Vacuum Tube Amplifier

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Abstract

The purpose of this project is to design and build a vacuum tube amplifier for home audio system. The vacuum tube amplifier takes analog audio signal as input and amplifier the signal to power output devices such as headphones and speakers. It will offer a better sound quality than the solid-state amplifier of same price. It also offers personalization by letting users choose compatible vacuum tubes for personal preferences. This report explains the design considerations and choices as well as verification results.

Key words: High fidelity, Hi-Fi, home audio system, vacuum tube, amplifier.

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1 Introduction

1.1 Purpose

Steve Guttenberg once states: Most people listen to music in their cars, portable players, or $10 computer speakers. Audiophiles are the 1 percent still listening at home over a hi-fi system [1]. Because of the expensive professional Hi-Fi audio system and the convenience of the smartphone, people hardly ever sit down in home, and quietly listen to the heavenly melody the nature brings to us. As a result, people are less concerned about the sound quality. Statistics have shown that most people own Beats headphones or Apple Ear pods [2], but the fidelity of those “elegant looking” headphones or earphones are not worth their price, since the frequency response of Ear-pods only range from 100 Hz to 10 kHz, which is way below human hearing range [3]. Also, the “Monster Beats by Dr. Dre Solo”, which has an exponential decay of its frequency response curve, will result in a huge imbalance between the bass, midrange and treble [4]. We found that most commercial headphones and earphones that targeting most of the consumer will not give us a pleasant listening experience.

To solve this problem, we decide to design and build an affordable vacuum tube amplifier to lower the barrier for the people who would love to enter the “audiophile” aspect of life. This product will use vacuum tubes to amplify audio signals with minimum distortions to reconstruct live and realistic sound for high-end listening experiences.

1.2 Subsystem

This project has four modules: power module, input module, output module as well as amplification module. As shown in figure 1, input module includes power inputs and signal inputs; power module includes three transformers and an AC to DC converter; amplification module has voltage and power amplification stages; lastly output module includes output transformer and headphone circuit.

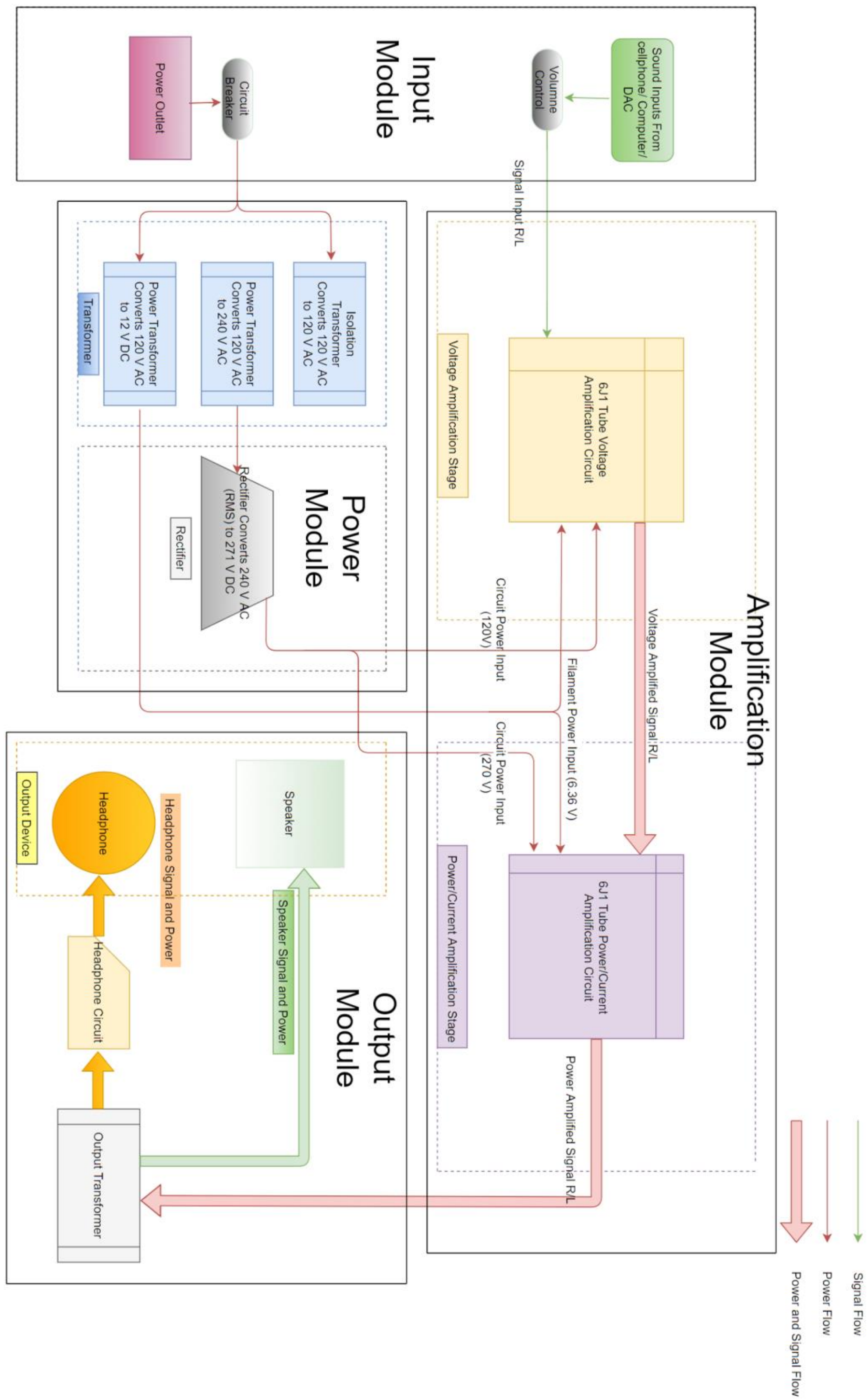

Figure 1: four modules have directional path indicated by arrows.

1.3 Functionality

For this product to work, these high-level goals must be satisfied:

1) Power module must convert AC voltage into low noise DC voltage with high signal to noise ratio.
2) Power module most supply sufficient voltage and power to vacuum tube circuits.
3) Amplification module must amplify signal with low distortion so that envelope of the input and output waveforms are close to identical.
4) Input signal must pass through volume control with minimum distortion, and amplitude can be adjusted using volume control switch.
5) Output module must be efficient so that maximum power can be transferred to target device.

2 Design

There are many freedoms to choose components in each module. Design choices as well as component functionality and schematics are discussed below.

2.1 Input Module

2.1.1 Volume Control

Since the amplifier module will amplify signals unbiased within its frequency range, the signal amplitude control is extremely crucial since any noise introduced will be amplified and it could create distortion and hissing noise. The resistor noise can be models in equation 1.

$$\mathrm{E} = \sqrt{4 \cdot k \cdot R \cdot T \cdot df} \tag{1}$$

Where k is the Boltzmann constant, R is the resistance, T is the temperature of the resistor in Kelvin, and df is the frequency bandwidth.

As equation shown above, we cannot control the frequency and temperature as well as Boltzmann constant. Ideally a low value resistor is desired to reduce noise to minimum. However, the input signal has certain impedance as well as the RCA and 3.5mm jacks, a low value volume control would reduce the input voltage gain. We choose volume control resistance value of 10k as our design choice because of these two factors.

2.1.2 Circuit Breaker

High voltage (270 V) is most dominant potential hazard since short might result in a tremendous amount to current. The circuit breaker is chosen to have 10 A maximum current considered our working current is only about 50 mA while the surge current when the device is turned on can reach 2 A. Circuit breaker is just like a fuse, but with less reaction time and does not to be replaced, this advantage will make circuit breaker a better choice of our circuit protector.

2.2 Power Module

2.2.1 Transformer

We have a dual transformer system. The first transformer is an isolating transformer, which has turns ratio of 1:1. We will feed 120 V AC from the wall outlet to the first transformer, such that V1 = 120 V.

According to the relation of turns ratio and voltage ratio:

$$\frac{N1}{N2} = \frac{V1}{V2} \tag{2}$$

$$\frac{V1}{V2} = 1 \tag{3}$$

Therefore:

$$V2 = 120\text{ V} \tag{4}$$

The purpose of this transformer is to isolate the neutral of the grid from neutral of the secondary coil in both transformers. By doing this, the circuit connect to the grid is totally isolated from our device, which will reduce the noise that created from other devices to our amplifier.
The second transformer is a step-up transformer. This transformer has turns ratio of 1:2, such that:

$$\frac{V1}{V2} = \frac{1}{2} \tag{5}$$

$$V2 = 2 \times V1 = 240\text{ V AC} \tag{6}$$

This transformer will step the voltage from 120V to 240V, which will be then be rectified and filtered to DC.

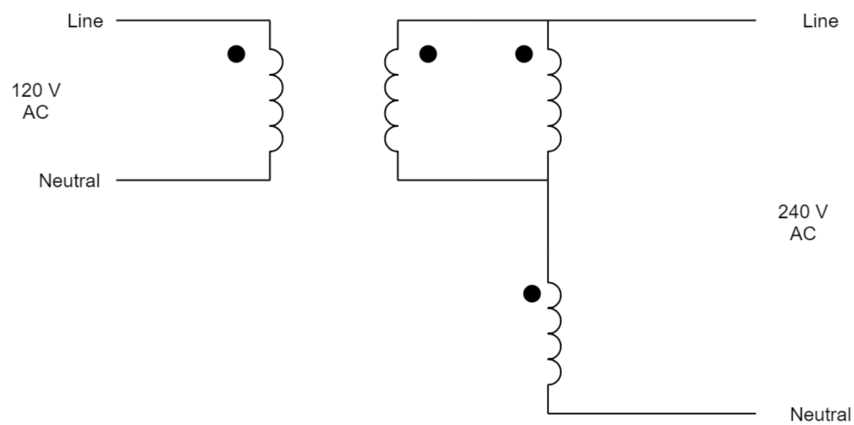

Figure 2: Transformer Circuit Diagram

2.2.2 Bridge Diode

We choose to use bridge rectifier for the following 2 reasons:

1) Bridge rectifier is a full wave rectifier, it provides a higher efficiency than half wave rectifier.
2) Our transformer does not have a center tap, so we will not be able to use regular full wave rectifier.

The voltage drop of each rectifier is approximately 0.3 V, which is negligible for voltage having an amplitude of 308 V.

The circuit ground is connected to earth ground from the power outlet to ensure that there is only one ground for the entire system, i.e. signal ground and power ground are the same ground. This will provide us safer operation environment.

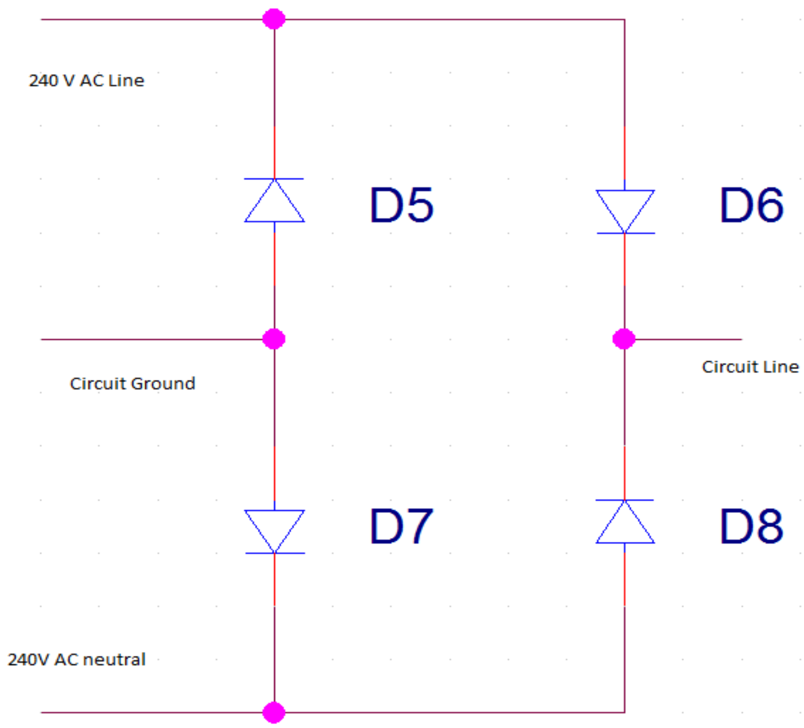

Figure 3: Bridge Rectifier Circuit Diagram

2.2.3 RC filter

The reasons to have the above design for the filter are listed:

1) The first capacitor should be small enough such that the surge current is less than the rating of our circuit breaker current.
2) Inductor will produce huge reverse voltage, which might damage to the bridge rectifier system as well as the plate of the tube.
3) Multiple stage of filtering that can reduce the ripple voltage as much as possible, while have voltage drop as low as possible.

Due to the above reason, we have 3 stage CRC filtering.

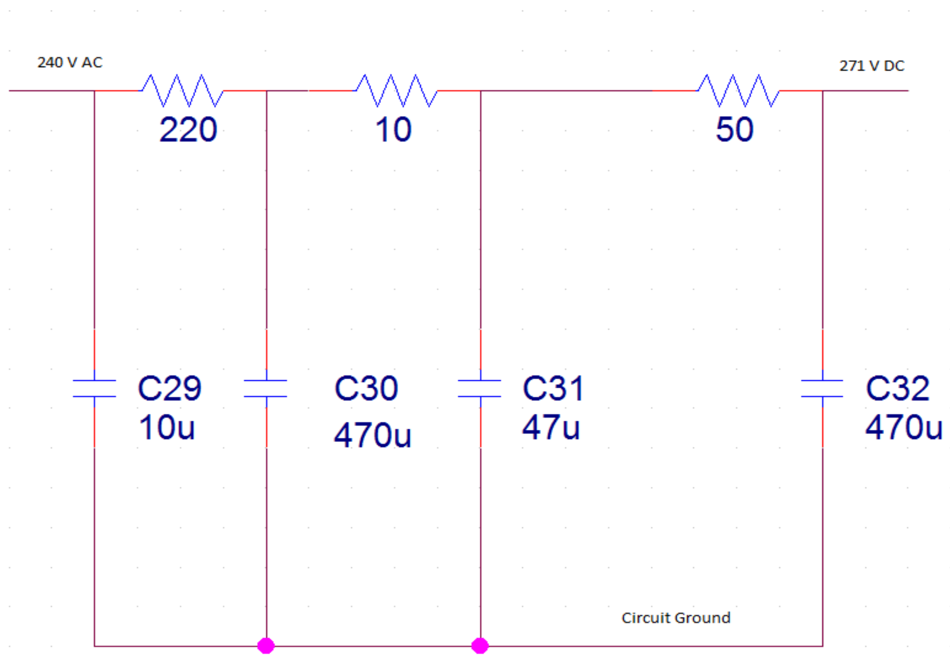

Figure 4: Filter Circuit Diagram

2.2.4 Filament supply

There are many choices for the filament heating. 6.3V is the required voltage to heat the filament, and both AC and DC would work since the both tube is indirectly heated. We choose DC to heat the filament due to its stable voltage. Theoretically DC heating method can reduce the time variation in power thus reduce hissing or humming noise [5].

2.3 Amplification Module

2.3.1 First Stage Amplification

The 6J1 tube is a pentode. Pentode is a special kind of vacuum tube that has 5 electrodes. There are 3 possible ways to utilize a pentode: regular mode, ultra-linear mode, and triode mode. Pentode mode has a wide frequency response range as well as a larger output impedance, which is less desired in efficiency and more power consumption. Secondly, the ultra-linear mode needs some sort of transformer center-tap. However, we do not have a center-tapped transformer. Triode has the best frequency and transient response among these three, but the output power is slightly less than Pentode configuration. Since our project targets headphones and bookshelf speakers with high sensitivity, we will choose the triode connection method. By connecting the screen to the plate using a 1 k Ohm resistor, we simply created a triode-connected pentode.

We also decide to use the auto biasing method. We want the grid to be -2 V relative to the cathode due to best operating point standpoint. Therefore, the biasing resistor can be calculated as

$$R_k = \frac{V_k - 0}{I_p} = \frac{2.0}{0.0009} = 2222\ \Omega \qquad (7)$$

Thus, the operating point is defined, as in figure 6.

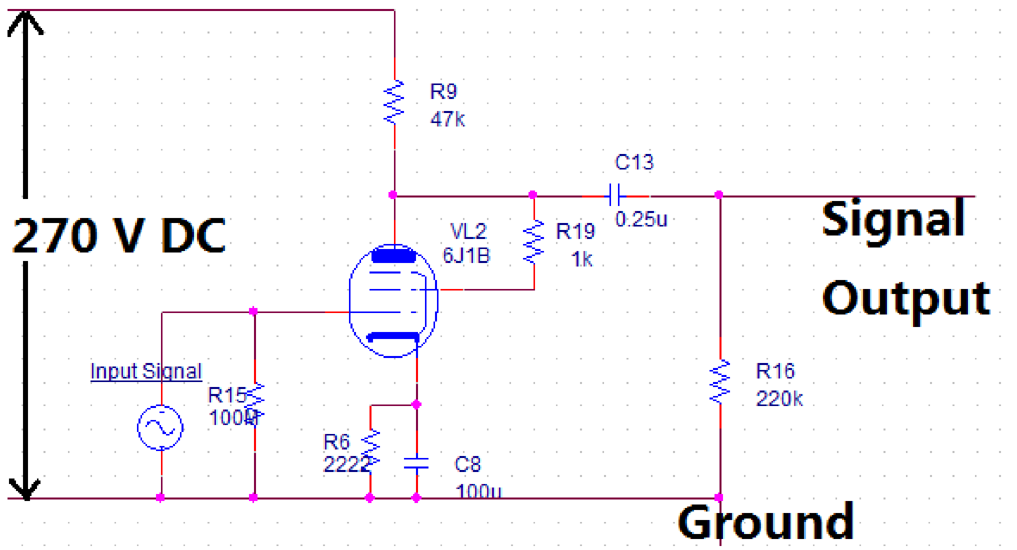

Figure 5: Circuit Diagram of First Stage Amplification

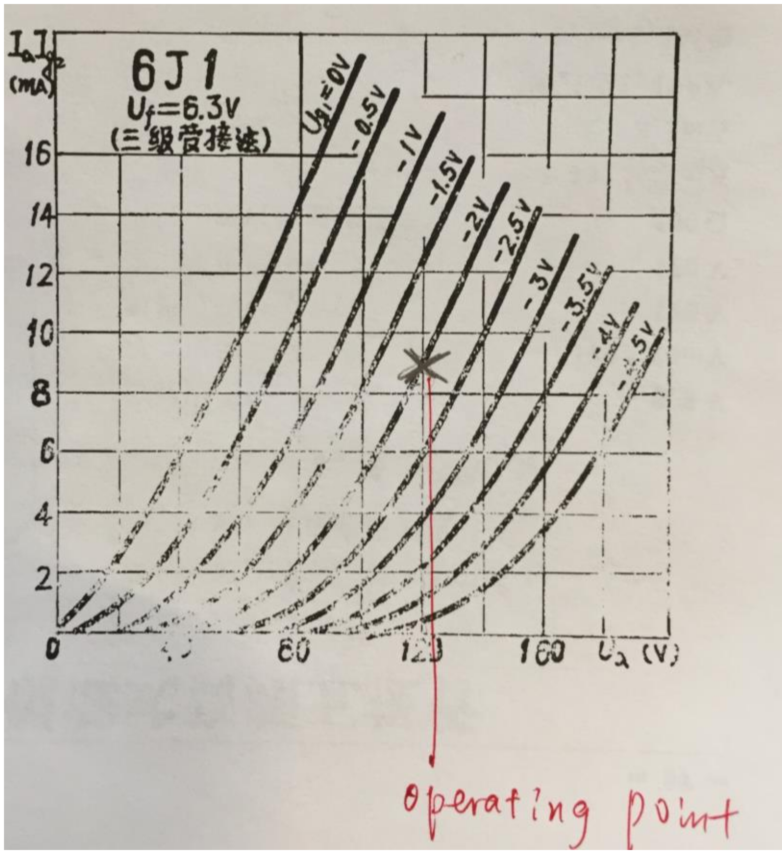

Figure 6: Operating Point of First Stage

2.3.2 Second Stage Amplification

The second stage is power amplification stage. We choose 6P1 as out power amplification tube. This small tube can output 5 W maximum, which is a lot for bookshelf speakers. 6P1 is a beaming tetrode tube, which means there are 4 terminals. However, to reducing the output impedance, we choose to connect this tube as triode mode.

Since the voltage input from the first stage can easily reach 10 V, we will bias the cathode to 9.68 V using auto biasing.

$$R_k = \frac{V_k - 0}{I_p} = \frac{9.68 - 0}{0.044} = 220\Omega \tag{8}$$

The plate is connected to the primary coil of the output transformer, which will take some of the voltage variation to the secondary coil, then transfer the energy to the speaker and headphone. The primary coil is an inductor. However, it will lose magnetic flux due to induced current in the secondary coil, the impedance of the inductor is quite constant in 20 - 20 kHz range. Resulting a good frequency response. The impedance of the output transformer is approximately 5 k, which is equal to the Thevenin resistance of 6P1 tube in the small signal model.

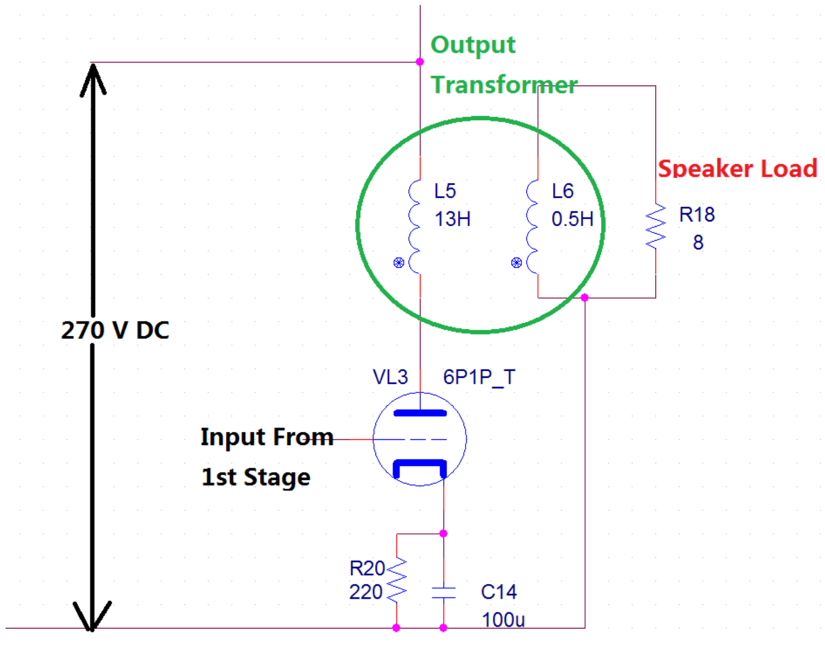

Figure 7: Circuit Diagram of Second Stage Amplification

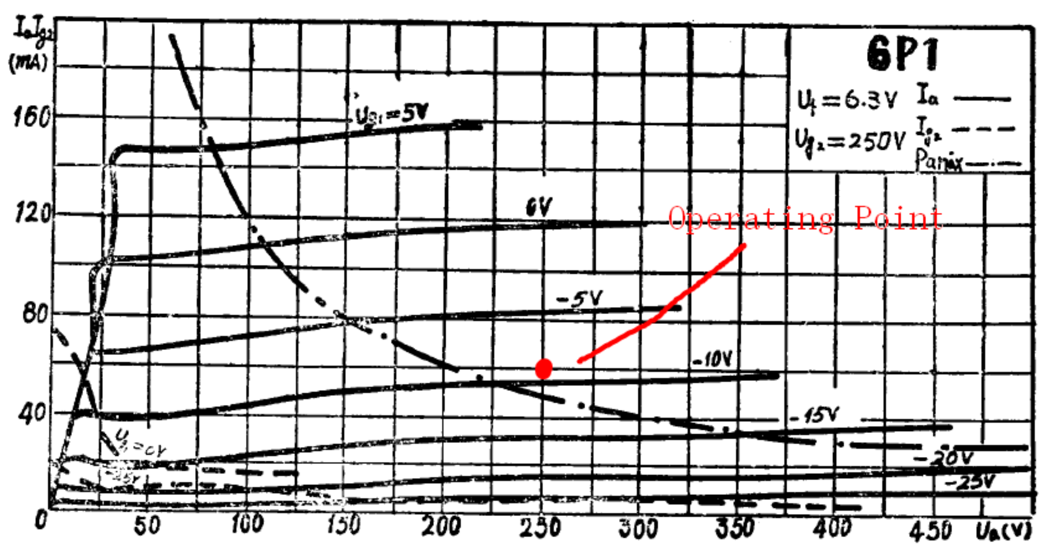

Figure 8: Operating Point of Second Stage

2.4 Output module

2.4.1 Output transformer

The purpose of output formers is to reduce input impedance and as well as reduce voltage amplitude. The impedance of second stage is much larger than the impedances of the speakers, thus a low impedance (4 ohms and 8 ohms) on the secondary side of the transformer is required. And high impedance on the primary side (5k) ensures power transference to the secondary side to power the speakers. Also, out transformer reduces the high voltage (240V) to roughly 10V, which will damage the speakers and headphones.

2.4.2 Headphone circuit

As shown in figure 9, the left and right channel of headphone circuit is connected to the 4 ohms pin of the output transformer. The resistors R42 and R43 is connected in parallel to reduce the power transfers to headphones due to the lower power consumption requirement. 150 ohms and 300 ohms resistors are selected to provide universal impedance match for headphones within range 16 ohms to 600 ohms. In this way, the amount of energy transferred to headphones are linear instead of quadratic.

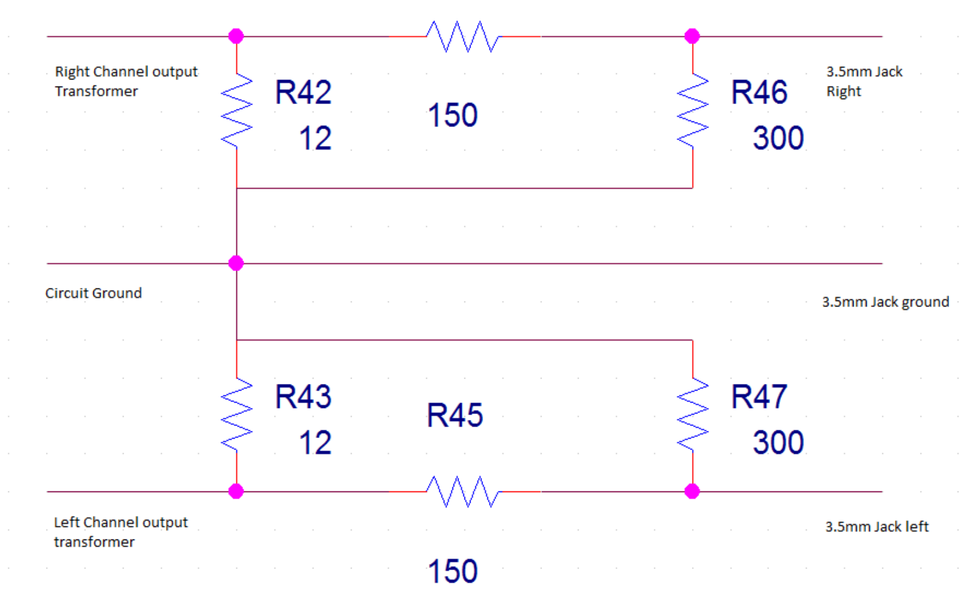

Figure 9: Circuit Diagram of Headphone Module

3 Verification

3.1 Volume Control

We applied 2 V peak to peak sinusoidal voltage signal to the volume control, the maximum voltage on the output pin is 0.702 V RMS (figure 10). The efficiency of transference is calculated in equation 9.

$$\epsilon = \frac{\text{Vin}}{\text{Vout}} \times 100\% = \frac{0.702}{\frac{2}{2\sqrt{2}}} \times 100\% = 99.27\% \tag{9}$$

Figure 10: RMS Voltage across the Volume Control Knob

3.2 AC to DC converter

Since it is impossible to impose 270 V DC to the oscilloscope, we simulated the output waveform of filter. We also used the FFT to see the highest harmonic noise in the output. The detail of the noise can be observed in figure 11, and the output DC and AC voltage measured can be seen in figure 12 and figure 13.

The highest peak of the FFT spectrum is located as 100 Hz, and its noise level can be calculated as:

$$P_{noise} = 20 \log \frac{V_{noise}}{V_{max}} = 20 \log 1 \times 10^{-4} = -80\ dB \tag{10}$$

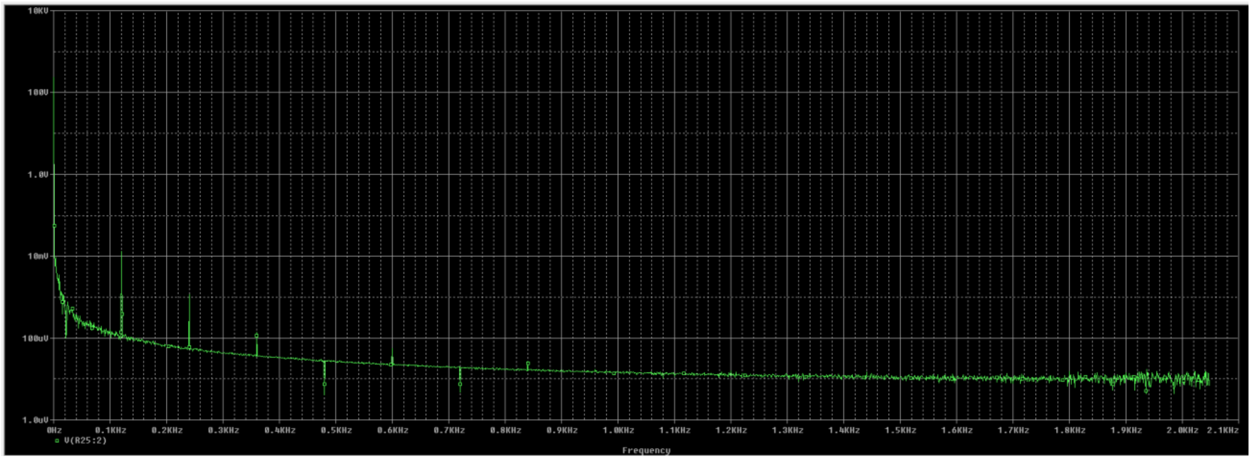

Figure 11: FFT of Output Waveform of AC to DC converter

Figure 12: Measured DC Voltage of AC to DC converter

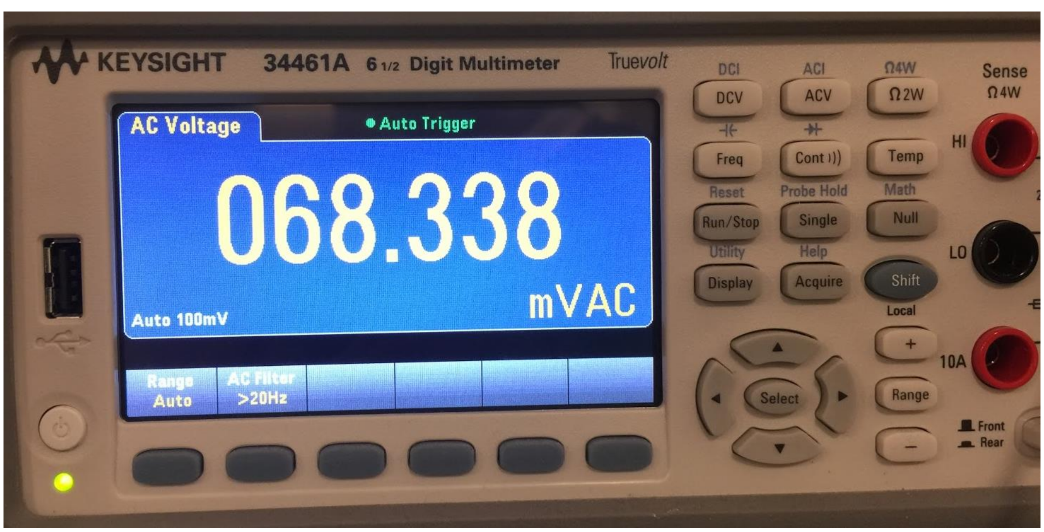

Figure 13: Measured AC Voltage of AC to DC converter

As figure 12 and 13 shown above, the DC voltage of 271 is sufficient to power the amplifier circuit and the noise of DC voltage is within 0.1 V, which satisfies the requirement for power module.

3.3 Amplification

We measured the THD of the output when the input is taking 1 kHz sinusoidal signal.
The THD can be calculated as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad (11)$$

Using the above equation as well as the FFT of output in figure 14 and figure 15, the THD of the right channel is:

$$THD = \frac{5.32\times10^{-4}}{1.33} = 0.040\% \quad (12)$$

And the THD of the left channel is:

$$THD = \frac{5.58\times10^{-4}}{1.33} = 0.042\% \quad (13)$$

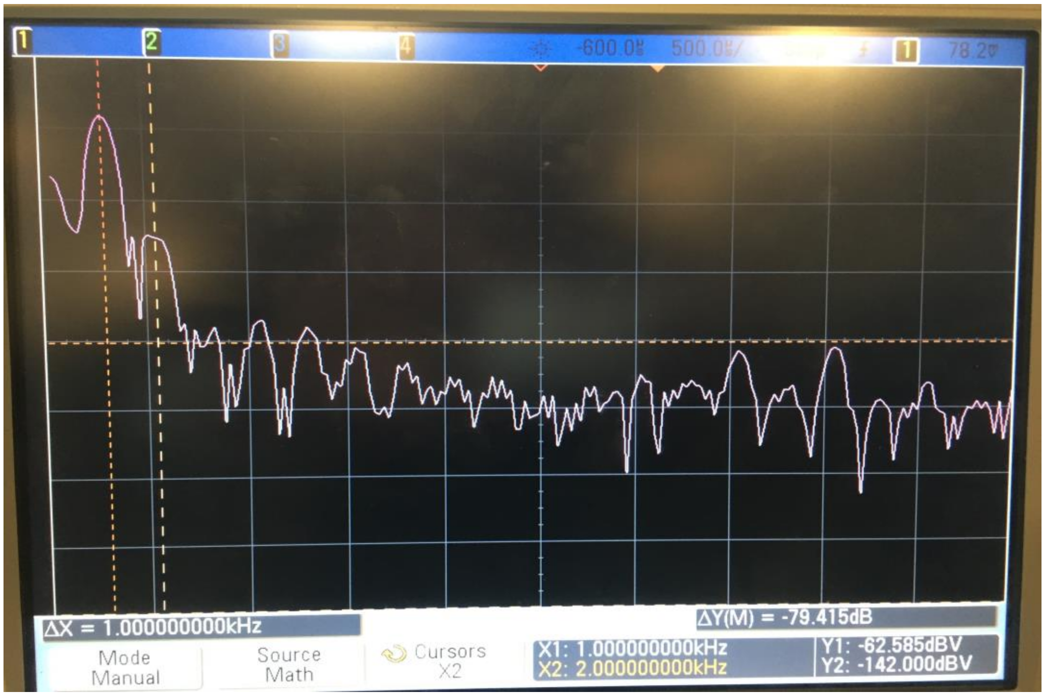

Figure 14: Right Channel Output Waveform FFT

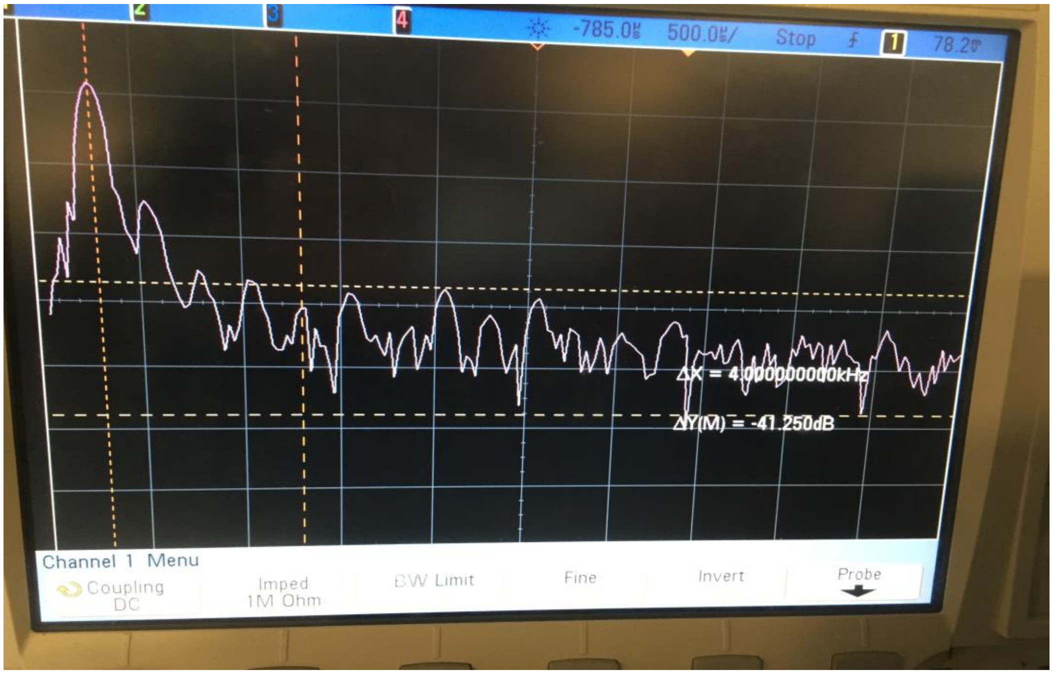

Figure 15: Left Channel Output Waveform FFT

We also tested the frequency response of the amplifier with and with the speaker. Figure 16 shows the frequency response with the speaker and figure 17 shows the frequency without the speaker.

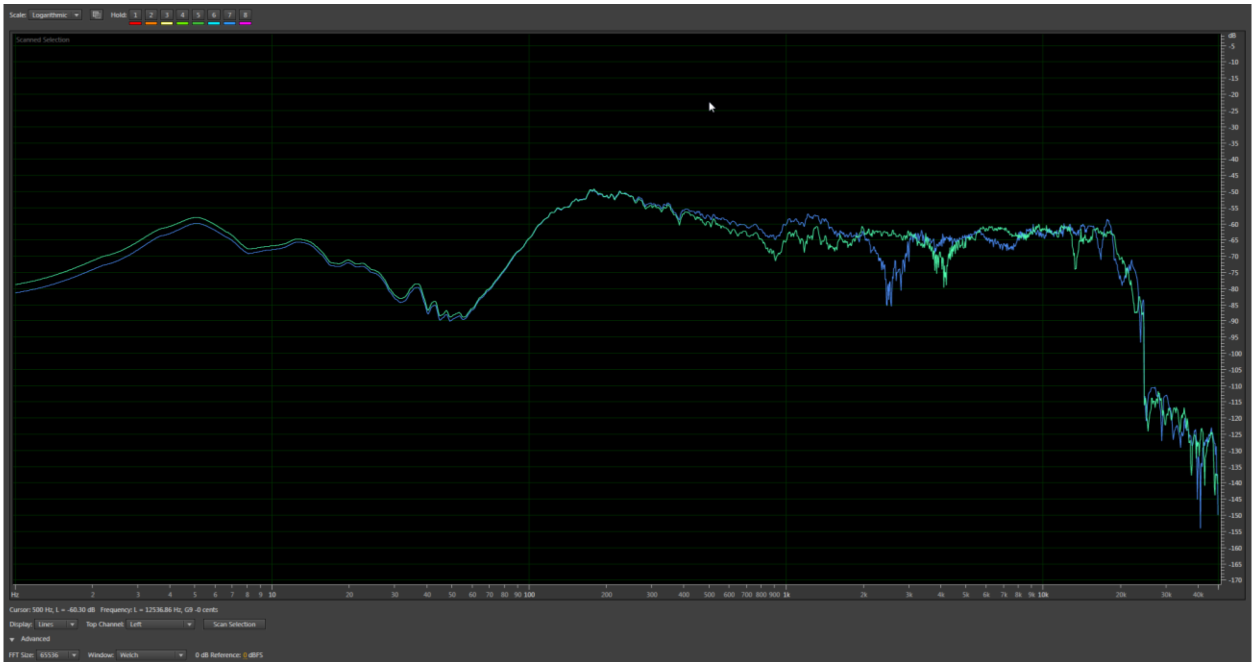
Figure 16: Frequency response with speaker

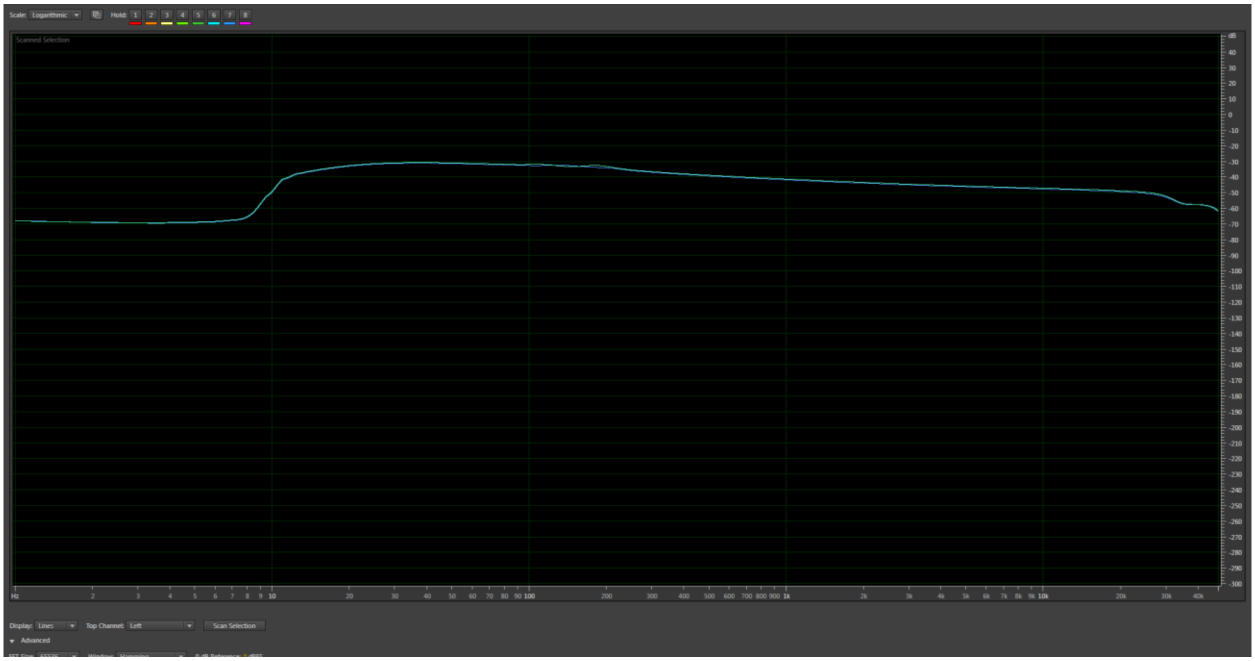

Figure 17: Frequency response without speaker

We found that the frequency response without the speaker (solely the frequency of the amplifier) is quite flat. And the band passing region is approximately 11 Hz – 41 kHz.

4 Cost

4.1 Parts

The cost of project prototype is listed in table 1. Although the mass production cost in US is calculated to be $120, the cost of production by purchasing supplies in China can effectively reduce the cost to $70.

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
Output Transformer	YunZhiSheng	15.32	10.48	15.32
Power Transformer	ShunHong Electric	35.49	29.33	35.49
CHNT double pole 10A Circuit Breaker	CHNT	17.63	5.41	17.63
HER508 HIGH EFFICIENCY RECTIFIER	RECTRON SEMICONDUCTOR	2.20	1.54	2.20
6J1 Vacuum Tube	ShuGuang	6.52	5.26	5.62
6P1 Vacuum Tube	ShuGuang	12.08	10.46	10.08
Vacuum Tube Socket	HuaYunDanYi	9.84	8.32	9.84
Potentiometers 10K ohms	Bourns	15.4	6.42	15.4
RCA input	Rean Neutrik	6.44	5.62	6.44
Chassis	FenLe	20.65	16.32	20.65
Canare 2S7F Speaker Cable	Canare	9.26	7.51	9.26
Canare L-2T2S Microphone Cable	Canare	5.32	3.96	5.32
470µ Aluminum Electrolytic Capacitors	Vishay BCcomponents	16.78	9.66	16.78
miscellaneous				29.53
Parts Total			120.19	199.56

Table 1: Cost of Parts

4.2 Labor

The cost of labor is estimated in table 2 the total cost of labor is 10000 $.

Team Member	Hourly Rate ($/Hour)	Total Hours (hour)	Total Cost ($)
Qichen Jin	$50	100	5000
Bingqian Ye	$50	100	5000
Labor Total			10000

Table 2: Cost of Labor

5 Conclusion

5.1 Accomplishments

We have successfully built our product, while we found that all the requirements in the RV table were met and all the high-level requirements are all satisfied.

During the designing and simulating, we learnt quite a bit about how vacuum tubes work, analog signal processing, and impedance matching. We also learnt a great deal when debugging the transformer circuit that how to ground the secondary, and to make the entire system as safe as possible.

Last but not least, after some tweaking and adjustment, both of us found the sound quality pleasing to our ear. Since both of us are audiophiles, it is essential that our sound quality of the product is satisfactory to 0.1% of the picky ear in the world.

5.2 Uncertainties

After finishing testing the product, we found some aspect of our design vague. The balance of the two channel is the biggest in our design. It is possible that, two channels will have different amplification factor even if we have the exact same schematic for two channels, because the high variation of plate current of the vacuum tube. To address that, we use a knob for each single channel. However, it will be very difficult for the user to adjust the knob to reach balance between the left and right channel.

5.3 Future Work

Due to the time constraint of out projects. There are several things we can improve. First of all, we can add additional Voltage Amplification stages to further increase power so that it can drive more power-hungry speakers like floor standing speakers. Secondly, we can use tube rectifiers instead of diodes, since tube rectifier offers more protection to the amplifier stages after the device is unplugged or powered-off. In terms of cost and spacing, we can use multiple winding transformers to reduce overall size and cost. Also, we can use high quality connecting wires and components to improve signal to noise ratio and frequency response. Lastly, we can try different biasing methods and different values of resistors and capacitors to better operate our device to perfect sound quality.

5.4 Ethical Considerations

We, as future engineers, complied with the ethic guide of IEEE 7.8 [6].

First of all, this product involves high voltage. High voltage can cause potential damage to properties and loss of product, it can also cause serious injuries such as skin burn, and even death. We ensured that every high voltage cable is properly insulated and fixed.

Secondly, this device can produce huge amount of heat. High temperature can cause property damage such as melting of the plastic, and bodily injuries such as burnt skin. We have installed a fan to ventilate the high temperature air near the tube and power resistor to lower the temperature.

Last but not least, in order to reduce the risk of malfunctioning, all of the power ground, signal ground, and speaker ground are connected to the earth ground. The chassis, where there is metal, is also connect to the earth ground to provide double insurance of preventing electrical shock.

6 Reference

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Appendix A: R&V Table

Requirements	Verification	Verification Status
RCA and 3.5mm Jack		
1. The input side and connection side should be perfectly connected, the connection resistance should be less than 0.5 Ω.	1. A. Connect two terminals of multimeter to the input side and the connection side of the inputs jack respectively B. Measure the reading from multimeter to make sure it's below 0.5 Ω.	Y
2. The switch should switch from one signal source to another signal source well.	2. A. Connect two terminals of multimeter to the input side of 3.5 mm and the connection side of RCA jack respectively B. Measure the reading from multimeter to make sure it's open circuit.	
Volume Control		
1. The output voltage should be greater than 0.98 of the input voltage	1. A. Connect two terminals of function generator with peak to peak voltage equals 2 V. Connect 2 terminals of oscilloscope to the ends of the variable resistor. B. Measure the reading from oscilloscope to make sure it's greater than 1.80 V.	Y
AC to DC converter		
1. The output voltages for converter should be at 270 V (±10V) respectively.	1. A. Connect the input terminal to wall outlets. B. Connect the output terminal to multimeter. Then turn on the switch.	Y

	C. Measure the reading from multimeter to make sure it's larger our planned value.	
2. The ripple voltage at output stage should be less than 0.5% of the output DC voltage.	2. A. Connect the input terminal to wall outlets. Connect 2 terminals of oscilloscope to the output terminal of the 6.3 V rectifier. Then turn on the switch. B. Using oscilloscope to measure the ripple voltage, and make sure it's less than 0.5% Vout. C. Using simulation to determine the ripple voltage of 120 V and 230 V rectifiers.	
Amplifier Module		
1. The voltage gain should be greater than 20.	1. A. Connect two terminals of function generator with peak to peak voltage equals 0.1 V to the input of the tube circuit. Connect 2 terminals of oscilloscope to the 2 terminals of primary coil. B. Connect 2 terminal of secondary coil with an 8 Ω resistor. C. Measure the reading from oscilloscope to make sure the output waveform has a peak to peak voltage greater than 1.0 V.	Y
2. The frequency response should be 40-19 kHz (±5%)	2. A. Connect two terminals of function generator with peak to peak voltage equals 1 V to the input of the tube circuit. Connect 2 terminals of oscilloscope to the plate and ground. B. Sweep the frequency of function generator from 20 to 20 kHz, manually record the output waveform amplitude.	

	C. Plot the data, make sure the 40-19 kHz band is at most 3 dB attenuated.	
3. The total harmonic distortion (THD) should be less than 1% @ 1 kHz.	3. A. Connect two terminals of function generator with peak to peak voltage equals 1 V to the input of the tube circuit. Connect 2 terminals of oscilloscope to the plate and ground. B. Set the frequency of function generator to 1 kHz, Using the tools on oscilloscope to find the THD.	
Output Module		
1. The transformer output impedance should be 4 ohms (±0.25) and 8 ohms (±0.5) respectively.	1.A. Connect ground pin and 4-ohm pin with Multimeter to measure the AC impedance. B. Connect ground pin and 8-ohm pin with Multimeter to measure the AC impedance.	Y
2. The resistors in the left and right channel (12 Ω, 300Ω and 150Ω) should have mismatch less than 2%. The overall resistance across headphone terminal should be matched within 2%	2.A. Connect two terminals of resistor with multimeter measure the AC impedance, do the same for the other channel. B. Calculate the mismatch between two resistors.	