gain of the system. The resulting gain now lies between 5V/V and 7V/V depending on the channel. This mismatch is due to the gain imbalance between triode channels, an artifact of vacuum tube fabrication methods.

When running the updated split rail triode circuit with the output buffer, the buffer once again blew out. Since the gain was reduced and the input signal to the buffer remained small, it became clear that there was something inherently wrong with the design. Initially it was decided to utilize another buffer to see if that would improve the output staging predicament. The Texas Instruments BUF634 was selected, primarily because it shared similar characteristics with the LM49600 but came in a more manageable TO-220 package for breadboard mounting (see Figure 19 below) [45]. However, despite the change in buffer chip, the buffer was blown again on another test run. Scrutiny now shifted to what was going out at the triode's output to determine what causes the buffer to blow. Analysis revealed a noticeable DC offset occurring at the circuit node linking the amplifier output and buffer input. The offset occurs at power up and slowly decreases down to ground. This output offset transient achieved a value over 24V, exceeding buffer supply and thus destroying the buffer.
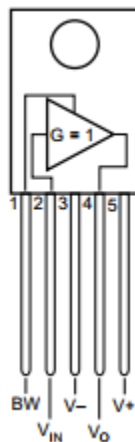
Figure 19: New Output Buffer Pinout in TO-220 Package, Texas Instruments BUF634 [45]
*BW pin unused in final design

The solution to this problem was easy; by adding a bias resistor (R3) to the output of the triode, the DC spike was minimized to under 2V and is now in a safe range for the buffer. However, this now created a high-pass filter on the output. The resistor was chosen to be large in order to maintain the current gain characteristics and the capacitor value was selected to ensure the corner frequency of the filter less than 20Hz. The new triode circuit design can be seen below in Figure 20. The addition of the output bias resistor negatively affected our frequency response, specifically at lower frequencies (see Figure 21 below), an audio test revealed that it wasn't very noticeable. Reduced low-end response is a reasonable trade-off to ensure that components don't blow on our final product. This circuit constitutes the final triode design.
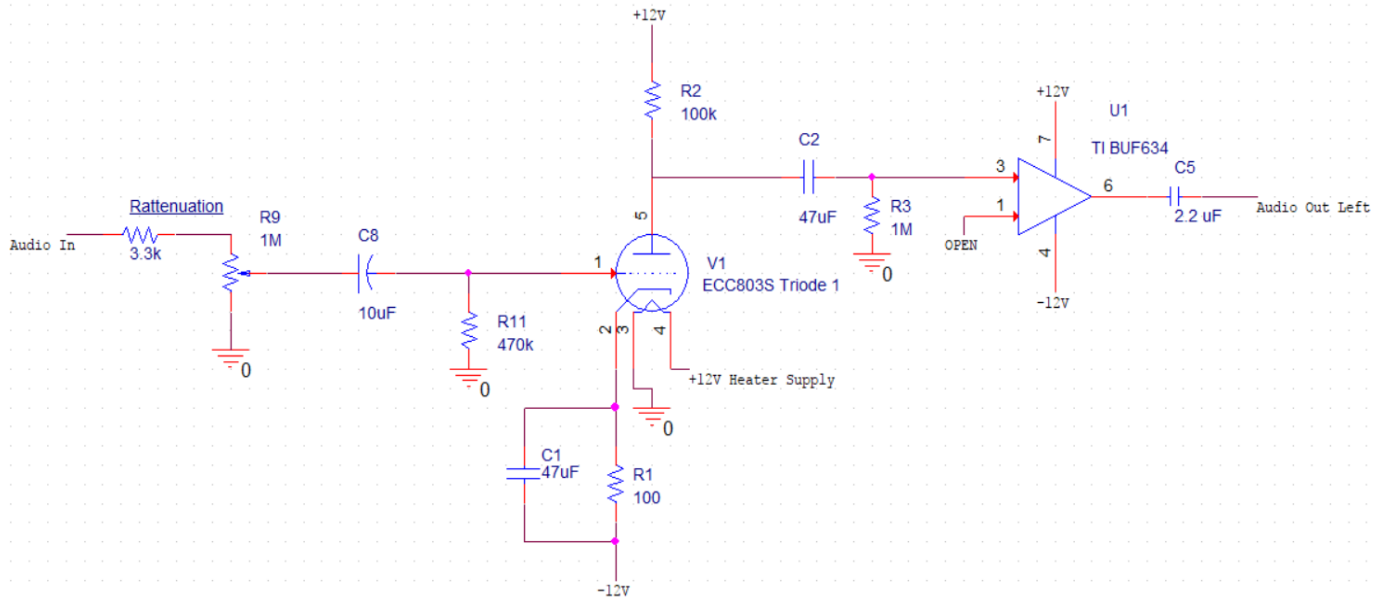
Figure 20: Finalized Triode Amplifier (only one channel shown)
*2.2 uF capacitor added to output of buffer in order to eliminate any DC offset that might have been added when signal leaves buffer.

NOTE: The final circuit diagrams presented in Appendix C display an output capacitor (C5) of 470uF. This larger capacitor addresses the reduced low-end response. As the load is resistive, the output creates a highpass filter. Increasing the size of the capacitor decreases the corner frequency.
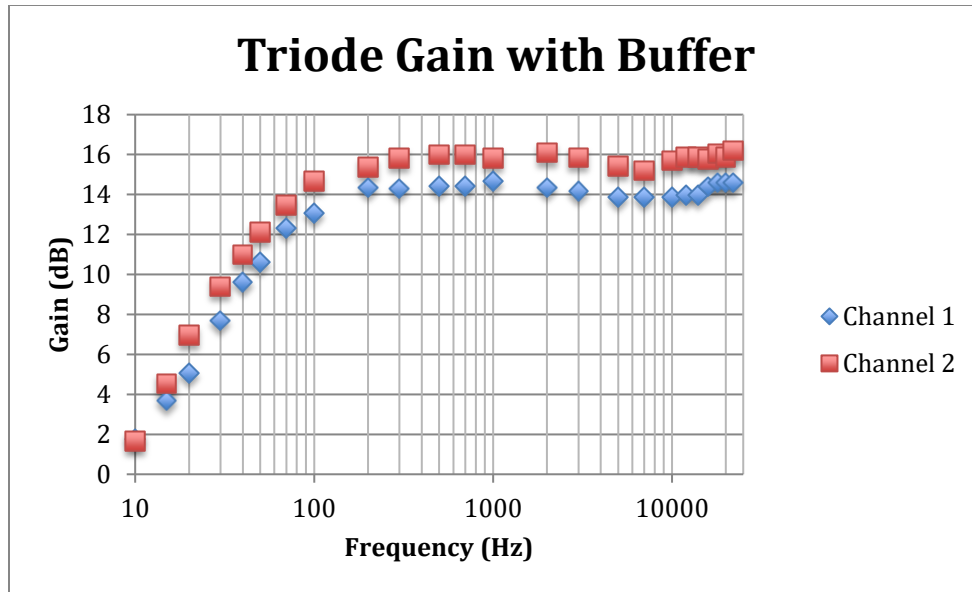
Figure 21: Triode Frequency Response with BUF634 Buffer attached to a 32 Ω load

Chapter 7:
Phase III: Solid State Amplifier Design and Input Network Design
Chapter 7 details the rationale and decisions behind the design and construction of the solid-state amplifier portion of the project. Additionally, Chapter 7 describes the process of creating a common DC blocking input attenuation network for both amplifiers.

With the triode amplifier and power supply complete, the design and construction of the solid-state amplifier came next. Making the solid-state amplifier a competitive candidate with the triode amplifier in terms of gain and ability to drive a range of headphone impedances requires a robust yet quick implementation circuit topology. An op-amp based circuit gives the best solution. A feedback type circuit topology with an op-amp affords the easiest way to adjust frequency response and gain. Additionally, op-amps have a low output impedance which means they can drive most low ohmic loads without any output buffer unlike the triode amplifier. Given such ease in implementing a solid-state audio amplifier based on a op-amp, the question remained of what would be a suitable op-amp based design. Luckily, through an online search, a website called General Guitar Gadgets listed some basic op-amp based headphone amp designs as a way of introducing the practice of amp building. One design the website calls for a stereo channel op-amp circuit capable of operating from +/- 5 Volt to +/- 18 Volt rails [43] (see Figure 21 below).
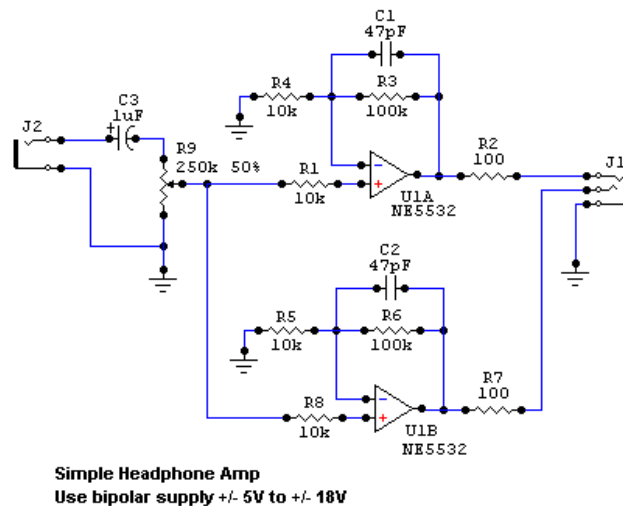
Figure 22: General Guitar Gadget's Simple Bipolar Supply Op-Amp based Headphone Amplifier [43]

General Guitar Gadget's stereo op-amp design appeared the right choice for the solid-state amplifier. The op-amp circuit can run off the +/- 12V rails from the regulator and does not require any output staging, allowing rapid prototyping. Performance wise, the feedback resistor ratios gives each channel a theoretical gain of 10 making the circuit easy to balance with the triode amplifier. For the initial implementation of the circuit,

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only one modification was made. Instead of utilizing the Texas Instruments NE5332 dual op-amp, we opted for the Burson Audio V5i dual op-amp. The Burson Audio V5i op-amp possesses audio optimizations meaning that the op-amp has minimal THD (less than .005% at mid-band audio frequencies), minimizes cross talk distortion (less than 95 dB) [44] and capable of direct replacement with the NE5332. The NE5532 suits the job for the Figure 21 circuit, however an audio optimized op-amp is preferred in order to keep signal distortion margins tight as well as giving the solid state amplifier some audiophile flair.

Upon initial prototyping and testing of the Figure 22 circuit with the Burson Audio modification one issue became very apparent: loading. Bench tests indicated a lack of gain and a DC offset at the output of each op-amp. Whenever a low ohmic load (sub 100Ω) was attached directly at the output of the op-amp, the gain was a marginal 1.5V/V. To add to the troubles a 100 mV DC offset manifested as well at the output. Such issues forced immediate reconsideration on the required circuitry for the solid-state amplifier. Rather than waste the time and research into developing a new op-amp audio amplifier, a quick solution was implemented. In order to drive low loads, one of the Texas Instruments BUF634 buffers from the triode amplifier was requisitioned to function as a output stage. Based on the success seen with the TI BUF634 in the triode amplifier, in theory the buffers could take on any loading the op-amp circuit might throw at it. To adapt the buffers to our op-amp circuit, a 1 MΩ resistor to ground was added at the output to ensure a stable voltage reference such that the buffers do not blow again. Additionally, two 1 nF capacitors were added to the output of each op-amp, removing any unnecessary DC offset to the buffers. Just like in the triode amplifier circuit, two 2.2 µF electrolytic capacitors were added to the output of each buffer to eliminate any further DC offset that might have occurred in the output stage effectively keeping output signals from the buffer centered around ground. With the adjustments made another round of bench testing was conducted. The op-amp audio circuit proved fully functional with each channel producing a undistorted signal with a gain around 10 V/V when presented a sinusoid input. See Figure 23 below for the modified version of the Figure 22 circuit. However, despite a functional solid-state amplifier, a few more adjustments were required before considering the design finalized,
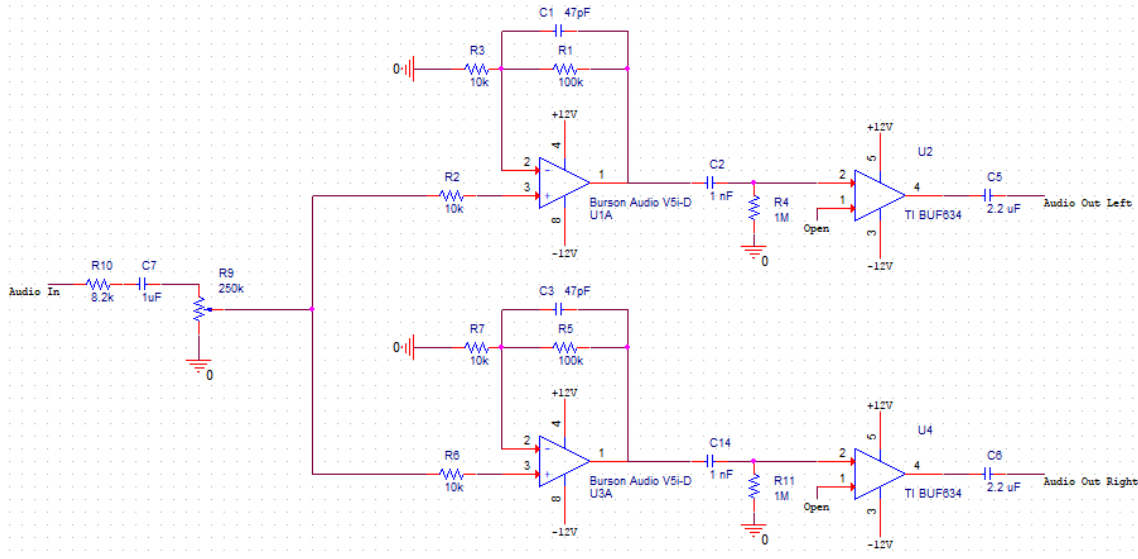
Figure 23: Modified Op-Amp Circuit derived from the Figure 22 circuit.
*Note Burson Audio Op-Amp in place of NE5532 Op-Amp as well as the presence of the TI BUF634 output buffers

NOTE: The final circuit diagrams presented in Appendix C display an output capacitor (C5) of 470uF. This larger capacitor addresses the reduced low-end response. As the load is resistive, the output creates a highpass filter. Increasing the size of the capacitor decreases the corner frequency.

The last detail that needed attention in making both the solid-state design and triode amplifier final was the input circuit. Both the triode and op-amp audio amplifiers required a common input circuit that blocks input DC, attenuates input signal, and offers volume control to ease in the switching between the two circuits. Additionally, our specifications required that both circuits only be controlled from one volume potentiometer, so a common input network was unavoidable. The decision was made to make an input network similar to the one seen in the initial Figure 21 design for the solid state amplifier. The input circuit involves a 250 kΩ potentiometer, a 1 µF capacitor, and a attenuating resistor of some sort. Previous testing with the triode amplifier and the buffers proved the essentiality of attenuation resistors. The input buffers have an inherent DC offset present when connected to either amplifier output as observed from bench testing. Despite the output capacitors and voltage reference resistor to ground the offset cannot be removed. Any output signal presented to the buffer input might appear at a higher potential than expected. To mitigate the risk of blowing the buffers due to a excessively large signal into the buffers, attenuator resistors at the input help keep amplifier output signals at stable levels that do not blow buffers (essentially any voltage that does not push the signal towards the buffer's rails). An 8.2 kΩ was selected as our attenuation resistor value. The decision was driven by bench testing with the solid-state amplifier receiving what was considered a "loud" input voltage signal (400 mVpp or higher). Typically, such an input would drive the output towards the 10Vpp range which puts the signal into a uncomfortable proximity to the buffer's supply voltages. However, with further testing at louder volume voltages with the solid-state amplifier with the 8.2 kΩ attenuator resistor, 1 µF capacitor, and the 250 kΩ potentiometer (set to "full volume") input network

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indicated the output of the solid-state amp put out a signal closer to 5 Vpp rather than 10 Vpp. This shows that the solid-state amplifier can operate comfortably without blowing the output buffers as long as the input attenuation resistors are present. See Figure 24 for input network circuit.
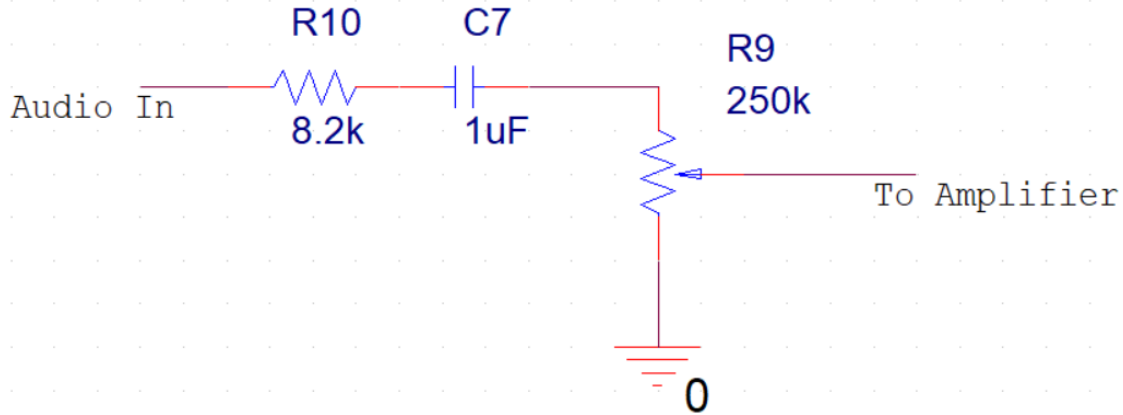

Figure 24: Input Circuit for both amplifier topologies
*note R10 is the attenuation resistor

With the solid-state amplifier set with an input circuit, the triode amplifier had to be modified one more time to accommodate input circuit changes ensuring a common volume control and signal input. This meant the new Figure 24 input circuit needed to be swapped in with the triode amplifier's 1 MΩ potentiometer and 3.3 kΩ attenuation resistor. The swapped occurred swiftly and after some functionality testing the triode amplifier still worked normally. However, a reduction in gain was noticed with the output dropping from about 10 v/v to 4.85 v/v. This presented a whole new crop of issues because both amplifiers needed their voltage gains matched to make amp switching seamless and less traumatic to audio driver loads (instantaneous change in volume can harm most headphone drivers). Rather than go through the trouble of adjusting resistor values around the triode amplifier, it seemed adjusting resistor values in the solid-state amplifier seemed a much simpler solution. Since the solid-state amplifier's gain value is primarily dictated from feedback resistor values, it now came down to putting in a lower resistor value in the feedback network to cut gain and get it close to the triode amplifier's gain. Referring to Figure 22, resistors R3 and R6, were replaced with 82 kΩ resistors which then dropped the solid-state amplifier's gain from 10 V/V to about 4 V/V. Unfortunately, that was as close the solid-state amplifier's gain could be matched with the triode amplifier's. Bench tests demonstrated that any values less than 82 kΩ drove the gain sub 4 V/V while values over 82 kΩ kept gain well over 5 V/V. 82 kΩ was the happy medium that kept gain as close as possible to the triodes. However, in the process of dropping the gain in the solid-state amplifier, collectively as a group we neglected a more pressing issue that was occurring with the solid-state amplifier.

The solid-state amplifier's signal integrity was in a questionable state. Most signal measurements performed on the solid-state amplifier during the initial prototyping were done with the oscilloscope in either an averaging mode or high-resolution mode. Such measurements modes did not allow the perception of noise that had manifested within the

outputs of the solid-state amplifier. Upon taking output oscilloscope measurements in a normal real-time acquisition mode revealed a very noticeable peak noise in output signal. Refer to Figure 25.
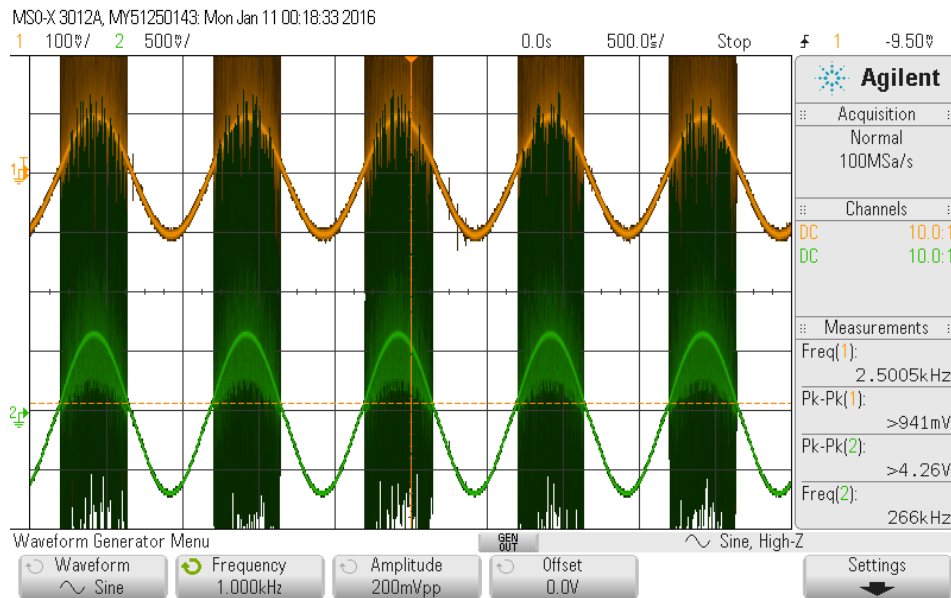
Figure 25: Peak Noise within Solid State Amplifier Output (Green Trace)
*Note peak noise persisted over the entire audible frequency range (20 Hz to 20 kHz)

Such peak noise was unacceptable. Noises like the one occurring in Figure 25 interfere with sound quality. Adding to the issue, frequency response testing in normal oscilloscope acquisition mode revealed a undesirable distortion only occurring between 30 – 50 Hz as well as some attenuation occurring at frequencies below 200 Hz. See Figure 26 below.
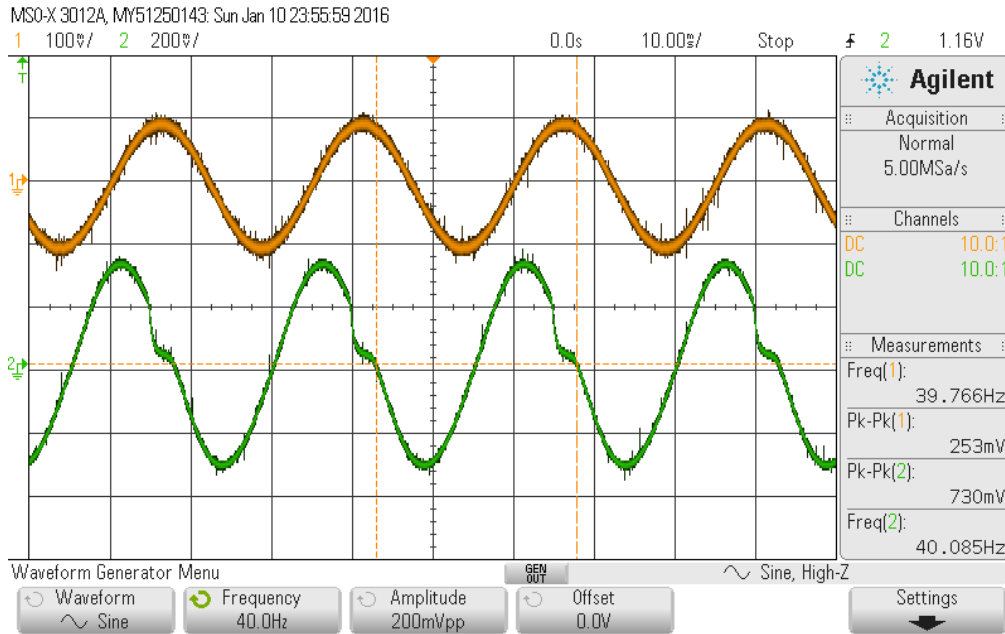
Figure 26: Distorted Solid-State Amp Output Signal (Green Trace) observed between 30-50 Hz.
*Attenuation was not captured in this figure, issue was addressed before this figure was captured.
Also note that figure was captured at 40 Hz.

Scouring over electronic design textbooks to ascertain what might be causing these issues, two things became apparent. One, the output signal noise as well as the 30-50 Hz distortion mostly likely was caused by power harmonics in the solid-state amplifier's split rail supply. Two, the low-end attenuation resulted from a high corner frequency, around 200 Hz which explains why any signal around that frequency and below attenuates. Addressing the attenuation issue first, a bigger output capacitor was required to drop the corner frequency. The corner frequency essentially determines where any meaningful gain starts from a frequency response perspective. Referring to the calculations below, the solid-state amplifier in its Figure 23 configuration produced a corner frequency of 159.155 Hz based on the RC configuration seen at amplifier at output.

$$1 \text{ nF Ouput Capacitor with } 1 \text{ M}\Omega \text{ pull down resistor}$$

$$f_{corner\ original} = \frac{1}{2\pi RC} = \frac{1}{2\pi * (1 * 10^6\ \Omega)(1 * 10^{-9})} = 159.155\ Hz$$

$$22 \text{ nF Ouput Capacitor with } 1 \text{ M}\Omega \text{ pull down resistor}$$

$$f_{corner\ new} = \frac{1}{2\pi RC} = \frac{1}{2\pi * (1 * 10^6\ \Omega)(22 * 10^{-9})} = 7.23\ Hz$$

Given that the original RC output configuration was giving a corner frequency close to 200 Hz a slightly bigger capacitor was required. Normally adjusting the output resistor works as well unfortunately that was not an option given the presence of the buffers. The 1 MΩ resistor needed to stay because it keeps the voltage reference between the output of the amplifier and the input of the buffer stable. Going any smaller or bigger than the 1 MΩ resistor threatens stability of buffer input. For the new capacitor value, 22 nF was

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chosen based on the calculation and because it was next available capacitor size in the project supply. 22 nF enables a corner frequency below 20 Hz which is good in terms of amplifying audible frequencies. With the attenuation issue solved in theory, the attention next shifted to addressing the peak noise caused by the power supply rails.

Mitigating the impact of the rail noise interfering with the solid-state amp's output signal merited the use of capacitors across the rails. Based on talks with the project advisor, Dr. Braun, the solid-state amplifier required a combination of large (at least 50 µF) and small capacitors (something in the nano-farad range) across each rail. The combination of rail capacitors helps with two things. One, it obviously filters out any noise generated by the split supply rails. Two, the large and small capacitor combo reduces the capacitor's equivalent series resistance (ESR) which minimizes any power loss occurring across the rail capacitors. Keeping Dr. Braun's recommendations in mind, three capacitors (47 µF, 1 nF, .22nF) were added to the local supply rails leading directly into the solid-state amplifier. Refer to Figure 27.

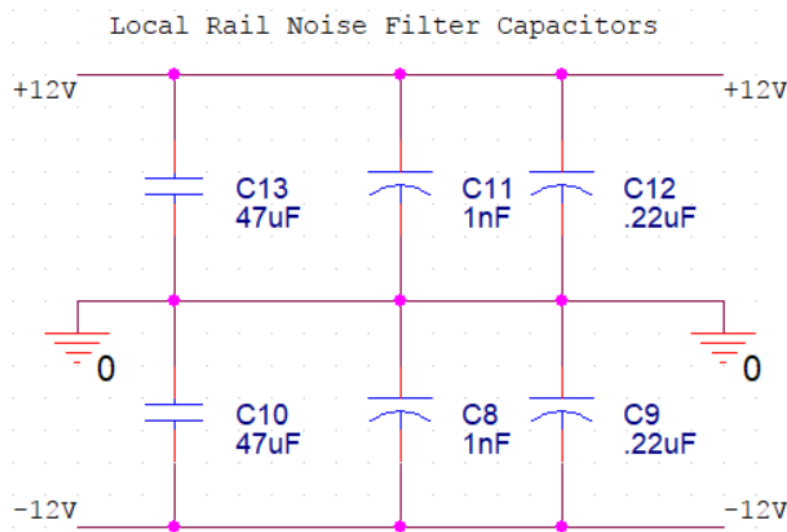Figure 27: Noise Reducing Capacitors at Rails Leading into Solid State Amplifier

With the addition of the rail capacitors to filter out noise, the solid-state amplifier was ready to be tested again to see if any of the above issues had been resolved. Ensuring the oscilloscope was set to a normal acquisition mode, the output of the solid-state amplifier was measured again this time with a more pleasing result. Refer to Figure 28.
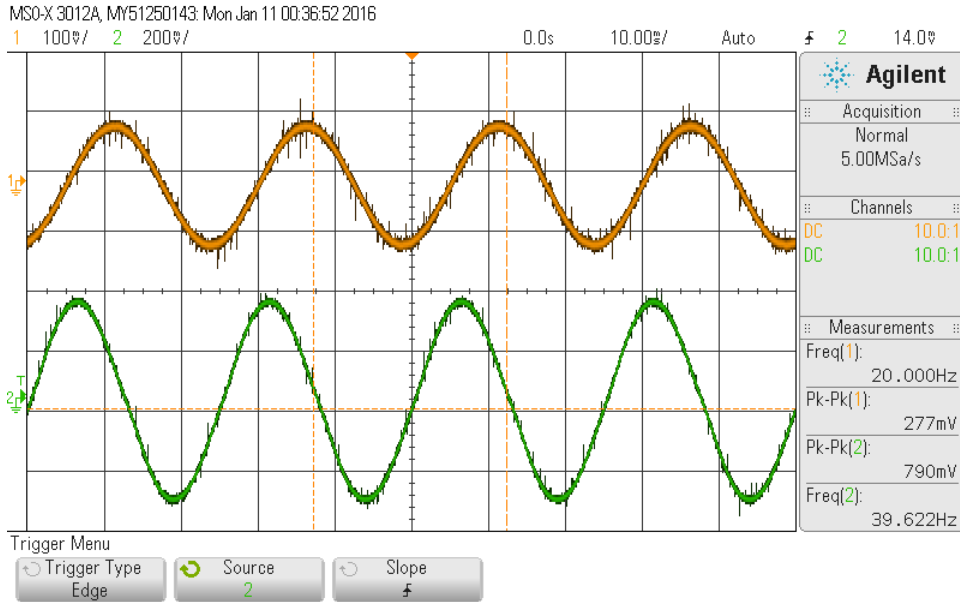
Figure 28: Output of Solid State Amplifier at 40 Hz (Green Trace)
*Note lack of peak noise, attenuation, or 30-50 Hz distortion

By placing rail capacitors and putting larger capacitors at output of solid state amplifier drastically improved the quality of the output signal. Now the output signal no longer observed any peak noise or particular frequency distortion thanks to the rail capacitors. Additionally, the frequency response greatly improved with no attenuation occurring below the 200 Hz range any longer due to the bigger output capacitors. Refer to Figure 29 for final solid-state amplifier frequency response.
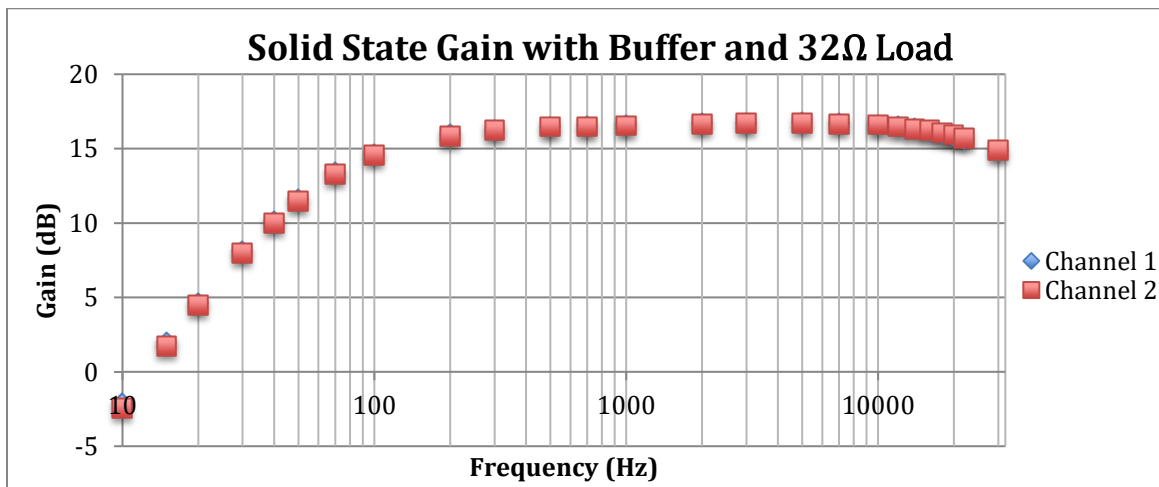
Figure 29: Frequency Response of the Solid-State Amplifier
*Note the tight response on both channels, hard to distinguish the response of Channel 1 or 2 on graph. Compare this with Figure 21 where triode channels have a slight drift between each other in their responses.

With the solid-state amplifier now fully finalized and functional an audio test was performed. Plugging a pair of 62Ω beats earbuds into the circuit and giving the circuit a medium volume audio signal (300 mVpp average) sound quality was checked. The solid-state amplifier performed

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admirably with slight hum in the audio. Pinpointing the source of the noise, the 250 kΩ potentiometer was introducing some noise into the audio. The noise was immediately resolved when attaching a ground wire to the pot. Based on the audio test, everything seemed functional the only thing to do for the solid-state amplifier was to ensure there is a chassis ground of some sort to the potentiometer to eliminate any noise it introduces. With the solid-state amplifier complete and tested. The project was ready to move on to the final phase: integrating both amplifiers onto a perf-board and setting up amplifier switching. Refer to Figure 30 for finalized solid state amplifier schematic.
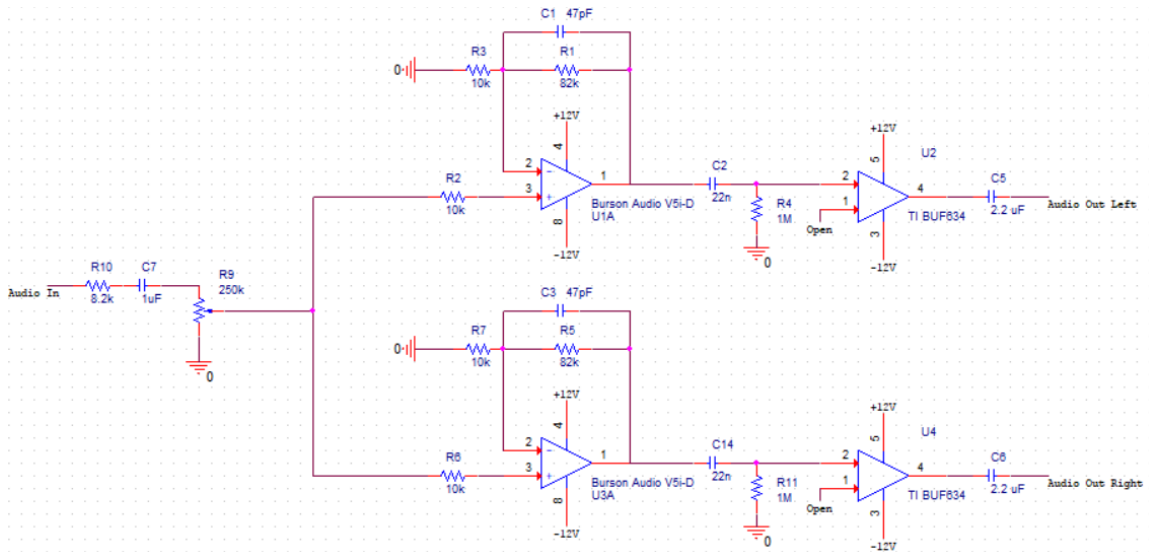

Figure 30: Final Solid-State Amplifier Circuit

NOTE: The final circuit diagrams presented in Appendix C display an output capacitor (C5) of 470uF. This larger capacitor addresses the reduced low-end response. As the load is resistive, the output creates a highpass filter. Increasing the size of the capacitor decreases the corner frequency.

Chapter 8:
Phase IV: Final Integration of Both Amplifier Designs and Amp Switching
Chapter 8 describes the final board integration of both amplifiers as well as the integration of a switching mechanism between the two amplifiers.

Given that all amplifier designs are finalized, the final piece of the project to give the whole setup functionality was a switch. Initially the focus was on the input to both amplifiers as a potential point to insert a switch. However, after some deliberation and inspection of the circuit, it was decided that it would be better to put the switch between the two amplifiers at their buffer outputs rather than the input. The decision was driven by the fact that the input side of the final board layup (see page 41 for final layout details) that was planned was starting to get crowded. By placing the switch at the output of each buffer reduced component crowding at input and simplified wiring from the buffers to the output audio jack. Instead of wiring two buffer outputs to a channel on an output jack due to a switch at the input, the presence of an output switch allows the changing of buffer outputs as well as reducing any risk of noise that might be caused from two buffer outputs sharing a node. With the location of the switch figured out now came the question of switch implementation.

Keeping the design as simple as possible, a mechanical switch seemed appropriate. However, the dual amplifier setup required a switch capable of switching four incoming channels (two channels from the triode amp and two channels from the solid-state amp) and routing two of those four channels to only two output channels. Group knowledge on switches was limited but with some online research an appropriate switch design was found: a dual throw dual pole type (DPDT) switch. Refer to Figure 31.
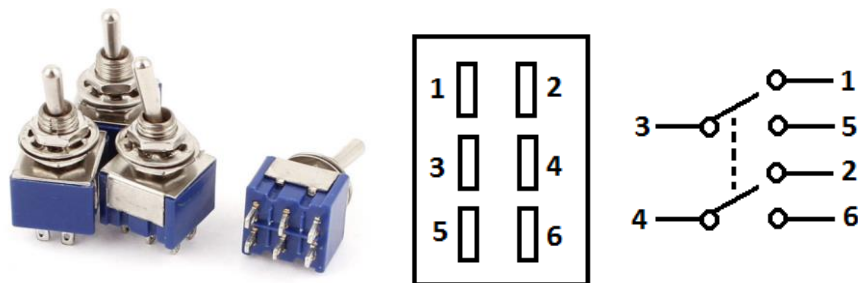
Figure 31: DPDT Switch and Circuit Diagram [46]

The DPDT switch was the perfect solution, now it was the matter of determining where to route input and output signals given the pinout seen in Figure 31. Since each amp setup puts out two channels for left and right audio, pins 1, 5, 2, 6 were allocated as the input side of the switch. Keeping the amplifier channels matched, left channel audio consists of switch pins 1 and 5 connected to audio out left of solid state amp and triode amp respectively (see figures 30 and 20). Same idea for right channel audio. Switch pins 2 and 6 respectively connect to audio out right of solid state and triode amplifier. With the left and right channels of each amp connected to their own set of switch inputs, switch pins 3

and 4 serve as the final output to the stereo audio jack. So now when the switch is flipped the left and right channels of one amp simultaneously connect to the output. See Figure 32 for signal routing in switch.
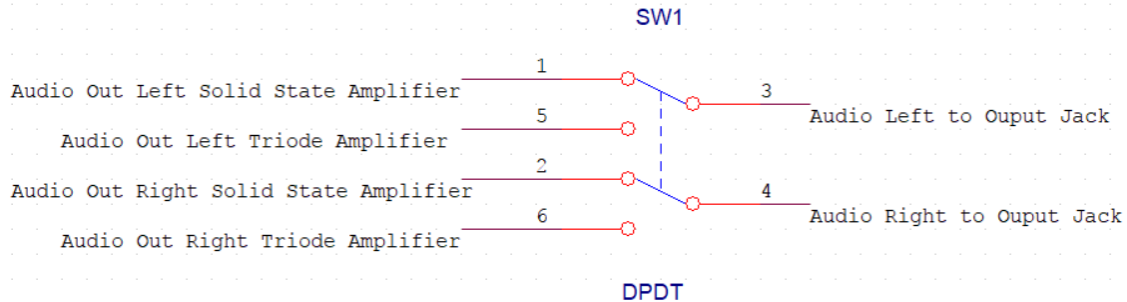
Figure 32: Signal Routing for Amp Switching

With a firm hardware design in place work shifted to getting the both amplifier setups integrated onto a single perforated prototyping board. Board layup once again represented yet another area of minimal experience for this project group. Rather than try to ad hoc solder on the perforated board in a pattern like the breadboard layout of the amps, more careful consideration was required. Ideally the audible noise must be minimized, which means that component connections must have close physical proximity as well as minimizing any long connections where possible.

Perfboard layout was first done on paper before any solder connections were made in order to minimize mistakes. For ease of use, input components, such as input jack and potentiometer, were placed on one side of the board and output jack placed on the opposite side. Not only is this the most intuitive design, but it provided ample room to insert all the necessary components. The solid-state amplifier components were placed on the right and triode components on the left. This allows the user to clearly distinguish between amplifiers. Careful consideration was taken to minimize the ground loops and the amount of wires used. Although the layout may not be perfect, as there is still a lot of wire jumpers throughout the board, this layout presented an easy-to-follow design which made finding issues easy and intuitive.

Chapter 9:
Final Project Analysis
Chapter 9 details final cost break down of project along with final project performance data.

With the completion of design work and final board integration of both amplifier topologies, the time has finally come to analyze the course this project has taken compared to initial estimations.
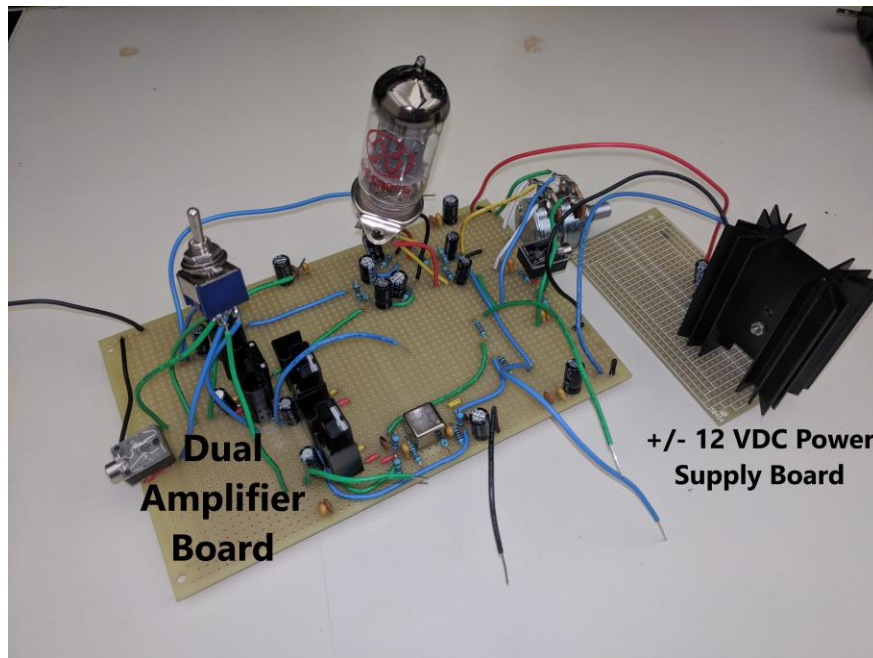
Figure 33: Final Board Layout of Dual Method Headphone Amplifier
*Note the loose wires coming out the board are test leads

Performance Analysis: Total Harmonic Distortion (THD)

One of the first metrics to test the completed amplifier setup is Total Harmonic Distortion. Initially in the requirements and specification project the goal was to have both amplifier topologies operate with a THD of less then .1% when injected with a 1 kHz sinewave signal. To see if both amplifiers truly operated under such a condition a THD test was run on the amplifier using an audio DAC interface and Arta Labs THD/FR test software setup on a laptop. A fellow student kindly allowed the group to utilize this test setup for running a THD test as well as a frequency response. Setup pictured in Figure 34.
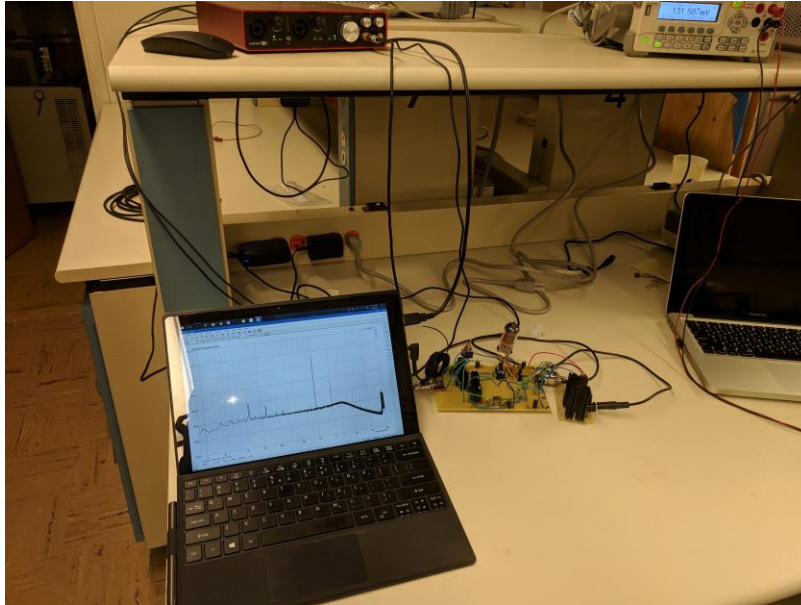
Figure 34: THD/IHD/Frequency Response Test Setup for Finalized Project
*Red box pictured above is the audio DAC interface between laptop and amplifier for running THD/FR tests

Using the test setup and Arta Labs software, THD of both amplifiers was obtained at multiple test frequencies: 250Hz, 1kHz, and 10kHz (see Table VI for results). Plots of these measurements available in **Appendix B** (figures 39-44). Analyzing the THD data, that triode amplifier appeared to have significantly lower distortion and noise than its solid-state counterpart. The initial THD specification of >0.1% unfortunately was not met. Fine tuning the amplifiers to meet that requirement was a stretch given the budget, time constraints, and current level of knowledge.

Table VI tabulates the results of total harmonic distortion testing of our final amplifier designs at three different frequencies.

TABLE VI
Amplifier Total Harmonic Distortion and Total Harmonic Distortion + Noise Measurements

Frequency (Hz)	Triode THD	Triode THD+N	SS THD	SS THD+N
250	1.08%	2.09%	2.51%	7.2%
1k	0.88%	1.97%	1.76%	6.98%
10k	0.8%	2.06%	1.35%	7.3%

*SS = solid state

Performance Analysis: Inter-Modulation Distortion (IMD)

Inter-Modulation Distortion (IMD) is the harmonic measurement of how a system reacts to 2 or more inputs at different frequencies, f1 and f2. As a result, harmonics occur at f2-f1, 2*f1-f2, 2*f2-f1, and multiples of f1+f2. The triode and solid-state amplifiers were provided a 13kHz and 14kHz sine wave inputs to check their IMD behavior. Appendix B, figures 35 and 36 display the resultant behavior. The only noticeable harmonic within the IMD analysis over the audible range was harmonic f2-f1 occurring at 1kHz. Overall, in audio applications, a lower IMD represents a better circuit because it indicates the circuit produces less distortion. Based on the IMD results the triode amplifier does not produce as much distortion as the solid-state amplifier. We conjecture that the triode amplifier had a better layout in terms of noise reduction than the solid-state amp which might have given the triode a better IMD percentage. IMD data presented in Table VII below.

Table VII tabulates the results of IMD testing of our final amplifier designs given a 13kHz and 14kHz input.

TABLE VII
Amplifier Inter-Modulation Distortion (IMD)

IMD Measurement	Triode IMD	SS IMD
13kHz and 14kHz input	1.34%	2.09%

*SS = Solid State

Performance Analysis: Frequency Response

The last metric to collect for the project was the final frequency response of both amplifier in their integrated board setup. The Arta Labs software in the Figure 34 test setup possesses the capability of creating frequency responses in a much more presentable way. Instead of doing frequency sweep measurements by hand through varying a function generator, a frequency response was produced by using a pink noise input generated from the audio DAC in the test setup. These plots can be seen in Appendix B figures 37 and 38. A few things should be noted from these plots, primarily low cutoff frequency, high cutoff frequency, and overall gain. These results are tabulated below.

Table VIII tabulates the results of Frequency Response testing of our final amplifier designs.

TABLE VIII
Frequency Response

Metric	Triode	SS
Low cutoff frequency (-3db)	30Hz	25Hz
High Cutoff Frequency (-3db)	40kHz	35kHz
Gain (dB)	19.5dB	12dB

Both circuits behave noticeably well between the audible frequency range of 20-20kHz. However, gain of the triode amplifier is significantly greater than that of the solid-state design. This informs us that there is a volume balancing issue and that the feedback resistors (R1 and R5 on the SS design) should be increased. This change will be made for future iterations of this project.

Table IX elaborates on the actual costs accrued throughout project cycle.

TABLE IX
Final Breakdown of Project Costs

Item	Original Cost Estimate	Actual Cost	Cost Justification
Audio Grade Vacuum Tube (JJ Electronic ECC803S used in the project)	$22.50	$43.46	Used two new production triode tubes in the prototyping process. Experimentation with designs called for two different triode types which is why two tubes were ordered instead of one. Additionally, brand new tubes needed to be utilized. the old tubes donated were worn and had broken heating elements.
Bulk Resistor Components	$10	$21.49	Original estimates were not accurate of current market pricing for bulk resistor components. Most bulk components prices online were $10 over original estimates.
Bulk Capacitor Components	$10	$21.49	Original estimates were not accurate of current market pricing for bulk capacitor components. Most bulk components prices online were $10 over original estimates.
Jacks and Potentiometers (originally tabulated as Vacuum Amp Support Circuitry)	$10	$18.61	Design troubleshooting involved experimentation with numerous potentiometer values. Six potentiometers ordered total, 5 more than anticipated. The potentiometers account for all costs in this category. Audio jacks were free, provided by EE department.
Burson Audio V5i Dual Op-Amp (x2) (originally tabbed as Audio Grade Op-Amp)	$5	$85	Original cost estimates for a audio grade op-amp were off. Most op-amps that are optimized for audio applications range from $10 - $70. The Burson audio op-amps were selected because they had desirable audio optimizations while having a median price of $35 per op-amp. Two were ordered in case one was destroyed during the prototyping process hence the drastic cost overrun for this category.

TABLE IX Continued

Item	Original Cost Estimate	Actual Cost	Cost Justification
PCB Fabrication (x2 custom boards)	$106	$15.26	Custom PCB boards were never utilized. Instead proto-boards were used since they were cheap and quick to implement.
Amplifier Chassis with machined holes	$40	-	No enclosure was ever made. The time remaining did not permit the construction of a enclosure.
Amplifier Switch (originally tabulated as Switching Circuitry)	$3	$5.54	Bulk switches were purchased. Bulk pricing slightly more expensive than initial estimate for switching circuitry cost.
Power Circuitry (Voltage Regulators and 24VDC wall adapter)	-	$34.42	Power Circuitry costs were never accounted for in initial cost estimates.
Shipping Costs	$35	$54.29	Shipments of components occurred sporadically instead of en masse. Ordering components and shipping them individually cost more than what was intended for shipping.

Estimated Net Cost	Actual Net Cost	Net Cost Overrun
$241.50	**$299.56**	**$58.06**

Chapter 10:

Project Thoughts and Impressions

Tim and Joey's subjective thoughts on the audio quality of the final project as well some final impressions.

Joey-Audio Test and Impressions on Sound Quality:

This part of the report is completely subjective, but I, Joey, a self-proclaimed audiophile, intend to give the reader my unbiased opinion on how the amplifier performs. The headphones being used were my Ultrasone Hfi780's with an impedance of 42 Ohms.

The first thing I noticed was a severe lack of audio below around 1kHz. This gave the music a very unpleasant and tinny sound. We discovered this is because our output 2.2uF capacitor and the resistive load of the headphones created a highpass filter. With a 42 Ohm load, the corner frequency created was around 2kHz, meaning anything below this was drastically cut out. When creating the frequency response using Arta Labs Software, we did not see this cutoff because the load was much higher, approximately 15kOhms. By increasing the size of the buffer output capacitor to 470uF (see Appendix C for final schematics) the audio sounded much better with small loads like the 42 Ohm Ultrasones. This change reduced the corner frequency to 8Hz.

The next standout issue was noise. There was an audible hiss present in both amplifiers, but more prominent in the solid-state amp. The hiss was present both with and without audio being played. It is my belief that this is largely due to a few things: cheap potentiometer, lack of chassis ground, power supply noise, and inherent perfboard noise. Once an enclosure is built, a PCB made, and better components bought, I expect much of the noise issues to disappear.

The third issue I saw with this amplifier design was volume balancing. The triode amp was noticeably louder than the solid state, and made switching back and forth between the two annoying. Because of the volume difference, it became hard to directly compare the tonal qualities between the two amplification methods, as was the original purpose of this project. This will be fixed in future iterations of this project, which I intend to make after this project ends.

Ultimately, the solid-state amplifier sounded decent and the tube amplifier sounded very good. The solid-state amplifier can be described as having clear bass, balanced mids, and balanced highs. It sounded as if all frequency components were relatively even and no tones stood out to me as overly sharp or soft. The triode presented strong, punchy bass, balanced mids, and balanced highs. However, I'm not sure if the difference in bass performance is related to volume, as bass tends to get "punchier" as volume increases.

Despite some kinks to be worked out, I am impressed with the audio quality of both amplifiers. As of now, it is not ready for resale, but I am hopeful I can work out the remaining issues and get this Dual Method Amplifier in marketable condition.

Tim – Impressions and Lessons Learned

I can't really speak to the specifics of the audio quality of the final project that is Joey's domain. However, I can say that I am proud and impressed we were able to get an operable dual method headphone amplifier.

Personally, coming into the project I had some doubts whether our not we as group could get such an amplifier operational. Initially we had zero idea on how vacuum tube circuits work and we had no prior experience with building a amplifier that operates in the audio frequency range. The most we knew was what we learned in the EE409 electronic design course (ie, prototyping, integrated circuits on breadboards, basic amplifier building/troubleshooting, and the complexities of working with a multiple IC system). However, despite my initial pessimism, the projected started to come together once we started putting our minds to it.

Things started off slow. We first realized that we needed to understand how to operate triode vacuum tubes before we could even begin prototyping a triode amplifier. This involved taking the time to look at old literature about vacuum tubes, building practice amp circuits, and consulting people who were knowledgeable about the subject. In the end once we felt comfortable with vacuum tube circuits we were able to quickly make one that worked within the audio frequencies. Once we got a triode amplifier built we were able to quickly capitulate on our EE409 knowledge and quickly implement an op-amp based amplifier. However, within the process of building the triode amplifier and the solid-state amplifier we encountered many obstacles which is where I think the most learning occurred.

For both amplifiers we had issues with balancing gain with frequency response. Often this involved a trial and error method of tweaking component values and seeing if that improved both amplifier's output. Most of the prototyping process was spent in the lab perfecting our amplifier hardware through multiple troubleshooting and data collection sessions. Perhaps the biggest challenge in the project was figuring out an output stage so that low ohmic headphone loads could be driven from the high impedance amplifier output. As a group, we experienced many disheartening bench tests where we blew buffer chips and couldn't figure out why. Despite the countless hours troubleshooting blown buffers, we persisted, pondered on solutions, and sought help were we could. Eventually when we were able to solve it the project came together perfectly.

In the end, Joey and I experienced a true engineering project cycle. So much knowledge and experience was gained by doing this project. I now have a better appreciation for the time, planning, and engineering that goes into a product. Through all those hours of troubleshooting, understanding what our circuit is doing, collaboration, and consulting knowledge base has helped me better myself as an engineer. And because of our diligent work we now have not only experience in working with audio amplifiers but vacuum tube electronics as well. I am very proud of how the project turned out even though the audio might not be on par with high quality audio amplifiers.

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Appendix A

ABET Senior Project Analysis

Project Title: Dual Method Headphone Amplifier

Student's Name: Joey Gross/Tim Murphy

Advisor's Name: Dr. David Braun

1. **Summary of Functional Requirements:**
   The Dual Method Headphone Amplifier offers two methods of signal amplification: triode tube and solid state. With the ability to actively switch between amplification methods, the user can compare the tonal qualities of each method. This amplifier must provide sufficient power to drive many different high impedance headphones.

2. **Primary Constraints**
   Our largest difficulty lies in understanding the operation of triode tubes. We lack the theoretical vacuum tube electronics background, which would have proved useful in the design of the tube amplifier. Further constraints include: THD < 0.1%, SNR > 70dB, full amplification across the full audible range (20Hz-20kHz), and a physical size constraint of 6"x6"x4" (See Table I).

3. **Economic**
   Human Capital - 2 people, ~300 man hours

   Financial Capital - ~$241.50 USD. Refer to cost estimation formula at bottom of Table V.

Manufactured/Real Capital – All electrical components and PCB created by third party.

Natural Capital – Small amounts of carbon from resistors; ceramics and/or aluminum and/or tantalum from capacitors; glass, barium, tungsten from tube; silicon from IC's; aluminum, glass epoxy, copper, and laminate from PCB; gold for connection points; and tin solder [10].

When and where do costs and benefits accrue throughout the project's lifecycle?

Costs over the lifetime of this project include the use of multiple tubes. Triode tubes burn out after a certain amount of time, especially with high power consumption [11]. The old, burned out, tubes become waste material that needs replacement.

What inputs does the experiment require? How much does the project cost? Who pays?

We estimate a cost for this project of $241.50, not including labor. The creators of the project, Tim and myself, along with help from Cal Poly's EE department, cover the expenses for this project. Additional required expenses include tools (e.g. soldering iron), raw materials (e.g. solder), and test equipment (e.g. oscilloscope, DC power supply, function generator, and multimeters).

How much does the project earn? Who profits?

> The project does not earn much profit. We estimate selling around 20 units, at slightly more than the cost of parts. The creators, Tim and myself, obtain the profit to offset project costs.

When do products emerge?

> A working product emerges within the last couple weeks of development (end of fall quarter, 2017).

How long do products exist?

> Products can exist for years depending on frequency of use. Maintenance costs include energy to operate and replacements tubes.

Estimated development time?

> Development estimates lie at 30 weeks. Refer to time estimation formula at the bottom of figure 3.

4. **If manufactured commercially:**

Over the product lifecycle the only foreseeable amount of project amplifier units made sits at 500. The high-end audio market, especially the headphone amp one, represents a very niche product base inevitably leading to small demand. The initial amplifier development coupled with labor costs $12,000. Assuming a fairly active audio enthusiast market for a given year, 100 units could be made annually, in total making the product available for 5 years. Using the baseline development cost of $12,000 combined with a $10,500 per 100 unit labor/assembly cost, first year's manufacturing expenditure comes down to $22,500. Subsequent manufacturing years neglect baseline development cost since that was covered in year one of manufacture leaving average annual manufacturing cost at $10,500. Potentially if units sold at $350.00 ($108.5 profit per unit), annual unit profit could net $10,850. Over the project's five-year product period, assuming 100 sales a year, the net sales generate $54,250. From a commercial point of view this embodies a disaster. The net revenue over product lifespan barely covers one year's worth of manufacturing costs. Ultimately this incurs a $5,750 deficit, projected cost of the project over a 5-year manufacturing period requires $60,000.

Consumer operation costs are currently unknown. This amplifier unit only costs the operator money if they power the unit using their wall outlet power. The total energy consumption of the project for a given period has not been tested. Operating costs vary upon how long the amplifier unit operates, cost of electricity, and the precise power consumption of the unit itself. More tubes may also have to be purchased if the current tube blows out.

5. **Environmental**

One environmental impact of this project comes from the use of heavy metals in the circuitry. The vacuum tube constitutes the biggest polluter in the project. Typically, vacuum tubes construction involves borosilicate glass, heavy metal plating and wiring, barium coatings, molybdenum, and nickel plating [10]. In large amounts, these metals, silicate and their waste products, constitute a toxic environmental threat. Typically,

moderate accumulation of these metals in living organisms can disrupt natural biological processes. Overtime organisms die with exposure to these metals. Marine ecosystems are especially vulnerable to this pollution. If the heavy metals reach concentrations of 73 µg/L [12] in a marine environment, a toxicity threat exists. This project requires special disposal care to avoid environmental pollution.

The manufacturing of this product also introduces an environmental impact. The creation of all our components produces waste. For example, the creation of a printed circuit board produces excess board, drill dust, excess tin, excess copper, and a variety of other solid and liquid wastes. Natural resources include small amounts of carbon, ceramics and/or aluminum and/or tantalum, glass, barium, tungsten, silicon, glass epoxy, copper, laminate [10], gold, and tin solder.

The power consumption of the amplifier constitutes another environmental impact. Most amplifiers of this scope and functionality (namely Class D amps) can typically amplify with 95% [13] efficiency. However this project utilizes both a vacuum tube and an analog IC amplifier configured for Class A operation. Class A amplifiers have power efficiencies less than 50%. [13] In addition, the vacuum tube requires 1000 times the normal turn on voltage of a transistor to properly operate. The power consumption of this project well exceeds a common Class D switching amplifier of the same specification. The increased power demands further draws energy from the utility grid, which already uses an inordinate amount of polluting fossil fuels to keep it powered.

6.   **Manufacturing**
Assembly represents the primary issue affecting the manufacture of this amplifier. Like any other electronics project, assembly of the unit requires a hands-on approach with soldering, wiring, and testing. Putting the electronics together into one circuit constitutes only a minor manufacturing bottleneck. Machining the project enclosure embodies the real manufacturing challenge. Putting the amplifier into a self-contained enclosure consumes time, requires machining, and our group lacks collective machining experience. Amplifier circuit board mounts need insertion, holes for the knobs, switches, and jacks drilling. Most of the assembly time comes from trying to integrate the amplifier into its enclosure.

7.   **Sustainability**
This amplifier intends continuous operation using high power components and requiring minimal maintenance. The RoHS compliant solid-state electronics like op-amp's, capacitors, and resistors constitute the only real sustainable part of the project. The rest of the project utilizes components (namely the vacuum tube) manufactured using non-environmentally friendly/sustainable methods. If the project fails to operate properly, there currently exists no maintenance or replacement plan to get the amplifier operable again. Replacing the vacuum tube if it burns out represents the only feasible maintenance solution. Any other issue that prevents amplifier full function merits project disposal. Additionally, this project lacks upgrade plans. Putting a higher gain triode vacuum tube in the amplifier circuitry serves as the only upgradeable part.

8.   **Ethical**
An ethical implication from this project might include the destruction of headphones. Although not intended, using low budget, low power headphones with this amplifier may

result in blown speakers. The Dual Method Headphone Amplifier should only drive headphones that have high impedance and/or high power requirements. In addition, we assume that the user maintains a volume level that protects from property and/or hearing damage.

In addition, the manufacturing of parts may also have their own ethical implications. Many tubes come from Russia, and components from Asia, where working conditions may be less regulated than domestic working conditions.

Ethically, the project embodies an environmental nightmare. Inefficient power consuming amp design, minimally sustainable electronic materials, and lack of maintenance options characterize the project shortcomings. In the IEEE code of ethics framework, this clearly violates the first IEEE ethical tenet "to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment". Clearly, the project affects the environment negatively and neglects how the resources it robs can impact others.

Using the ethical egoism mindset, this project represents an indispensable learning opportunity. The amplifier project represents a critical part of our engineering education as well as an exercise in audio electronic design. If building this project adversely affects the environment, so be it, as long as it does not see commercial implementation and incur environmental/sustainability issues due to mass production. The project is not intended for commercial production, but rather to inform and fulfill personal interests.

9.   **Health And Safety**
Given the amplifier's partial heavy metal composition and high power consumption, risks exist with the project. The first immediate safety concern comes from the vacuum tube's high operating voltage and power consumption. Improper handling of circuitry surrounding the tube can result in accidental release of capacitor energy, resulting in shock and possibly injury. Use caution when handling the amplifier. In addition, hearing loss may occur if the high volume is used for extended periods of time. Always operate with care and turn the volume all the way down before turning the amplifier on.

A secondary concern comes from the toxic metals in the vacuum tube itself. As described previously, the triode vacuum tube utilizes metals such as barium, molybdenum, and nickel in its constitution [10]. Though open-air exposure of these metals to a user does not pose any health threat, diffusion of these metals in the environment or water supply can have toxic effects especially if organisms ingest these metals. The tube's toxic composition merits proper hazardous waste disposal procedures.

Trace amounts of lead may be present in the solder or component leads. Use caution when handling the amplifier.

10.   **Social and Political**
Audio enthusiasts and individuals seeking a headphone audio boost comprise the main project stakeholder base. Upon project completion, the stakeholder base gains access to a device that enables quality headphone audio.

Social and political ramifications only manifest from the components utilized in amplifier construction, especially the vacuum tube. As mentioned before, the bulk of new production vacuum tubes come from Russia. However, some Russian tube makers fall under ownership of known mob related owners or acquired through very dubious methods. Essentially certain elements of Russia's shady cartel-like business world try to corner the niche tube market and exploit it for their own purposes [37]. Buying a Russian made tube does not mean a low quality product, but rather means it could support an organization that uses criminal business tactics. Socially, this affects workers and small owners of other tube factories. Funding this corruption bestows an incentive for these shady business owners to intimidate, extort, and threaten other small tube makers to further their own nefarious business goals.

11.   Development

Product development for the amplifier(s) requires many tools for building and testing. Physical tools include: soldering iron, wrench, and a metal machining/bending device. Test equipment includes: multi-meters, DC power supply, signal generator, oscilloscope, and their corresponding connectors. We also require lab time.

In terms of learning experience, ultimately the project gave perspective on utilizing and understanding old analog technologies like vacuum tubes in electronic applications. Normally most electrical engineering curriculums like to emphasize the use of transistors and digital type circuitry to make efficient amplifiers. Through our literature search, we gained insight into the use of vacuum tube electronics especially with help of a very old IEEE article [25] and a University of Michigan website [28].

Appendix B
THD, IMD, and Frequency Response Plots
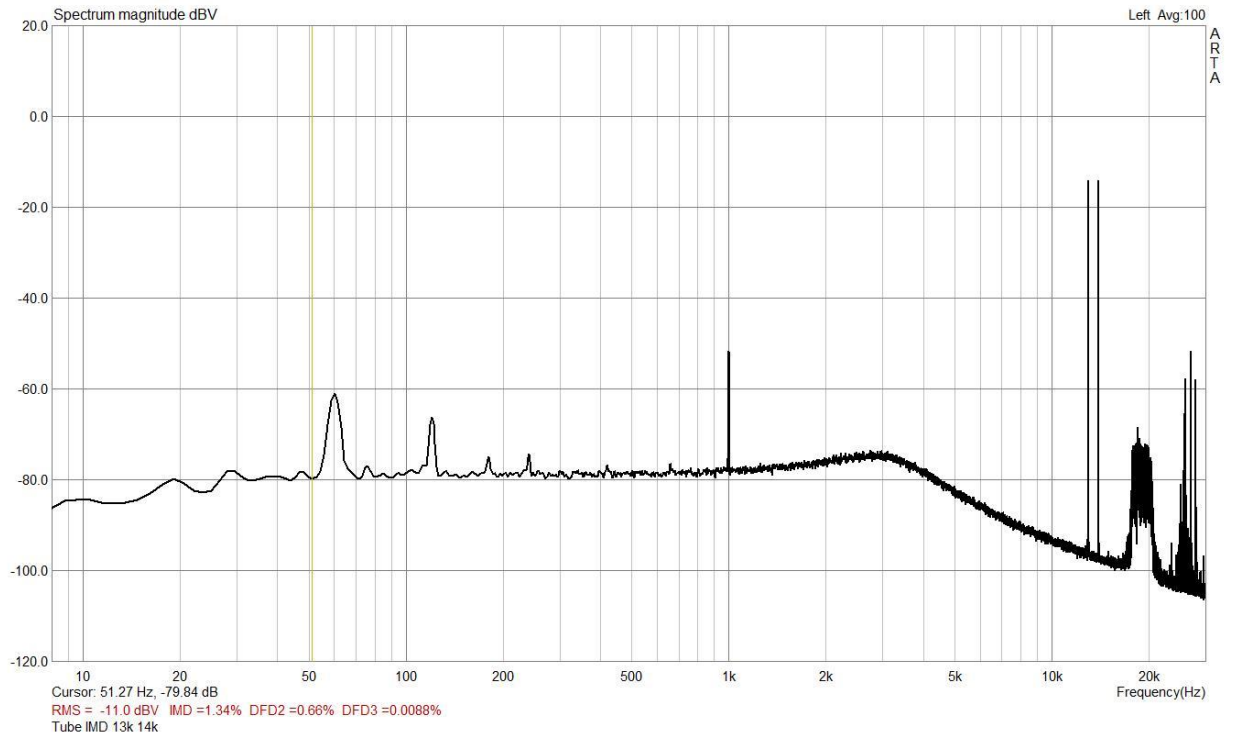
Figure 35: Triode IMD Measurement given input signals at 13kHz and 14kHz
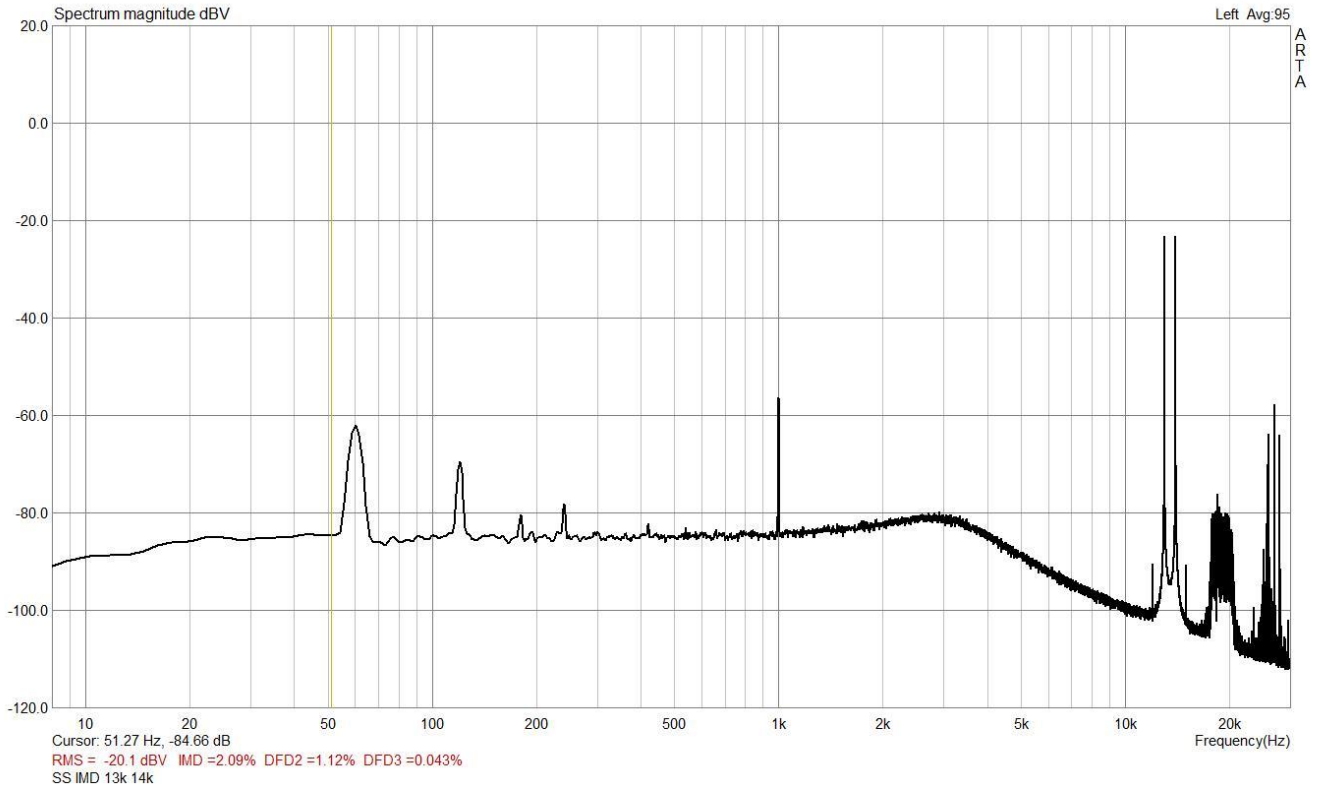
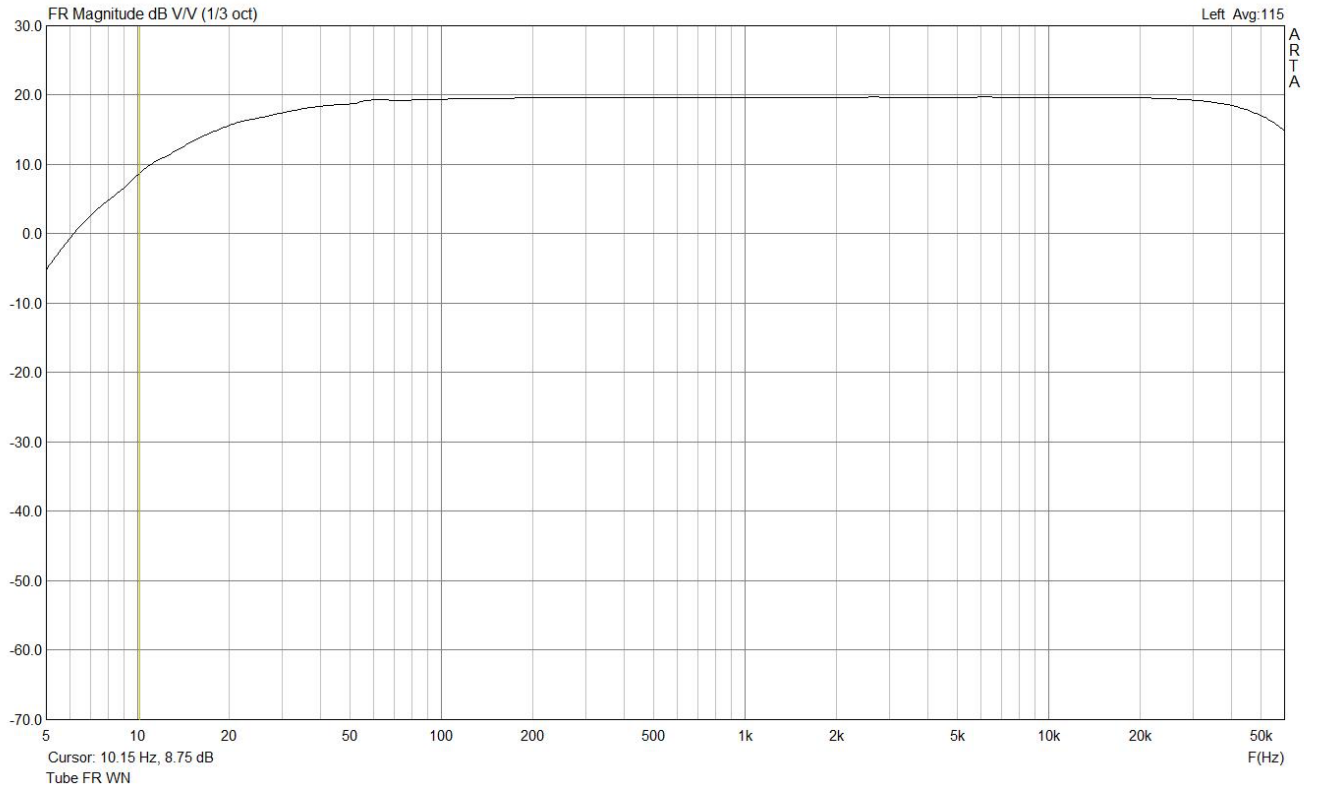Figure 36: Solid State IMD Measurement given input signals at 13kHz and 14kHz
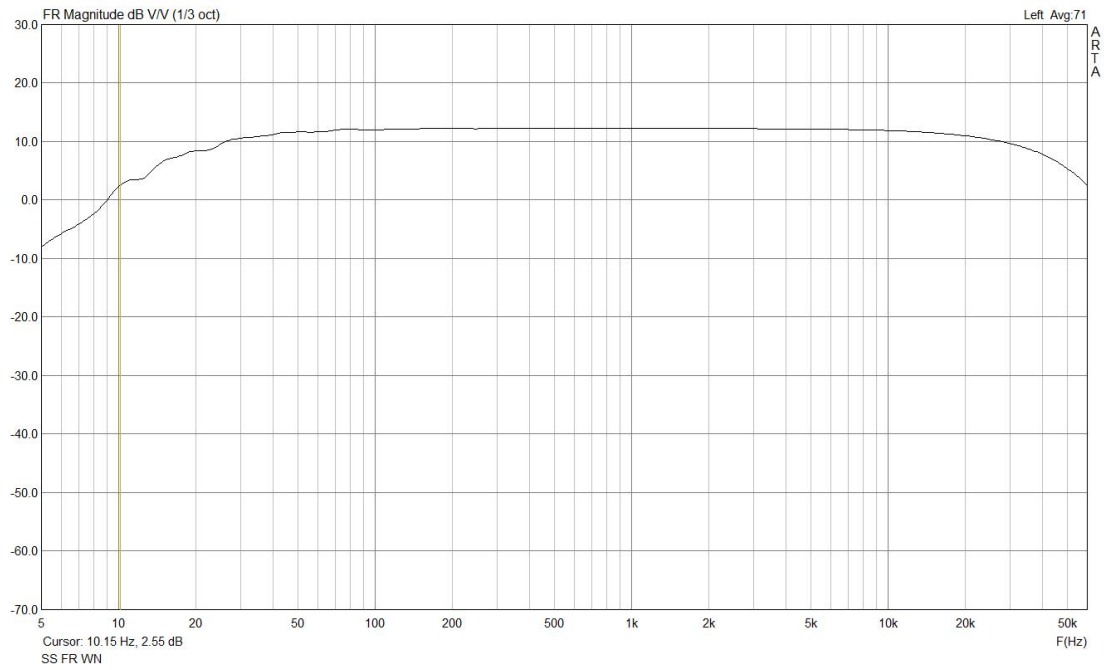
Figure 37: Triode Frequency Response

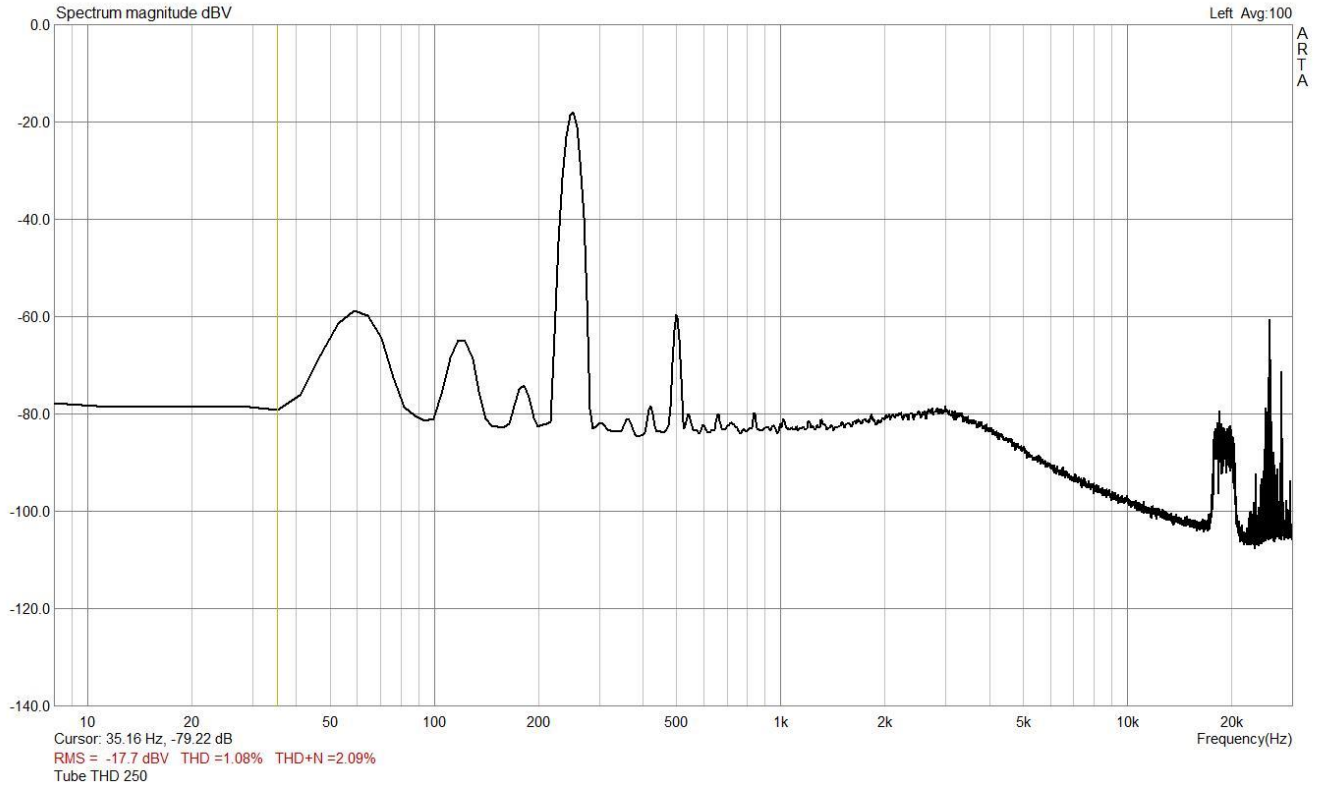FR Magnitude dB V/V (1/3 oct)   Left Avg:71

Cursor: 10.15 Hz, 2.55 dB
SS FR WN

Figure 38: Solid State Frequency Response

Figure 39: Triode THD and THD+N with 250Hz test signal
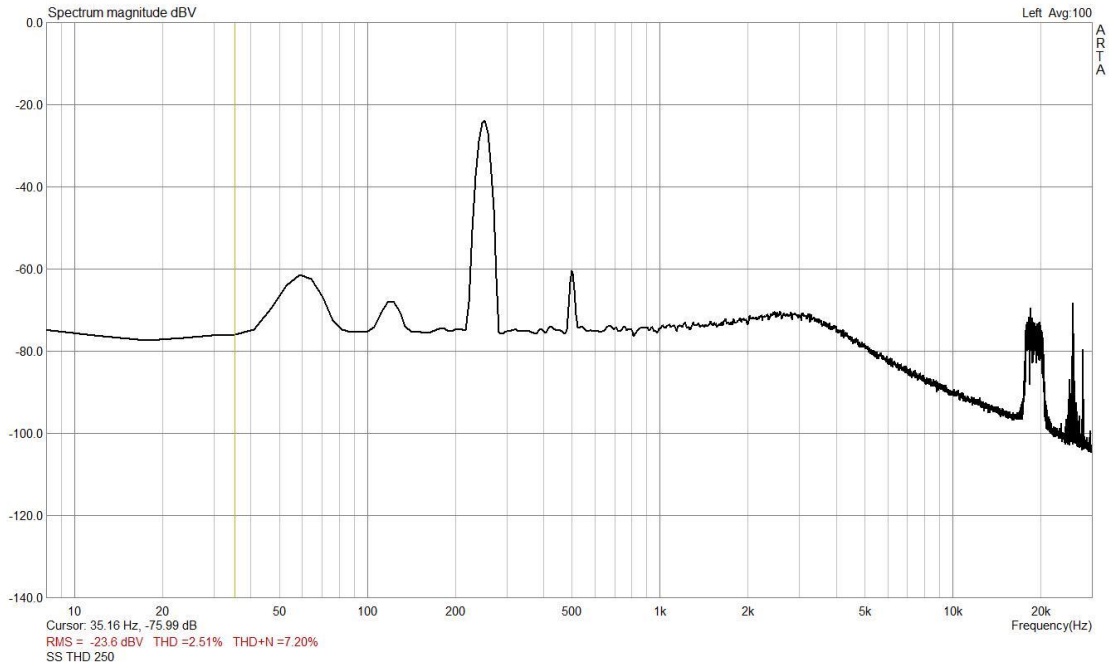
Figure 40: Solid State THD and THD+N with 250Hz test signal
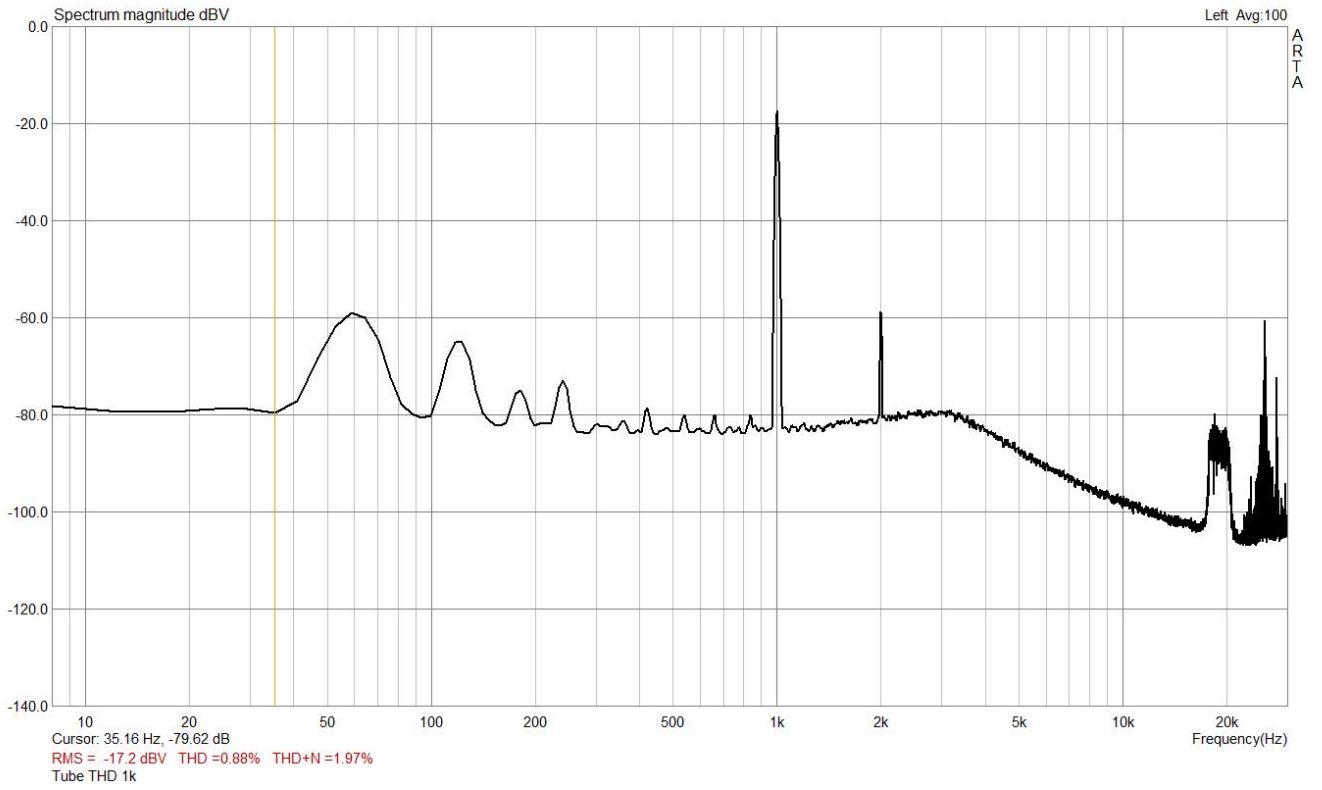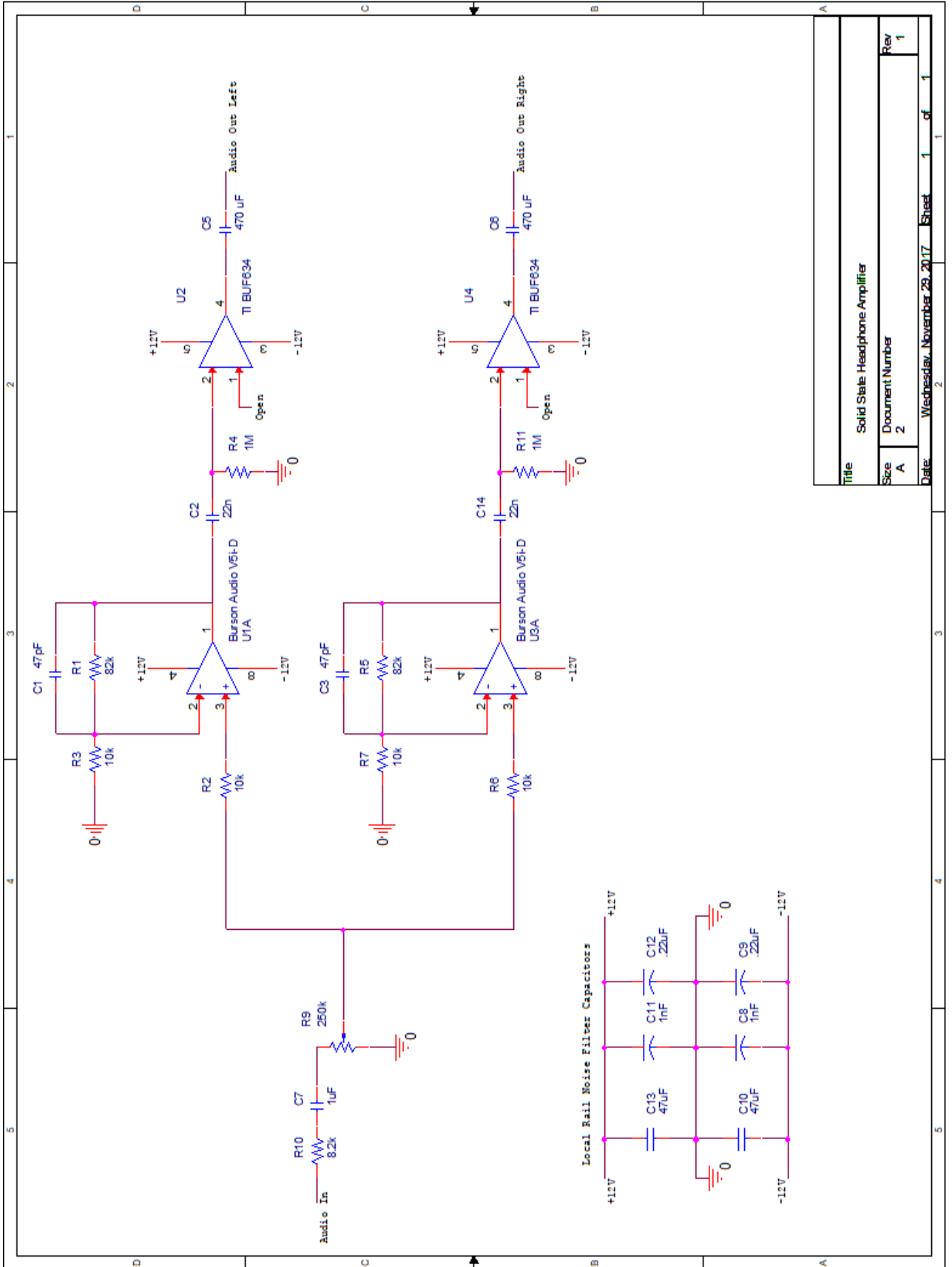
Figure 41: Triode THD and THD+N with 1kHz test signal
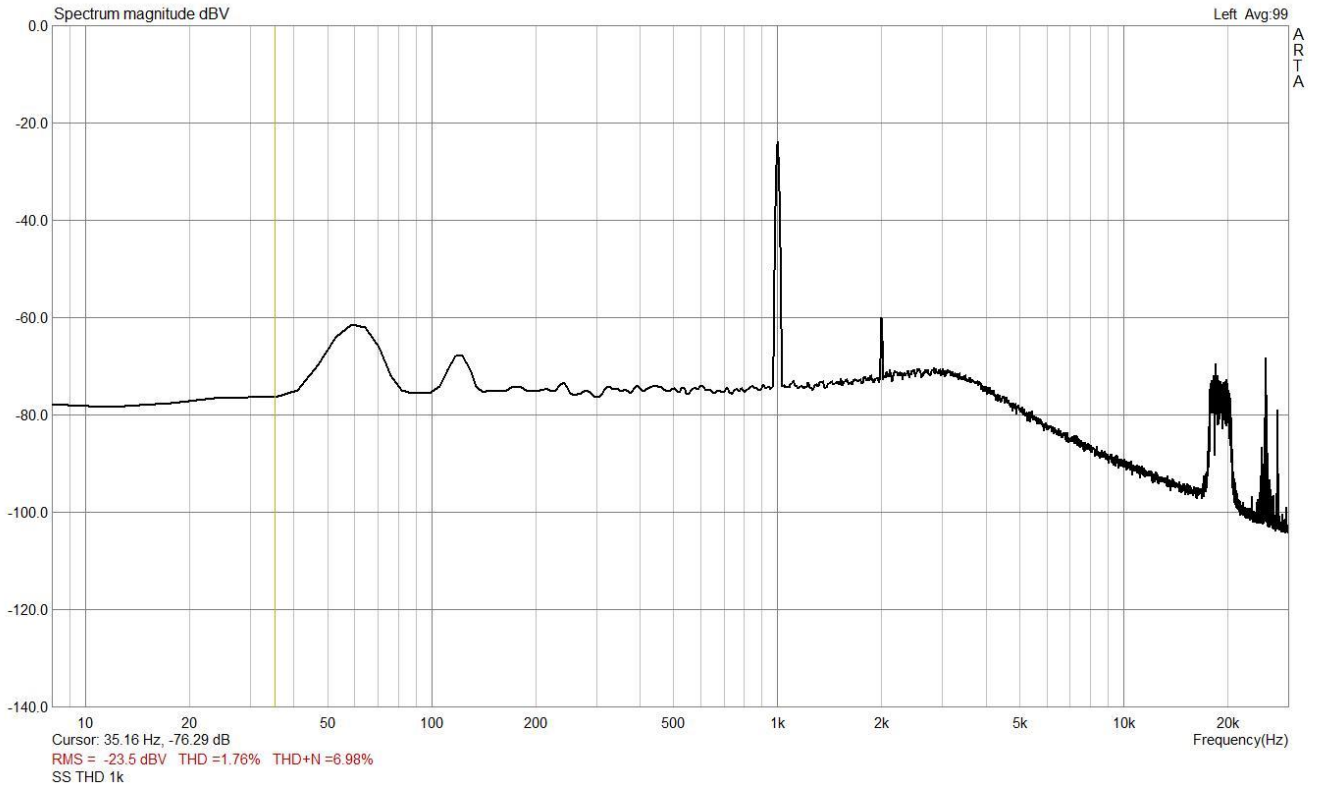
Figure 42: Solid State THD and THD+N with 1kHz test signal
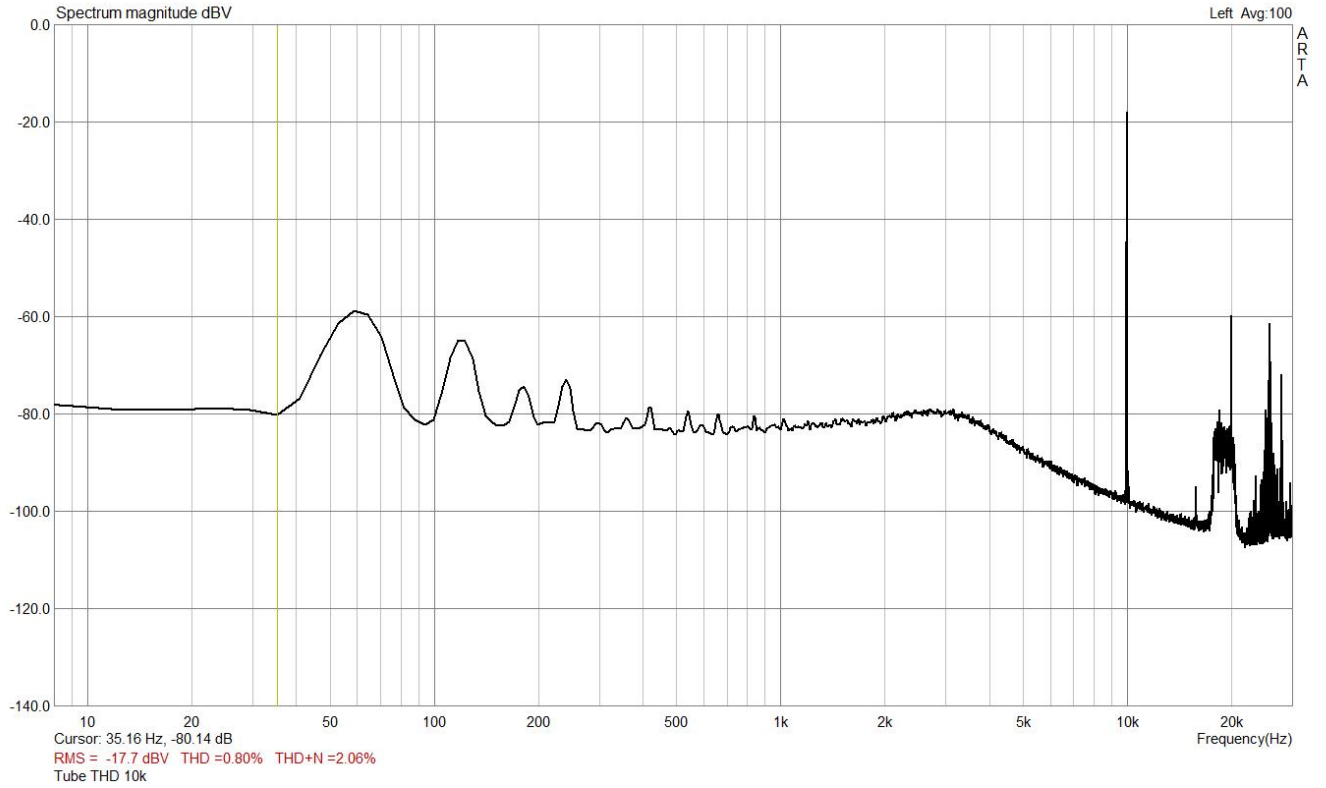
Figure 43: Triode THD and THD+N with 10kHz test signal
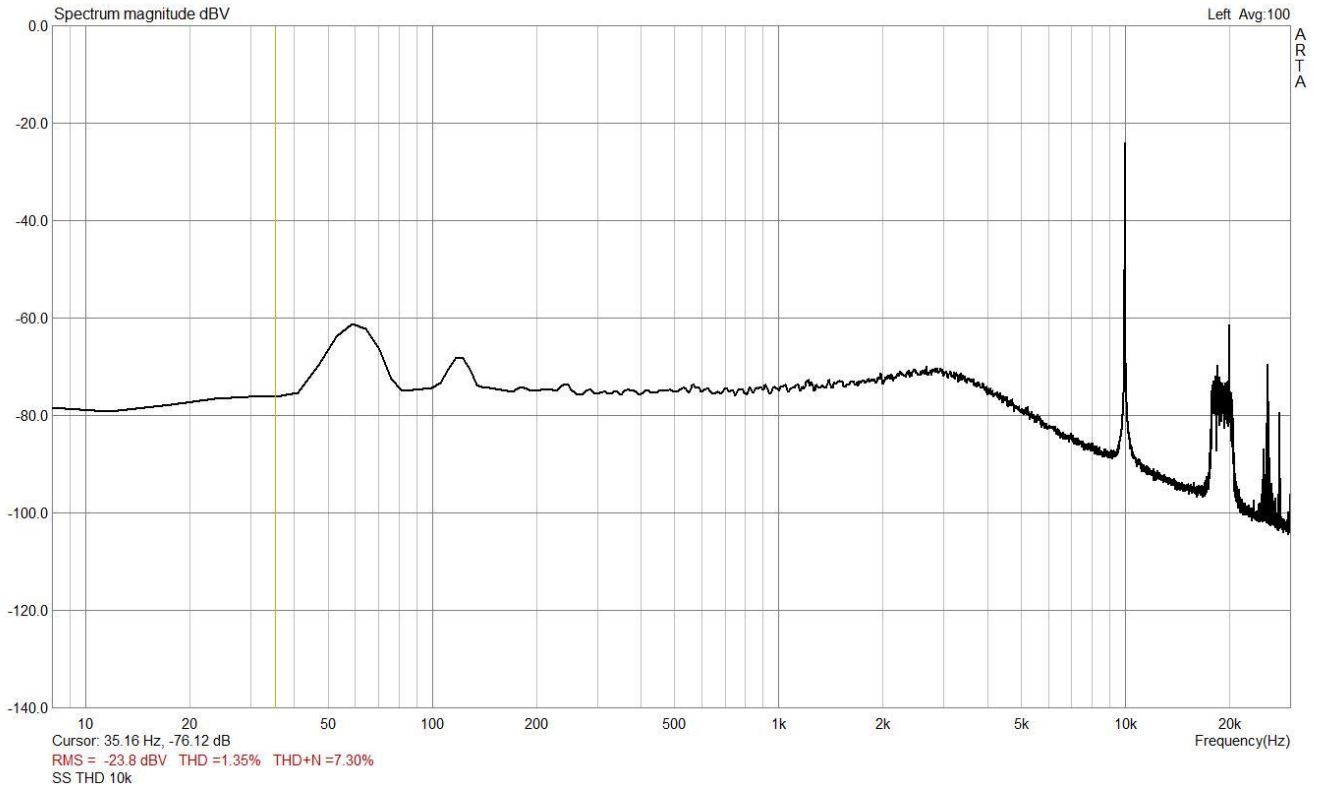
Figure 44: SS THD and THD+N with 10kHz test signal
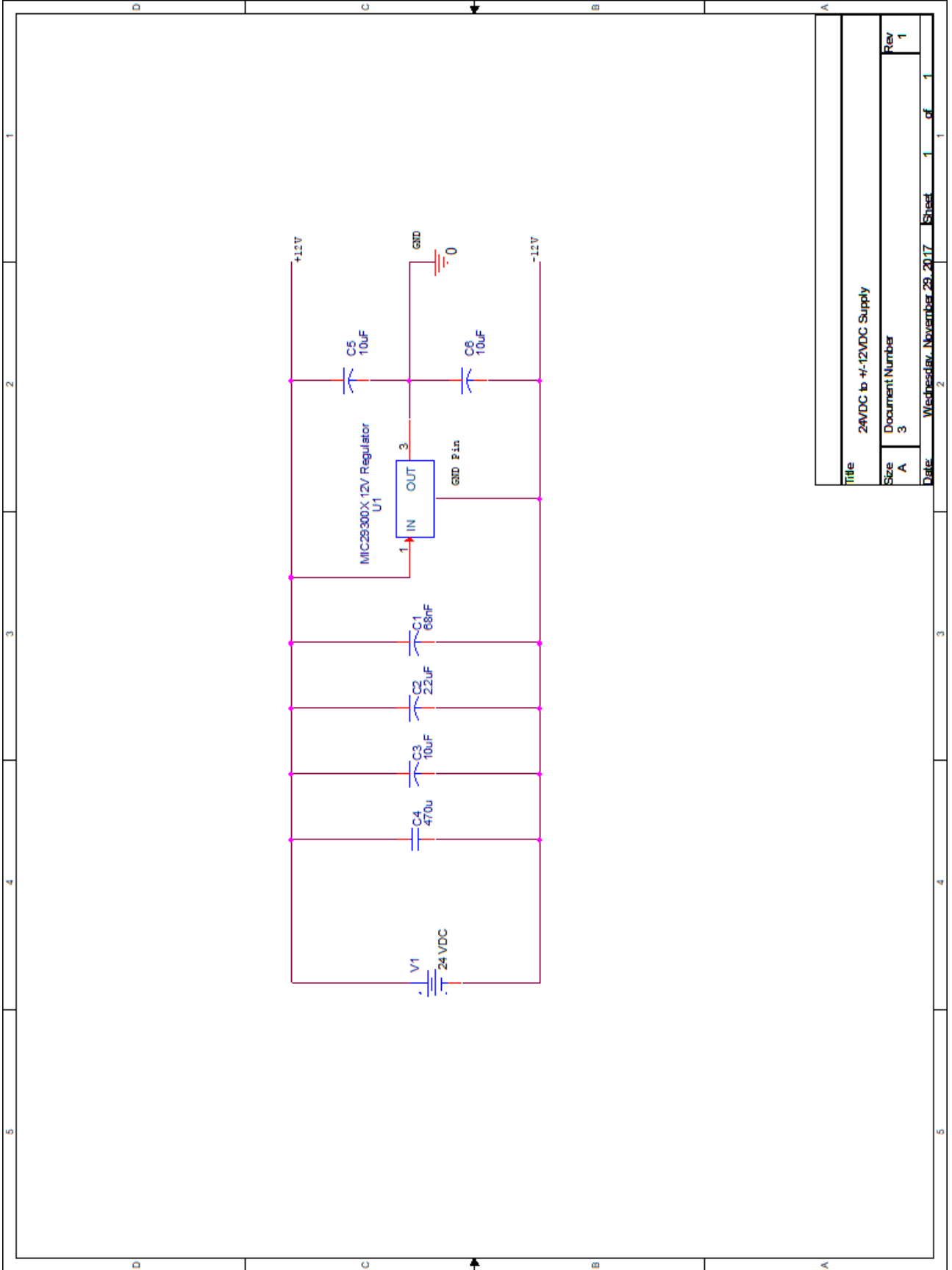
Appendix C
Final Project Schematics

Refer to OrCad Schematics Below

Triode Headphone Amplifier

Solid State Headphone Amplifier

Dual Method Headphone Amplifier