ECE 445
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Senior Project Proposal

Vacuum Tube Amplifier

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1 INTRODUCTION

1.1 Motive

The project goal is building a affordable vacuum tube amplifier to lower the barrier for the people who would love to enter the “audiophile” aspect of life.

A good sounding audio system consists of a pair of passive speakers, amplifier(s), a digital to analog converter (DAC) and lastly a sound source. Among all four parts, we would argue that the sound quality would improve the most by investing a set of speakers and amplifier(s). The reason is that the DAC chips has been involving and it has higher signal to noise ratio and dynamic range, lower THD from the hardware perspective. And in software perspective, the DSP algorithm has been improved as well. As a result the gap between built in DAC and audiograde DAC has been reduced over the years. And the sound source has been improved over the decades as well, it has less noise, which reduces the background noise. However, the neglect in analog circuit prostoned the development of amplifiers. And the audio grade amplifier can easily cost several grand or even more because the analog circuit is much more harder to design than digital counterpart and there is not much interest for the massive time, energy and investment spent for a lot of companies or individuals.

Our goal is to mainly tackle on the amplifier portion of audio system. There are basically two types of amplifiers, solid state amplifier and vacuum amplifier. From the market perspective, there is no budget vacuum tube amplifier available in the US market. Besides, there is some low cost solid state amplifier available and

some of them do their job really well. In order to test the performance of our amplifier, we would use a pair of full range bookshelves drivers for testing.

1.2 Background

First invented by Lee De Forest in 1906, vacuum tube amplifier has come a long way. There are many kinds of vacuum tubes. Our tube, 6J1 is a pentode tube. As Fig. 01 shown. Pentode tube have 5 electrodes, namely, the cathode, the anode (plate), the grid, the screen, and the suppressor. The geometry is shown by Fig. 02.

The tube itself can be considered as a diode, triode or transistor. With only cathode and anode, the heater increase the temperature of cathode, which is connected to electron rich terminals (ground), makes the electron free to jump into the space between cathode and anode. If a positive voltage is applied on anode, an electric field points downward is formed. Those free electron will fly to and absorbed by anode under the influence of electric field. Since electrons are only allowed to move in one direction, this is called diode.

If a grid is inserted between cathode and anode, then we created a triode, which the electron flow can be controlled by the electric potential on the grid.

Furthermore, the screen is connected to a voltage source that is half of the plate voltage, makes the potential difference smoother, thus reduce the capacitance between cathode and anode. The suppressor usually connect to ground, to reduce the speed of electrons that are close to anode, to prevent electrons from bouncing back.

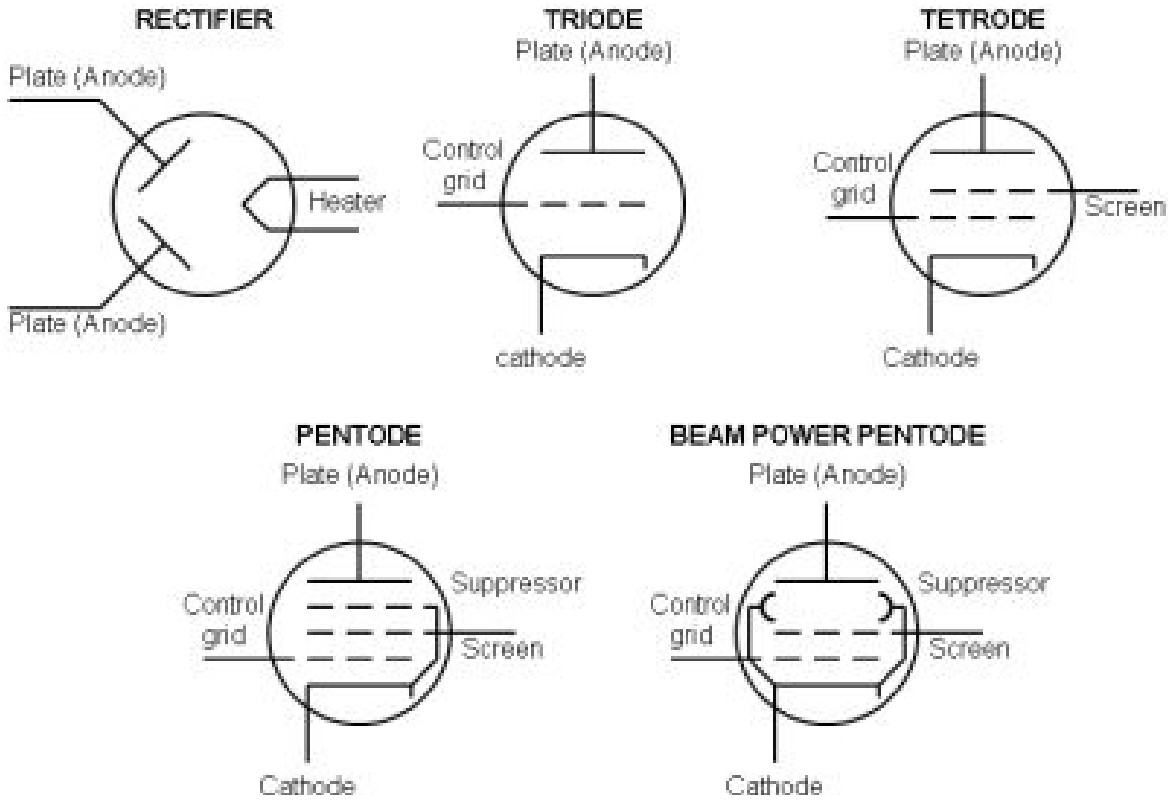

Fig. 01 Different Kinds of Tubes [1]

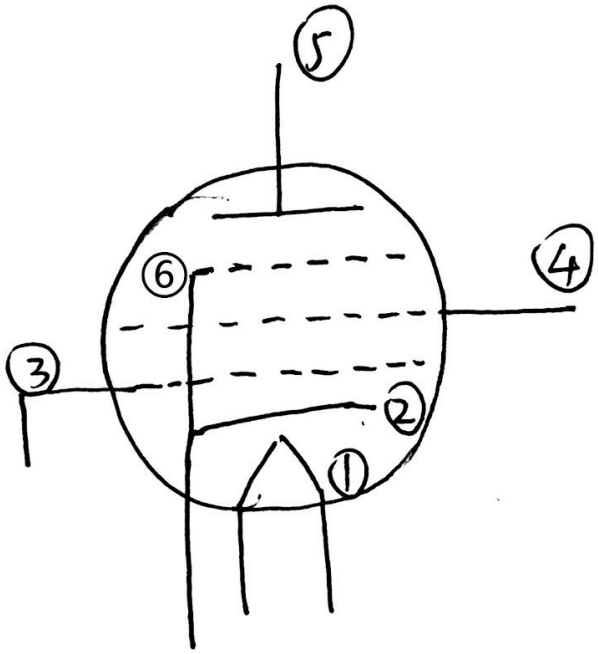

Fig. 02 The Geometry of Pentode Tube

1. Heater (Filament)
2. Cathode
3. Grid
4. Screen
5. Anode (Plate)
6. Suppressor

1.3 High Level Requirement List

Frequency response: 60-18 kHz minimum.

Signal to noise ratio (SNR): ≥ 70 dB, the background noise should be neglectable compared to the sound.

Total harmonic distortion (THD): ≤ 3% @ 1 kHz.

Stereo isolation: ≥ 50 dB @ 1 kHz. The left and right channels need to visualize people about the sound coming from different distance as well as angles rather than just two speakers.

Good clarity and separation of frequencies of sound, for symphony, as least three different instruments can be heard at the exact time.

Speaker sensitivity: 87 ± 3 dB.

Speaker impedance: 4 Ohms.

Speaker wattage: 15 W maximum.

Speaker frequency response: 60 - 18 kHz.

Headphone sensitivity: 90 ± 3 dB.

Headphone impedance: 300 ohms.

Headphone wattage: 100-300 mW.

Headphone frequency response: 60 - 18 kHz.

2 DESIGN

In overall perspective, amplifier can be divided into several parts, as Fig. 03

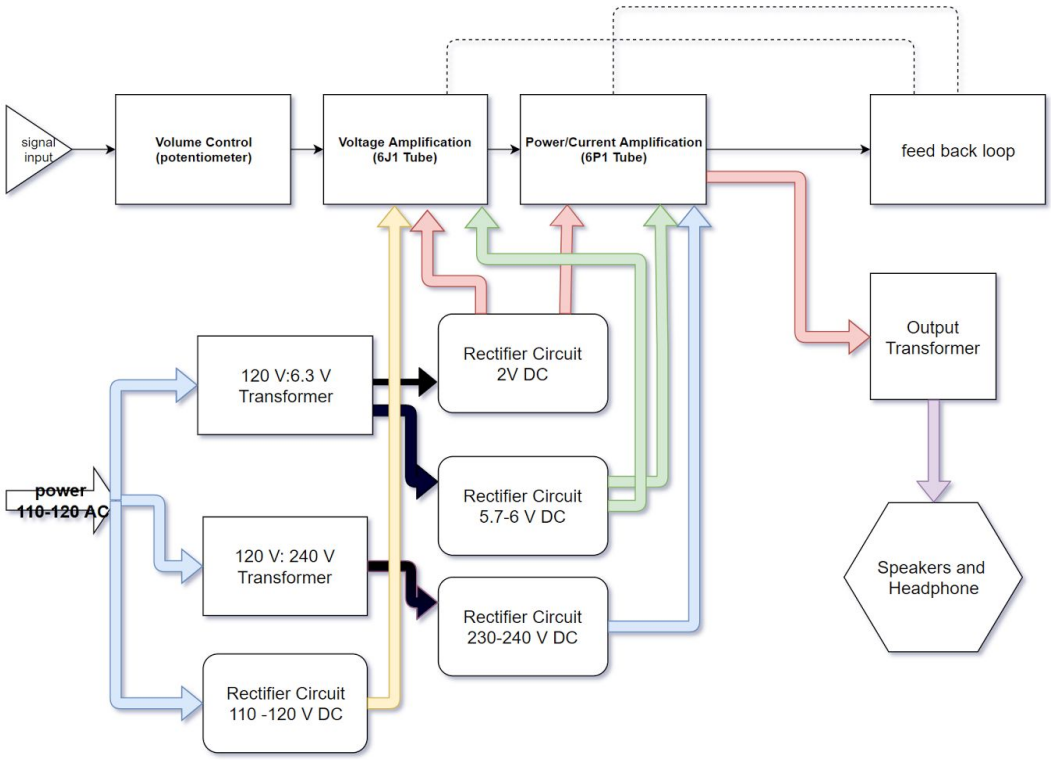

Fig. 03 Flow Chart of Amplifier System

2.1 Analog signal inputs (sound inputs)

For our amplifier, we choose to use unbalanced connectors: 3.5mm jack and as well as RCA pair. In transmission perspective, both cables feeding speakers and receiving signals will have some distortion due to interferences and impurities within the cables. One way to reduce the noise it to increase the voltage of transmission lines. Unbalanced cables such as RCA can run maximum 2 volts, while balanced cables such as XLR has voltage around 6V. Theoretically balanced cables can better, but it cost twice as much as the RCA. Since in most cases

speakers and amplifiers are relatively close to each other, the interference is negligible, RCA and 3.5 mm jack connections is a solid choice.

2.2 Impedance matching

To transfer the maximum amplitude of signal (mostly voltage), we need to be aware of the output impedances and input impedances of connections in different parts shown in Fig.03. To maximize the signal, it is best to lower the output impedance in the Tube circuits and use large resistors for the input impedances. For the final output to speaker, a output impedance matching the AC resistances of speakers and headphone are desired.

2.3 Rectifier circuit

There are two uses of rectifier circuit. Provide DC positive voltage to heat up filament for both of the tubes as well as providing DC biasing to the input signal for grids. Those DC voltages can be obtained by rectifying circuit shown in Fig. 04. We use the output of 6.3 V AC transformer as input, and the turn on voltage of four diodes can adjust the Vout value. Then we can carefully choose a matching resistance and capacitance to stabilize the Vout value so that the fluctuation of voltage to be smaller than 0.5%. 6.3 V AC transformer should generate roughly 2V biasing for the grid as well as 5.7-6 V DC to heat up filament. A 220-230 V DC can be also generated using 120 V to 240 V transformer. And a 110-120 V DC can be generated by connecting rectifier circuit directly to the power supply.

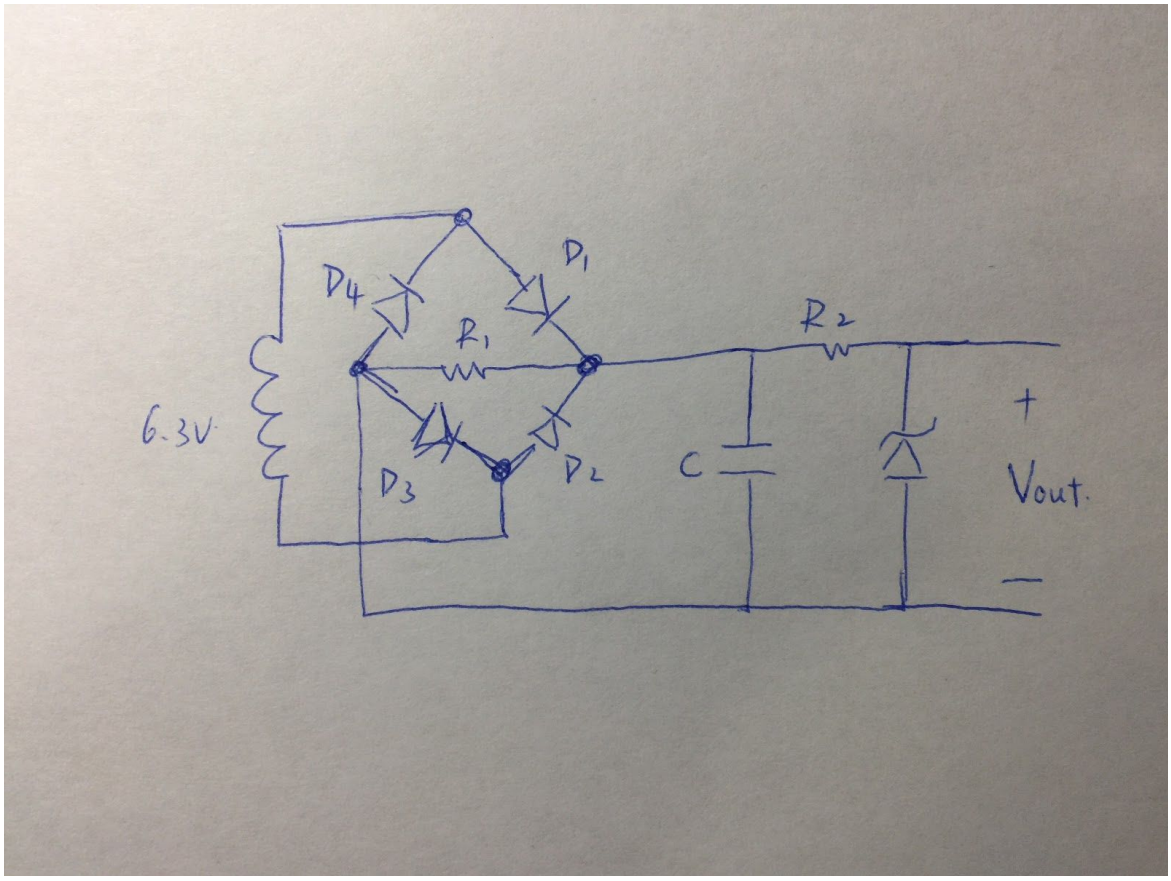

Fig. 04

2.4 Volume Control

An amplifier must be able to adjust the overall volume for the loudness to be pleasing and acceptable. This can be done in two different ways: adjust the input signal or through a volume control knob inside the amplifier. In our impedance matching to our input analog signal, we want most of the voltage analog input transfer to the later voltage amplification tube. To do that, we can put a resistor with magnitude of 10k in series with a potentiometer of value 100k. We lose a minimum of 0.828dB (9.1%)the amplification but gained a wide range of volume control by sweeping the potentiometer. Volume Control diagram is shown in Fig. 05

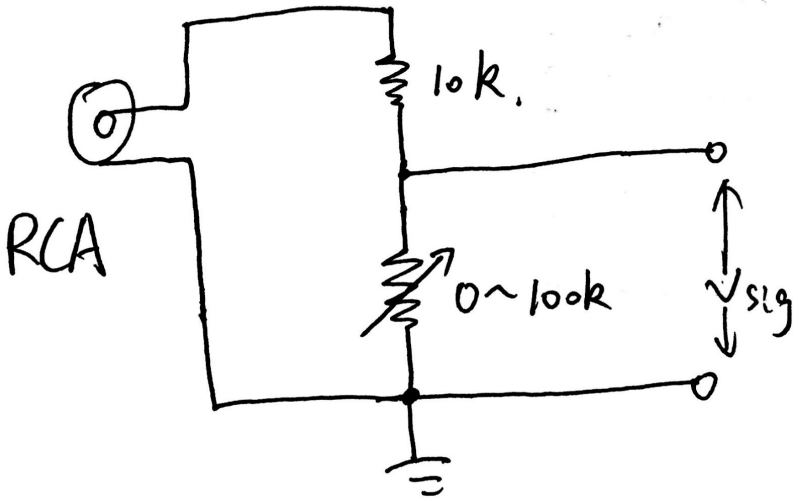

Fig. 05

2.5 Filament Powering

We will use a 6.3 Vrms AC to power the filaments of 6J1 and 6P1. The 6.3 Vrms is directly output from transformer. The detailed circuit is as Fig.

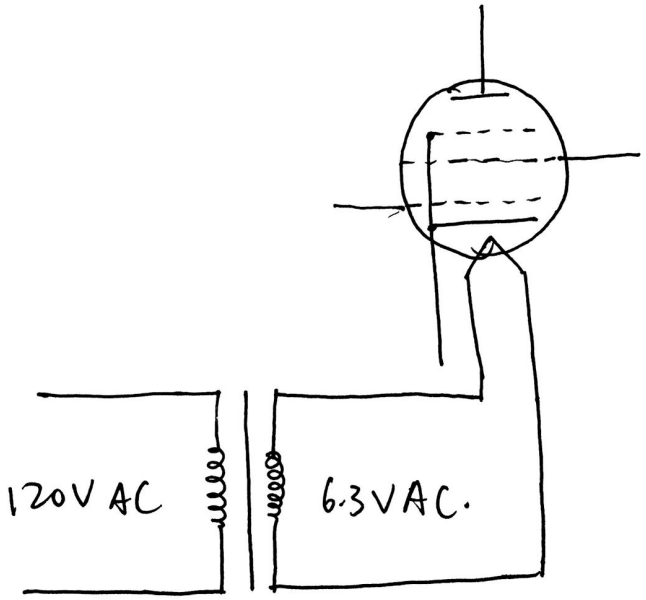

Fig. 06 Powering of Filament

2.6 Voltage Amplification

Basic circuit: We will use common cathode connection. The basic circuit is as Fig. 07.

From the datasheet (see Fig. 08 below), we found that the typical plate voltage (Vp) is 120 V, we want to operate in a linear region, thus we choose our plate current (Ip) is approx. 9 mA (The exact value is TBD). Thus, we need to bias the grid to be -2.0 V. In other word, the cathode has a 2.0 V higher potential. Grounding the grid using a resistor of approx 1 MΩ (The grid can be considered as open circuit, thus a large resistor can do the ground). To make the cathode 2.0 V higher than ground, we use another resistor.

$$Rk = \frac{Vk-0}{Ip} = 2.0/0.0009 = 2222\Omega$$

So we will bias our circuit as Fig. 09

Using the above biasing condition, we can calculate transconductance:

$$gm = \frac{\partial Ip}{\partial Vg} = 0.009/(60 - 120) = -1.5 \times 10^{-4}\Omega^{-1}$$

Using the small signal model, as Fig. 10. We ignore any internal capacitances, since their magnitude is pF level, which can be considered as open circuit for audio circuit that runs below 22 kHz.

$$Vout = -gm \times vgk \times (rp||Rp)$$

The exact value will depend on Rp, which is part of design that cannot be determined by theoretical calculations.

The design should meet the following specification:

Amplification Factor (μ) ≥ 16;

Frequency response: 30-19 kHz minimum;

Signal to noise ratio (SNR): ≥ 90 dB;

Total harmonic distortion (THD): ≤ 1% @ 1 kHz.

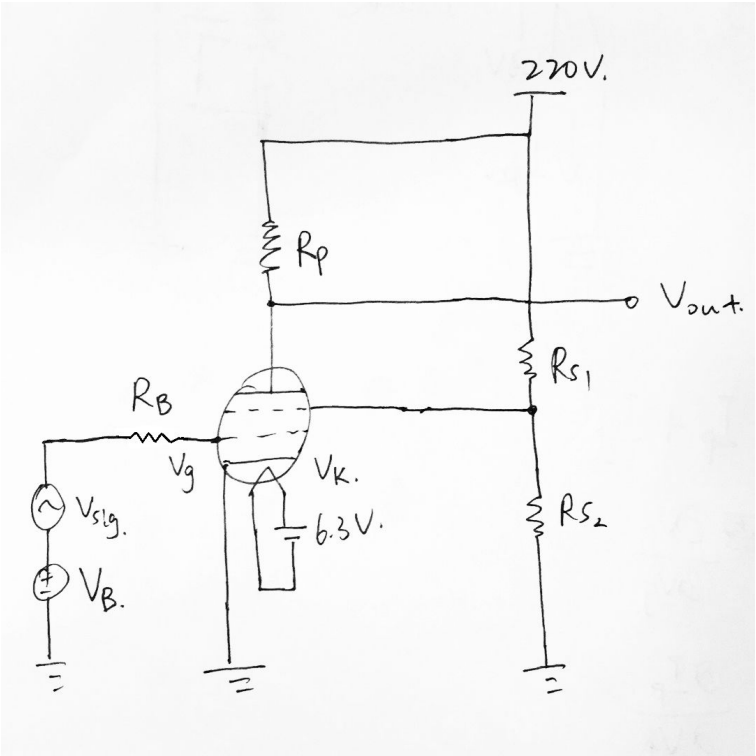

Fig. 07 Basic Circuit

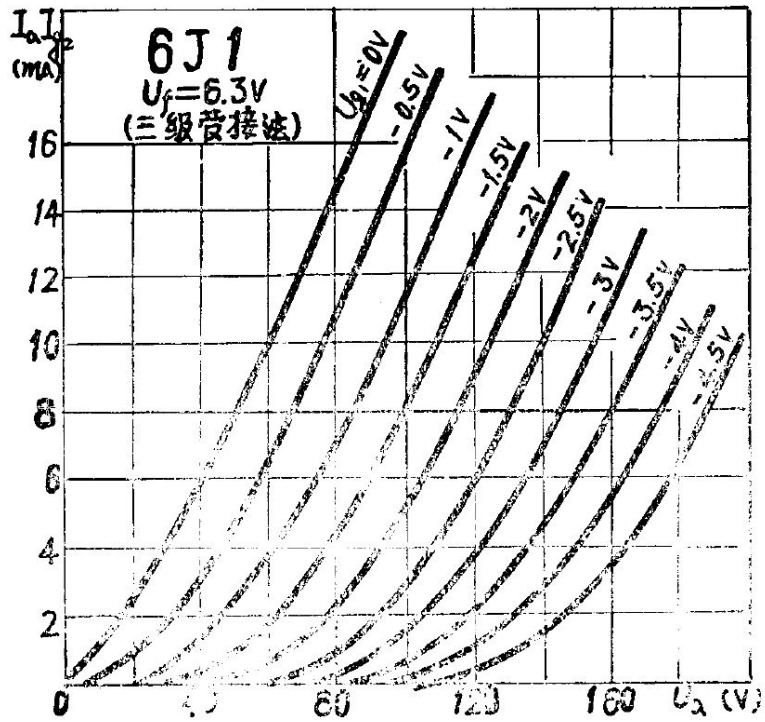

Fig. 09 Ig-Vp Curve of 6J1 Tube [2]

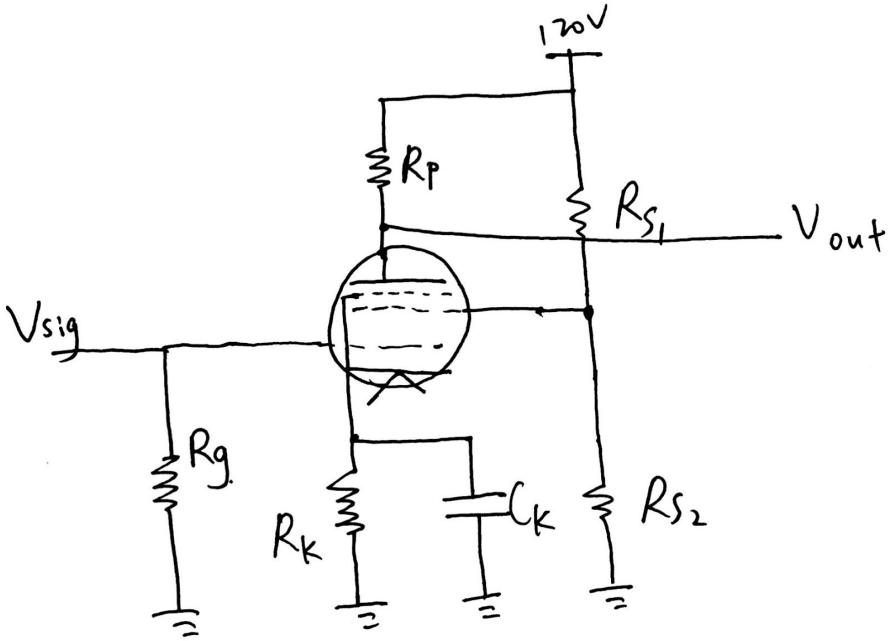

Fig. 09 Detailed Biasing Condition

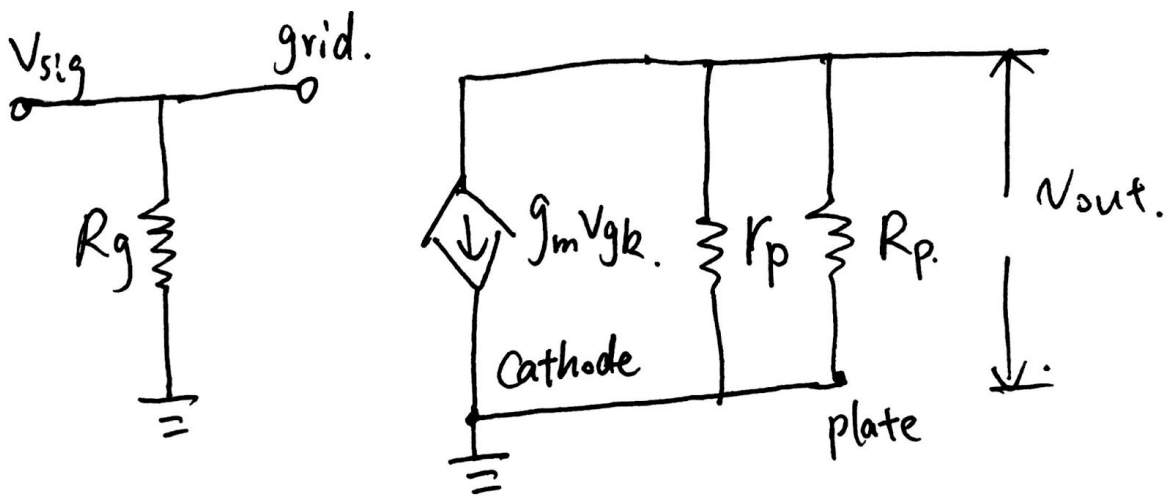

Fig. 10 Small Signal Model of Vacuum Tube

2.7 Power (Current) Amplification

We will use 6P1 tube as our power amplification tube. We will also power the filament using 6.3 V AC. We will force the plate voltage (Vp) to be 220 V, and expect the operating point grid current (Ig) to be 80 mA. The grid should be biased to 0 V.

The design should meet the following specification:

Minimum output power: 3.8W;

Frequency response: 40-18.5 kHz minimum;

Signal to noise ratio (SNR): ≥ 75 dB;

Total harmonic distortion (THD): ≤ 3% @ 1 kHz.

2.8 Output Impedance Matching

According to the datasheet of 6P1 (Fig. 11, 12) [3], the plate of 6P1 will linked to 220 V power supply through an output transformer. The specific design parameters are still TBD. The transformer will have input impedance of 5000 Ω

and output impedance of 8 Ω. The suggested circuit diagram is as Fig. 14. More characteristic equation is shown in Fig. 13 [4].

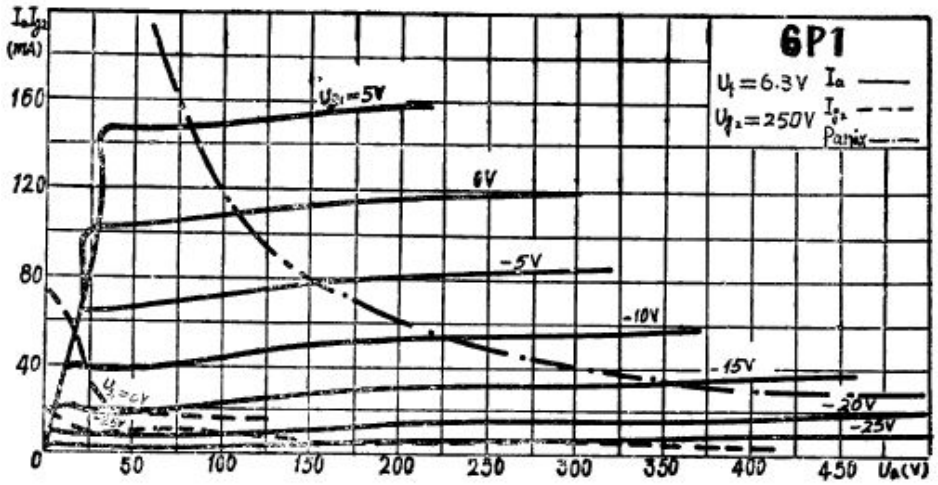

Fig. 11 Ig-Vp Curve of 6P1

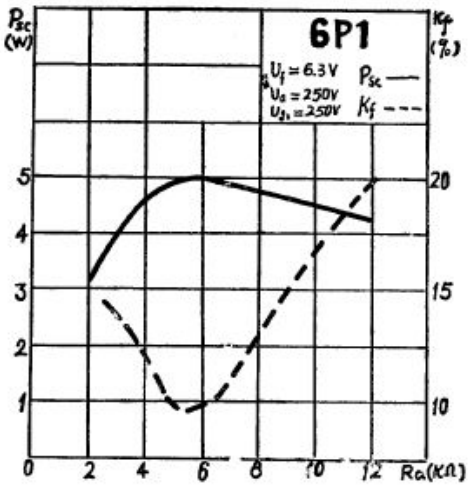

Fig. 12 Thevenin Equivalent Power and Impedance

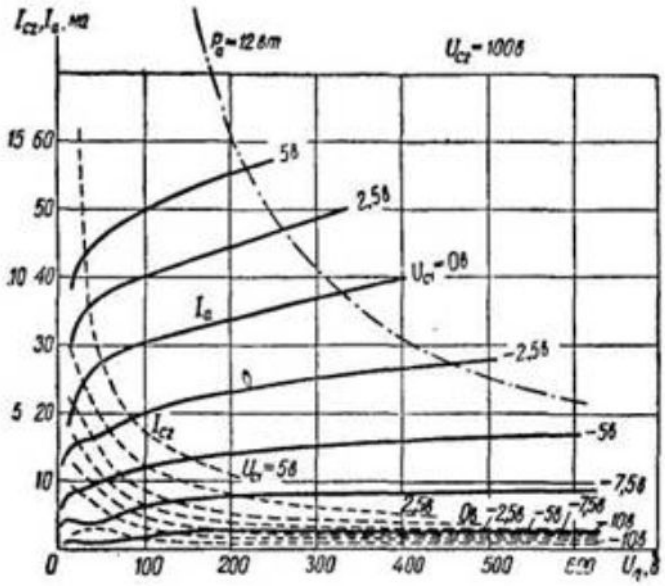

Рис. 2. Характеристики лампы типа 6П1П

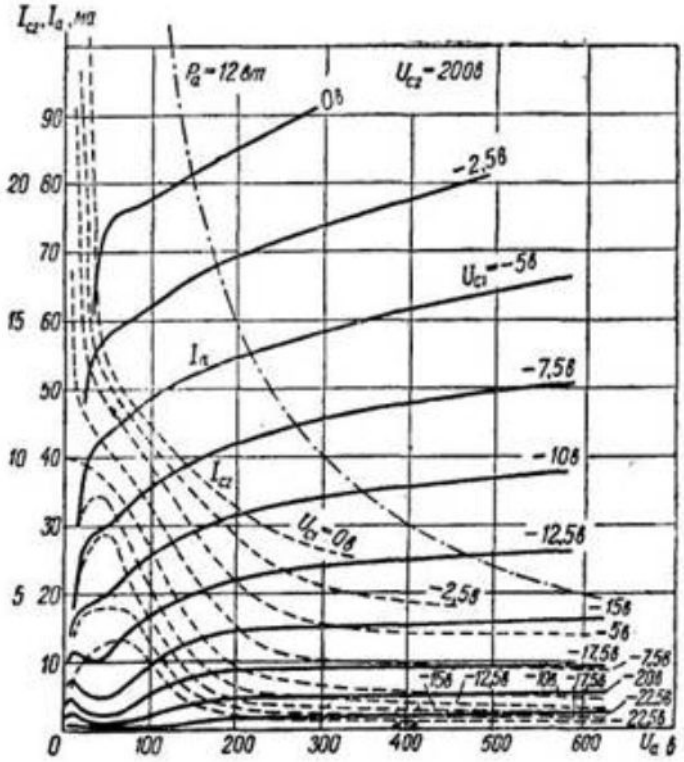

Рис. 3. Характеристики лампы типа 6П1П

Fig.13

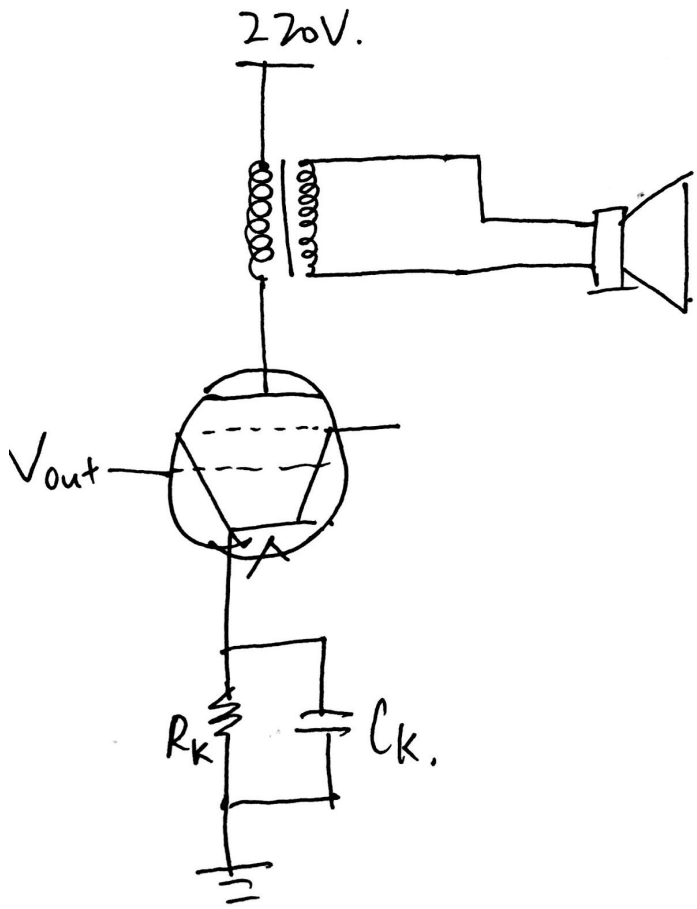

Fig. 14 Power Amplification Circuit

2.9 Block Level Requirement (RV table)

Module	Requirements	Verification
Rectifier circuit	Vrip ≤ 0.5% Vpp	
	Imax ≥ 1 A	
	T ≤ 90 ℃	
Preamp Module	μ ≥16	
	Freq. Resp. 30-19 kHz	
	SNR ≥ 90 dB	
	THD ≤ 1% @ 1 kHz.	

Power Amp Module	Psc ≥ 3.8 W	
	Freq. Resp. 40-18.5 kHz	
	SNR ≥ 75 dB	
	THD ≤ 3% @ 1 kHz.	
Output Module	No DC output	
	Efficiency ≥ 85%	

2.10 Risk Analysis

This project may have two types of risks: Physical risks and financial risks.

Physical risks include electrical shock from high voltage, explosion of capacitors if polarity is wrong, cullet from broken vacuum tubes, sharp parts of tools like soldering iron, etc.

The financial risks are more subtle, this will include losses of properties if purchased parts are damaged. Improper use of lab kits, apparatus can also lead to damage of public lab equipment.

The physical risks and financial risks that due to improper operation can be mostly avoided if we follow the safety rules, while there are still financial risks due to damaged parts.

3 ETHICS and SAFETY

We will follow all ethics that any engineer have to be considered as a good engineer. We will make sure the product meets safety standards, specifications, and benefit the human being.

Since our project involves with voltages that are higher than 200 volts. according to the first ethic guide of 7.8 [4], we need to make sure that we will not expose any metal contacts that are powered on to keep ourselves safe. And we will use insolation gloves if needed. For our project, the circuit part of amplifier must be sealed with good ventilation to prevent circuit and tube overheating. And a case will be utilized to prevent exposure from the high voltages part of the circuit.

We will follow all regulations and rules of the senior design lab, in specific:

1. We will never leave any circuits unattended that might cause electric shock or scald.
2. We will always work in pairs.
3. We will make sure that all high voltage lines and equipments are properly insulated and without flaw before use.
4. We will never power on a circuit that's not finished or still in progress.
5. We will use insulating gloves if we are dealing with high voltages.
6. We will dispose broken tubes properly.

4 SCHEDULE

Feb 12	Design, simulate all rectifier circuit. Build as much as we can.
Feb 19	Finish building rest of rectifier circuit, test, debug all rectifier circuit.
Feb 26	Unit test of tubes, tube characteristics matching, I-V curves plotting.
Mar 5	Design, simulate preamp circuit. Modify the design if needed.
Mar 12	Design, simulate power amp circuits. Modify the design if needed.
Mar 19	Design, simulate feedback. Modify the design if needed.
Mar 26	Solder parts to form modules.
April 2	Test and debug of individual modules.
April 9	Solder modules to form product.
April 16	Final debug and testing

5 REFERENCES

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