25 Watt Vacuum Tube Audio Amplifier

ECE 791/792 Progress Report

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Project Goal:

Our goal is to make a 25-watt four stage audio vacuum tube amplifier. Through research and hands-on approach, we hope to learn an alternative method of amplifying and rectifying electrical signals. As seniors in electrical engineering, we have been exposed to both the transistors and the diodes in classroom and laboratory environments. In order to expand our knowledge about electrical engineering, we decided to take it upon ourselves to learn about the vacuum tubes and build an amplifier.
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1. Overview

The invention of vacuum tubes and vacuum tube amplifiers has been one of the most notable breakthroughs in the early 20th century. It allowed an electrical signal to be amplified therefore opening a new frontier in electrical engineering that was not possible before. A few of its first uses were in telecommunication and RF radios, which ultimately led to broadcast television. Nowadays with all of the above generally taken for granted and solid state transistors dominating the amplifying aspect of electrical engineering, it’s very rare to hear someone mention a vacuum tube. It is unfortunate that the new generation of electrical engineers do not know much about such complex and fascinating devices.

From the name “vacuum tube”, it is easy to figure out that it’s a tube with a vacuum inside of it. However, it’s not that simple. There are few crucial components inside the glass casing that actually make it all work. The components are Cathode, Anode, and the Grid. The Cathode is a negatively charged electrode that releases electrons when heat is applied. Almost all the vacuum tubes require 6.3V and variable amount of current (on average 400mA to 1A) in order to heat up the cathode to the point when it starts releasing electrons. The released electrons are negatively charged and get attracted to the less negative/positive anode. The Anode is a plate that surrounds the cathode and does not have any heat applied to it. However, it does get hot in the process and gets passively cooled through the glass envelope. As a result, a vacuum tube only allows flow of electrons in one direction and therefore by default is a diode. What makes the tube an amplifier is the grid. The grid is located between the cathode and the anode and is used as a gate that passes or blocks the movement of the electrons. Therefore, the voltage applied to the grid controls the flow of electrons from cathode to anode. The grid serves the same role as the base and the gate in BJTs and MOSFETs. A vacuum tube with the 3 components mentioned above is called a triode. A triode is the first and the most basic vacuum tube used for amplification. Adding a second grid, called a screen, to a vacuum tube turns it into a Tetrode. Tetrode tubes reduce the Miller capacitance effect between the control grid and the anode plate which is unavoidable at high gains in triode tubes. Also, the additional grid causes an electron-accelerating effect which significantly increases the gain of the tube. Tetrodes however are not used in audio amplification because of a so called “tetrode kink”. “Tetrode kink” is caused by electrons bouncing off the anode plate and the screen, which increases distortion. To prevent such an effect a Pentode was developed by introducing the third grid called a suppressor grid. The job of a suppressor grid is to collect the stray electrons which in turn reduces distortion and makes a Pentode a very popular tube used in audio.

![Figure 1, The Basic Triode](image)
2. Design

2.1. Amplifier Specifications

Output Power: 25 W into an 8 Ohm speaker
Input Signal: 1 V Peak
Frequency Response: 20 Hz to 20 kHz

2.2. Components

Output Tubes: Dual 6L6 Beam Power Tetrode (Also sometimes called a Pentode)
Driver, Input, and Phase Splitter Tube: 6SN7 Dual Triode
Power Transformer
Output Transformer
Diodes
Resistors and Capacitors
Tube Sockets
Chassis
2.3. Approach

The approach to designing this amplifier begins at the output stage. It is here that the output power, class of operation, and configuration (single ended, push-pull) are determined. The datasheet of the output tube is important, as it supplies information on different modes of operation the tube can be operated in and the maximum output power that can be produced with those configurations. Once the configuration is determined, the grid driving requirements for the output tubes can be determined. A driving stage can then be built with a tube suitable for a driver stage. The amplifier will be run in a push-pull configuration, so it will require a phase splitter stage. An input stage will be used as well. The power supply will be designed for the required plate voltages of each tube. Figure 3 below shows the data sheet for the 6L6 output tube. With certain operating points, it is possible to produce a maximum signal output power of 26.5 watts. This is sufficient as the amplifier will be designed to produce at least 25 watts of signal output power. The other conditions, such as peak AF grid-to-grid voltage, plate voltage, maximum-signal plate current, and effective load resistance will be crucial in determining the ratings of transformers and requirements from driver and input stages.

<table>
<thead>
<tr>
<th>PUSH-PULL CLASS AB1 AMPLIFIER, VALUES FOR TWO TUBES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Voltage .................................................. 360</td>
</tr>
<tr>
<td>Screen Voltage .................................................. 370</td>
</tr>
<tr>
<td>Grid-Number 1 Voltage ......................................... 22.5</td>
</tr>
<tr>
<td>Peak AF Grid-to-Grid Voltage ................................ 45</td>
</tr>
<tr>
<td>Zero-Signal Plate Current .................................... 88</td>
</tr>
<tr>
<td>Maximum-Signal Plate Current ................................ 132</td>
</tr>
<tr>
<td>Zero-Signal Screen Current .................................... 5.0</td>
</tr>
<tr>
<td>Maximum-Signal Screen Current ................................ 15</td>
</tr>
<tr>
<td>Effective Load Resistance, Plate-to-Plate .................. 6600</td>
</tr>
<tr>
<td>Total Harmonic Distortion ....................................... 2</td>
</tr>
<tr>
<td>Maximum-Signal Power Output .................................... 26.5</td>
</tr>
</tbody>
</table>

Figure 3, Data Sheet Information for 6L6 Biasing
2.4. Configuration

2.4.1. Input Stage

The input stage of the amplifier will be constructed with the first half of a 6SN7 dual triode tube. The purpose of the input stage is to provide moderate input impedance with relatively low noise. It will be providing some gain as well. The configuration of this stage will most likely be that of a simple common cathode amplifier.

2.4.2. Input Stage Progress

As of now, the design of the input stage has not been altered in any way. The design of the amplifier is based entirely on the modified version of the Williamson Amplifier, originally designed in the 1940’s. The cathode bias resistor has been bypassed by a simple RC network, which provides attenuation of the loop gain at and above 20 kHz and keeps the phase shift in the critical region consistent. This is the template for which the amplifier will be designed. Global negative feedback is applied at this stage as well. The negative feedback will consist of a single resistor connected from the output transformer to the anode of the input tube, which will provide 20 dB of feedback. This will cut down the gain at the input by a factor of 10 and the subsequent stages will also drop in gain. Potentially more feedback could be needed as the 6L6 output tubes will be producing odd harmonic distortion.

2.4.3. Phase Splitter

The phase splitter is the second stage of the amplifier. This is a relatively simple stage that will take the signal from the input stage and split it into two signals of equal magnitude and opposite polarity. This is essential for the push-pull operation of the output stage. The design of the phase splitter is quite simple. Matched resistors are placed at the plate and anode of a triode tube. The signal voltage swings across the anode and cathode at exactly 180 degrees out of phase from one another. The gain of the circuit is slightly less than 1, around .9. This is trivial, given that voltage gain coming from both the input and driver stages will be more than sufficient to make up for the loss in gain. The phase splitter will be made from the second half of the first 6SN7 tube.

2.4.4. Phase Splitter Progress

The design of the phase splitter stage has not been altered.
2.4.5. Driver Stage

The driver stage provides adequate voltage gain to drive the grids of the amplifier’s output tubes. Since its purpose is voltage gain, it will need a low output resistance. Because of their low distortion characteristics, both ends of a second 6SN7 tube will be used to drive the two 6L6 output tubes.

2.4.6. Driver Stage Progress

As of now, the driver stage design has not been changed.

Figure 4, Data Sheet Pinout of a 6SN7 Dual triode

2.4.6. Output Stage

The output stage of the amplifier will consist of two tubes, each of the 6L6 type. These are beam power tetrodes that are inexpensive and can easily be configured to produce the required output power for this amplifier. Push-pull configuration will be used in the output stage. Push-pull operation is useful because while one tube is conducting, the other is not. This allows for less power to be dissipated in the tubes and more to be delivered to the load. Each tube will be run in Class AB1 operation, meaning no positive grid current will flow. This class of operation will also produce a maximum of 26.5 watts of signal power, which is sufficient for this design. An output transformer will be used to match the impedance of the output stage to the 8 Ohm load.

2.4.7. Output Stage Progress

More analysis of the output stage has been completed. Explain about the biasing network. Explain also about the tubes. For a while, the designers of this project were concerned with having a completely original amplifier design. The Williamson topology is a milestone in amplifier design and will be nearly directly followed for this project. Adjustments will be made only because from the original design, the output tubes are made for more power running in Class AB1.
The biasing networks are of particular interest to this stage. This network controls the DC biasing of the output stage. The first half controls the DC balance of the grids. The second half sets the anode current for both tubes. It is important for both tubes to have identical anode currents so that there is no DC magnetization in the transformer. The circuit can be seen below in Figure 6.

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**Figure 5**, Data Sheet Pinout of a 6L6 Tube

**Figure 6**, The Williamson Amplifier
2.5. Power Supply

In designing the power supply it is crucial to find out the voltage and current rating of all the vacuum tubes. The tube with the highest voltage requirement will dictate the minimum amount of voltage that a transformer has to supply. Since all the tubes are fed in parallel, a resistive voltage divider will be used to provide the adequate HT voltage for each tube type. In order to have enough current, all the tubes' individual ratings have to be added together. For this project 2 different tubes will be used, the 6L6(2) and the 6SN7(2). The 6L6 tubes require 360V of plate voltage and 44mA of plate current. 6SN7 tube requires roughly 250V and 20mA. As a result the transformer selected to drive those tubes must be able to step up the voltage up to 360V peak and provide at least 128mA. Most transformers are made with 2 secondary coils. The second coil is designed specifically for the heater and supplies 6.3V at about 5A. These rating are pretty standard for almost every tube. A Full-wave rectifier in this set up consists of 4 diodes whose ratings have to be at least 5A and have a peak inverse voltage of ~600V. Smoothing capacitor, RC Ripple smoothing and Voltage divider network should be designed to be able to handle the voltage (~360V) and the current (~0.13A). Therefore the peak power output of the power supply will be around 46W. Components used inside of the power supply must be selected carefully in order not to fry anything.

![Block Diagram of Power Supply](image-url)
2.5.1 Final Design and process

The original design of the power supply changed only slightly after more in-depth research. The power transformer and the full wave rectifier bridge has not changed. They are the 2 main components of the power supply and relatively easy to pick out based on the voltage and the current requirement of the amplifier. The rest of the power supply gets a little bit more complicated because it has to do with filtering. Due to large number of filter properties and specifications it is often very hard to choose just one. Initial design included a network of RC filters which would attenuate the voltage ripple to less than 1 mV. After some basic simulations it was found that using RC filters is not very efficient and requires a lot of current. As a result, a CLC filter was chosen instead. CLC filter also called a “PI” filter is a great alternative to an RC or capacitor only filters. As stated earlier PI filter has a lot of specifications which must be matched to the requirements of the amplifier. Those include capacitance, inductance, DC voltage, DC current, resistance, size, and price. During the process of selecting the inductor it was discovered that resistance vs price is the hardest decision to make. Originally, the resistance of the inductor was overlooked but after few calculations it became apparent that it is very important to account for it. As a rule, the higher the inductance the higher is the resistance of the choke and the higher the inductance the better filtering can be achieved. It is obvious that one would want a low resistance and high inductance in a choke. Unfortunately such chokes are impractically expensive. For this particular amplifier it was found that a choke with internal resistance no higher than 70 ohms should be used. That would give about 40 volts headroom above what is required by the 6L6 tubes. Taking into account the tolerances of the electric parts 40V seems reasonable. Using this information a 5 Henry choke was selected. Its DC current rating is 200mA, DC voltage 600V, and resistance of 65 ohms. Capacitors in the filter can be selected from 32uF and up depending on how much ripple voltage is acceptable. In our setup it is preferred to have a ripple factor of 1% of input audio signal. The input signal will be about 4V peak to pear, therefore the acceptable ripple voltage should be 40mV peak to peak. 100uF capacitors should attenuate the ripple down to 20mV peak to peak.

<table>
<thead>
<tr>
<th>Component</th>
<th>Rating</th>
<th>DC voltage</th>
<th>DC current</th>
<th>Resistance</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor</td>
<td>5H</td>
<td>600V</td>
<td>200mA</td>
<td>65Ohms</td>
<td>15%</td>
</tr>
<tr>
<td>Capacitors</td>
<td>100uF</td>
<td>550V</td>
<td>600mA</td>
<td>~1.5 ohms</td>
<td>20%</td>
</tr>
<tr>
<td>Transformer</td>
<td>115Vac</td>
<td>(300-0-300)*1.41V</td>
<td>170mA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Rectifier Bridge Pack</td>
<td>1.4 V</td>
<td>600V</td>
<td>1A</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 1, Power supply components
3. Hardware

3.1 Tubes

2 6SN7 tubes were purchased at a local Ham Fest that took place past fall. The tubes are intended for use as “test pilots” in designing the early stages of the amplifier and testing out the power supply. Also 2 6SQ7 tube were donated by one of the faculty members to serve the same purpose as the 6SN7.

![Figure 8, Test Pilot Tubes](image)

3.2 Testing Equipment/Chassis

The following board was build in order to test the tubes and practice designing of just one stage vacuum tube amplifier. A document was also found with a suggested layout and chassis size for the Williamson amplifier. The design will consist of two chassis, one for the main amplifier and one for the power supply. A drawing of the layout can be seen below.

![Figure 9, Test Chassis](image)
4. Testing and Performance

4.1. Frequency Response

The frequency response of the amplifier can be determined by using a function generator as an input signal. By using a sine wave with the proper amplitude, the frequency of the signal can be changed and at certain frequencies, the signal would be greatly attenuated. The frequency response can be determined by observing the output as the frequency is changed.

4.2. Actual Output Power

A resistor will be ordered at can manage the high output voltage and power of the amplifier. Using Ohm’s law, the output power dissipated at the 8 ohm load will be computed by squaring the output voltage and dividing by the resistor’s impedance.

4.3. Total Gain

An oscilloscope will be used to measure the amplitudes of both a test input signal and the corresponding output signal. The gain will be determined by dividing the amplitude of the output signal by that of the input signal.
5. Fall Semester Summary and Projections

Experimentation will be a key component in the learning process for this project. So far, it has been determined that the two 6SN7 dual triode tubes acquired through the visiting of a local ham radio festival do indeed work. Two things were done to determine this. An ohmmeter was placed across the filament pins of the tubes. The ohmmeter read around 2 ohms for both tubes, indicating the filament was intact. Exactly 6.3 volts DC was placed at the filament. The tube’s filaments glowed red and drew .6 amps exactly from the DC supply. This was a terrific sign, as the 6SN7 datasheet calls for .6 amps to run the filaments.

Much of the early design work and experimentation rested on the design of the power supply. Having a large RC network caused problems as it limited current and dropped considerable voltage along the supply line. The new design with a low impedance choke greatly improved these issues. Now that the power supply design has been finalized, with the exception of resistors to drop voltage to appropriate levels, more experimentation can begin.

With the acquisition of two 6SQ7 triode tubes and two 6SN7 dual triodes, simple one stage amplifiers can be built. This will reacquaint the designers with several things that have been seen, but not practiced since their junior year of their college career. Simple one stage amplifiers will be constructed to simply become better acquainted with the tubes and their operating levels. Simple designs such as the common cathode and the phase splitter will be experimented with as they are essential to the design of the actual amplifier. Also, the cascading of simple amplifiers will be done to observe the loading effects of different stages.

While experiments are being conducted, the original design of the Williamson amplifier will be analyzed in detail. Several factors will be looked at, such as tube operating points, gains at each stage, and biasing at each stage. Along with the experimentation, this in-depth analysis of the original Williamson design, will make clear many of the design issues of this project. Once the design is finished, the remaining parts will be ordered.

The construction of the amplifier will begin as soon as all necessary parts have been obtained. Once finished, the testing stage will begin, which will consist of adjusting bias points at the output stage, determining the acceptable minimum amount of negative feedback, measuring output power and total gain, and measuring the frequency response of the amplifier. Should the amplifier be completed with reasonable time left, a second amplifier may be constructed? This will allow the audio signal to be run in stereo. The aesthetic effect of having two amplifiers and two speakers would also be quite nice.
6. Responsibilities

Both of group members contributed equally to this project and to the written reports. Matt Andrews’ primary focus was the entire amplifier i.e. deciding on the final configuration of the stages, the type of the amplifier, tube selection, and testing them. Yuriy Kharin’s primary focus was on the design of the power supply and ensuring that a DC signal with acceptable ripple will be supplied. Also Yuriy designed the wooden chassis for testing tubes and one stage amplifiers. For the spring semester both students will be involved in designing/building/testing of the amplifier in order to become equally proficient with vacuum tube amplifiers.

7. Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Transformer</td>
<td>$71.15</td>
</tr>
<tr>
<td>Output Transformer</td>
<td>$62.26</td>
</tr>
<tr>
<td>6L6 Tubes (2)</td>
<td>$36.95</td>
</tr>
<tr>
<td>6SN7 Tubes (2)</td>
<td>$65.90</td>
</tr>
<tr>
<td>Tube Sockets (4)</td>
<td>$27.80</td>
</tr>
<tr>
<td>Chassis</td>
<td>$30.00</td>
</tr>
<tr>
<td>Power supply Inductor</td>
<td>$30.00</td>
</tr>
<tr>
<td>Power supply capacitors (2)</td>
<td>$15.00</td>
</tr>
<tr>
<td>Power supply Rectifier pack</td>
<td>$10.00</td>
</tr>
<tr>
<td>Basic Components (other resistors, capacitors, etc)</td>
<td>$20.00</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$369.06</strong></td>
</tr>
</tbody>
</table>

*Table 2, The Budget*
8. Timelines

8.1. Project Timeline:

- Select: Type of amplifier/Output power/Vacuum tubes/Transformer s by 09/30
- Design the circuit on paper/order remaining components by 2/10
- Cascade all the stages and test/tune. by 02/26
- Ready to present by 04/16

- Order all tubes and transformers by 1/24
- Build and tests individual Stages. Order the chassis by 02/19
- Mount the amplifier on the chassis by 03/24

8.2. Academic Timeline:

- Prepare written and oral proposal by 10/29
- Register for UNH-URC by 02/06
- Prepare final written report by 05/08

- Prepare Progress report by 12/12
- Prepare UNH-URC poster by 04/16
Deadline Approaching