Construction and enhancement of stereo vacuum tube amplifier with precision machined enclosure

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Abstract

The purpose of this project was to build a high fidelity tube amplifier from a kit, and machine a beautiful enclosure to house the electronics. Improvements were made to the circuit, and the amplifier was then tested for audio performance.

Figure 1: The finished amplifier.

Introduction

Since their invention, transistors have provided an increasingly economical and accurate way to amplify electrical signals. Despite the technical advantages of solid state amplification, amplifiers utilizing vacuum tube triodes are still widely used for audio amplification due to the warm sound they produce and the pleasing quality of the distortion introduced at higher amplifications. Tube amplifiers are commercially available at a premium price. The aim of this project was to modify an inexpensive tube amplifier kit to archive high-end amplification performance with a finer enclosure.
than any commercially available. The construction of the enclosure served as an in depth introduction to the materials and methods of the machine shop. This report documents the process of building the amplifier and its enclosure, circuit enhancement, and the experimental characterization of the amplification performance.

![SolidWorks rendering of the enclosure](image)

**Figure 2:** A SolidWorks rendering of the finial enclosure.

**Designing and Machining the Enclosure**

The bulk of the time spent on this project was in the design and construction of the enclosure shown in Figure 1. Process photographs are shown in the Appendix and are referenced here as superscript roman numerals.

The enclosure was designed with top quality in mind. The base is made out of a solid 8.5″x11″x2 3/4″ chunk of South American cocobolo hardwood. The top and bottom are made from aluminum billet. All of the components in the box were made from scratch, from raw materials, including the box, knob, button and feet. The enclosure was completely designed and dimensioned before fabrication in the solid modeling suite SolidWorks. A rendering of the enclosure is shown in Figure 2 and an exploded view in Figure 3. The SolidWorks drawings were used to machine the components of the enclosure, on the lathe or milling machine. SolidWorks drawings were also used to facilitate the creation of machine instructions for computer numerical control (CNC) milling.
Figure 3: An exploded view.
Sitting below the aluminum top plate, the base is made from a single stunning piece of figured cocobolo (Figure 4). Forming the sides of the box, and peaking through the aluminum top plate to frame the knob and button, the base was the most complicated piece of the enclosure to fabricate. First the wood was milled flat and to size. Next, the cutouts for the button and knob were made while the wood was still solid. Using the CNC mill, a long rigid one inch diameter cutter was used to mill out the inside from the bottom. From the top, the outside was profiled to include the round corners and the top was milled away everywhere except for the control area (Figures 5, 6, and 7). The top plate was milled and drilled from the bottom to accommodate the electronics. A fixture plate was made, and the top plate was screwed down (through the transformer holes) and profiled. After extensive hand sanding and filing, the top plate was fitting onto the wood box to reveal a beautiful transition from aluminum to wood (Figure 7). The inside of the box is lined with .25 inch aluminum plate to mount internal components and improve shielding. The bottom of the box contains an access plate, also made from aluminum. Using the conventional milling machine, the bottom plate was squared and milled flat, drilled and counterbored. Using a fixture plate (through the feet holes), the bottom plate was profiled by CNC.

Figure 4: These renderings show the bottom and top sides of the wooden base. These detail the one-piece design of the wood, and the intricacy of the machined surfaces.

Machining Conclusion

This project certainly served as a crash course in the machine shop. An entire world opened up to me that I never knew existed, but am happy to have experienced. With the machine shop in your tool bag, you can make anything that you can dream up, and the results are perfect and beautiful. The cost of this perfection, however, is time. Nothing is obtained quickly in the machine shop, and every last detail needs to be planned ahead of time. Also, before you can even start making parts, one must figure out how to hold parts. The setup is often the most time consuming aspect of the machine shop. Once the setup is complete, the tenuous task of making the part begins. It is not unusual for one part to take several days, and the possibility of ruining parts is high. Here is a short anecdote: the transformer cover in figure 9 had to be fabricated twice. Initially, this part was made with the height and width accidentally transposed, and the error was not caught until completion. The moral of the story (and a good motto for the machine shop), is layout your parts, and check and recheck your work.

Another aspect of the machine shop that was intimidating at first was the wide scope of the
tools. Of course there is the milling machine and the lathe, but there is literally a tool for every situation, for each machine. There are end mills, fly cutters, boring bars, cutters, drills, cutting taps, rolling taps, knurling tools. There are tools for measuring the inner diameter, outer diameter, height, length, and thread pitch. There are a whole plethora of tools for “dialing in” you setup, which is how you locate exactly where the cutter is with respect to your work. In the beginning of the project, I felt daunted by the feeling that there were so many of these tools I had no idea how to use. Over the course of the project, however, it became clear to me why there are so many tools in the machine shop: each tool makes life easier. There are many ways of doing a task in the machine shop, but the best way is to use the right tool for the job. Toward the end of the project, I could identify a large portion of tools in the shop and their use, and found appreciation for every one of them.

Although it was a lot of work, I cherish the experience in the machine shop. It serves as a useful tool in my bag of tricks, and gave me glimpse into the world of manufacturing. Now I often look at everyday items and ponder the process by which they are made, and what the setup involved. If I find myself needing to make custom parts for the laboratory, for industrial applications, or for fun, I will no doubt turn to the machine shop again, and slowly carve out items of perfection.

**Figure 5:** This photo features the tongue control area. The volume goes to 11. The volume indicator serves to provide a volume scale as well as provide a secure mounting surface for the volume potentiometer.
Figure 6: The bottom of the amplifier is shown above. The backside of the wood tongue is shown which surrounds the control area. The button and potentiometer are also shown top-center. The holes around the perimeter are for securing the bottom plate.

Figure 7: The control area provides control for power and volume, and is surrounded by the wooden tongue, which was left intact from the original wood block.
Figure 8: The four aluminum feet were made entirely on the lathe, and turned to accommodate flat head screws.

Figure 9: Angle blocks and a $\frac{1}{8}$" diameter end mill were used to cut these louvered vents in the power transformer cover.
The Amplification Circuit

I selected the S5 electronics K12-G amplifier kit[4] to build my project around. Each channel provides eight watts of output power, utilizing two 10GV8 triode tubes in a push-pull configuration.

The amplifier kit from S5 electronics came with the PCB1, tubes and electronic components, power and output transformers, and a wooden plank. Assembly of the amplifier involved soldering the transformers and components to the PCB, installing tubes, and screwing the assembly onto a wooden plank. The stock amplifier can be seen in figure 10. After a several day “break in” period, the amplifier was tested with an oscilloscope. In addition to testing with the oscilloscope, a prolonged listening test was performed over course of several weeks before the amplifier was disassembled and modified.

![Figure 10: The assembled kit without electronic or enclosure modifications. The reader is encouraged to take note of this photograph and compare with the final assembly seen in figure 1.](image)

Electronic Modifications

There are many modifications that can easily be done to a tube amplifier, the most difficult part is selecting which ones to perform. Of course peak listening performance is desired, but budgetary constraints also apply. After doing extensive research on the internet, it was decided that three modifications would take place.

Transformers

The stock output transformers were small and had little shielding. Upon inspection it was obvious that the materials used in the construction of these transformers was of low quality. After consulting

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1Printed circuit board
many DIY forums on the internet, there were several sets of output transformers that were highly recommended. I chose the Hammond PT-1609 output transformers for several reasons. First and foremost, users claimed that they improved the listening experience. In listening tests, the spectral range sounded much less “cluttered”, with no competition between frequencies. Overall frequency response was reported to improve, especially in the low-frequency range. A visual comparison between the stock and the Hammond PT-1609 output transformers can be seen in figure 11. The transformers were also wired in ultra-linear mode, which gives a cleaner output, however outputs less overall volume. Amplifiers wired in linear mode are reported to have the ability to resolve lower bass frequencies, while the higher frequencies are “smoother” and somewhat more palatable to listeners [1].

![Figure 11:](image)

**Figure 11:** The two stock output transformers were replaced with two Hammond PT-1609 transformers, which claim to improve frequency response. They were wired in ultra-linear mode, which gives a truer output at the cost of a small decrease in volume.

### Capacitors

Of all the modifications mentioned in the tube amp community, none were recommended more highly than replacing the coupling capacitors. In fact, it was clear consensus as to which capacitors to use for this task: Auricap .22 µF capacitors. As quoted from *SoundStage* magazine:

“The Auricapped (amp) sounds fundamentally neutral, but its presentation has notable bloom and, as with the very best tube preamps, the ability to portray space – around performers and as an entity itself. Its sound is spacious. There is no tubey glaze, but also no etch or edge. Instead, there is clarity, vigor, and grace . . . very detailed and very enjoyable.”

Coupling capacitors provide a way to block DC voltage while allowing alternating current to pass\(^2\). Unfortunately, in audio circuits they can degrade the quality of low frequency signals (the bass, as it were), especially if the capacitors are leaky, sub-tolerance, susceptible to unwanted electromagnetic signals, or of general bad quality.

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\(^2\)The audio signal is just an alternating current we wish to pass through the circuit, while blocking the DC voltages that power the tubes.
The original coupling capacitors were de-soldered. Upon trying to install the Auricaps I discovered that the leads did not fit into the circuit board. The circuit board was drilled out to accommodate the larger leads, and then the Auricaps were soldered in place. A visual comparison of the stock coupling capacitors against the (much stouter) Auricaps can be found in figure 12.

![Image of stock coupling capacitors compared to Auricaps]

**Figure 12:** Six stock coupling capacitors (.22 µF) were replaced with Auricaps, which are high quality capacitors designed to be used in high-fidelity audio situations.

### Power Supply

On a lesser note than the two previous modifications, the power supply was reworked to provide cleaner DC power for the amplifier. Included in the modifications of the power supply was an ultra fast diode on the rectifier circuit and an RC noise filter network on the secondary side of the power transformer. Snubbers were placed on the heaters pins of the tubes to prevent damage from any voltage spikes that may occur, especially during powering up the amplifier[3].

### Experimental Characterization

Tube amplifiers are notorious for bad specifications while the listening experience is superb. Nonetheless, specifications measured in a laboratory situation serve as a rigorous tool for classifying amplifiers. Many audio tests require specialized equipment, however, many measurements can be taken with an oscilloscope, which is what was available in my situation.

### Frequency Response

The frequency response of an audio system measures the amplitude of the output voltage as the frequency is varied\(^3\). Generally speaking, a perfect amplifier should have a flat frequency response, meaning that all frequencies should be reproduced with the same amplitude.

Let us discuss the experimental setup. A sine wave was generated by a signal generator, and fed into the input of the amplifier. The signal was amplified, and the output was measured across a load (a 4 Ω resistor) with an oscilloscope. The signal generator was also fed directly into the oscilloscope to make sure that it was supplying a constant voltage amplitude across all frequencies. The frequency was swept through from 10 Hz to 100 kHz, and the amplitude of the amplified signal was noted. This experiment was done both before and after the modifications, and the results can be found in figure 13.

\(^3\text{In audio applications, the frequency response is generally measured from 20 Hz to 20 kHz, which is comparable to the resolvable frequency range of the human ear. It is, after all, humans who get to enjoy these amplifiers!}\)
There are several features that are interesting to note. From 100 Hz to 10 kHz the amplifier responded almost identically before and after the modifications. Above 10 kHz the signals begin to diverge. The stock amplifier has a peak at about 30 kHz, while the modified amplifier experiences a severe “dip” occurring at approximately 40 kHz. These frequencies are well above the range of human hearing, so it is expected that either of these features will not affect the listening experience.

If we look at the bass frequencies, however, the stock amp drops off much faster below 40 Hz, while the modified amplifier gives better response. The lower limit of human hearing is approximately 20 Hz, so this improvement falls within the human hearing range. Unlike high frequencies, humans can also “feel” lower frequencies that their ears can not detect, which can improve the “listening” experience.

**Square Waveform Performance**

It is much easier for an amplifier to accurately reproduce smooth signals than waveforms with sharp edges. A square wave signal provides an insightful testing ground for true amplifier signal regeneration. The 10kHz test is shown in figure 14. Notably, the modified amp reduces the initial transient spike. The roundoff at the leading edge of the square wave is also improved by the modifications. In the case of the 40Hz test (figure 15) the effect of the modifications is less clear. Both waves show a significant transient response, and the modified amp introduces a non linearity in the low amplitude response.
Figure 14: The output of both the stock and modified amplifier when supplied with a 10KHz square wave.

Figure 15: The output of both the stock and modified amplifier when supplied with a 40Hz square wave.
Total Harmonic Distortion

The total harmonic distortion [6] characterizes the distortion introduced in the amplification process, and is given by equation 1

\[ THD = \sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2} \]

where \( V_n \) is the voltage of the \( n^{\text{th}} \) harmonic. Using Fourier frequency decomposition on a 1 kHz sine wave, figure 16 was obtained. Using equation 1, the total harmonic distortion was calculated to be 1.8%.

\[ THD = 1.8\% \]

Figure 16: A time-frequency Fourier transform was used to calculate the total harmonic distortion. Here we see the fundamental at 1 kHz, and the second and third order harmonics are at 2 kHz and 3 kHz, respectively. If we were to perform a Fourier transform on a pure sine wave, there would only be one spike at the fundamental, and no harmonics.

Listening Test

In my opinion, the listening test is the most important characterization of an amplifier. After all, I do have to listen to this thing. Although it only provides a qualitative analysis, it is always included alongside quantitative results in tube amp specifications.

Before the modifications, the amp sounded great. At once I recognized the “warmth” to which tube amp enthusiasts often refer. The high frequencies were very pleasing, although slightly muddled. The mid-range frequencies sounded fantastic. It was neither harsh nor aggressive, but was
certainly present. The bass sounded clean, but lacked overall volume. Overall, a very pleasant listening experience, but nothing compared the delectable audio nectar my ears would soon ingest.

After the modifications, it sounded like a whole new amplifier. This open space was created for all of the frequencies to breath. There were no contentious tones, rather just frequencies moving in harmony to create beautiful music. The muddled high-frequencies in the stock amplifier were now bright and distinct. Midrange performance was mostly unaffected, retaining its original warm character. The low-frequencies filled out nicely, having more presence than before with a distinct thud. The bass also seemed to extend to a deeper range than before the modifications. Overall, money and time well spent.

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Appendix: Process Photographs

Figure 1: A Bridgeport milling machine. Wood is clamped to prevent splintering of the base as the tongue is profiled on this CNC milling machine. We generated machine instructions from our SolidWorks drawings in a process known as CAM. Each milling operation is programmed one by one, and you have to be careful not to instruct the robot to destroy your part.
Figure II: Toe clamps are used to hold the wood base as it is drilled for the power button and the volume knob. These holes were drilled early in the process to provide convenient fixturing locations during the machining process.

Figure III: Dial calipers are used to measure the width on the tongue. Precise measurement technique is an imperative skill to have in the machine shop.
Figure IV: The top plate is machined by CNC from half inch aluminum plate secured to a custom fixture plate below.

Figure V: The bottom plate is machined by CNC from quarter inch aluminum plate secured to a custom fixture plate below.
Figure VI: The machining of the right power transformer cover. This was a delicate operation because the transition from the yellow wood to brown wood is quite fragile.

Figure VII: A vertical height gauge is used to accurately measure the height of objects placed on a precision-ground granite surface plate. Using the right tool for the job saves time and frustration in the machine shop. Here, the height of the power transformer was measured while it was still a solid chunk of aluminum.
Figure VIII: Machining the vents of the power transformer cover. This was a tedious operation due to the deep cuts and the small cutter that was required. This was the first one, which had dimensions transposed and was subsequently scrapped.

References


