

Lightweight Hybrid Guitar Amplifier

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Abstract

This document details the accomplished work, work in progress, and future work with regards to the Lightweight Hybrid Guitar Amplifier. The design, testing procedures, and results are included.

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1. Introduction

1.1 Project Overview

1.1.1 Purpose

Guitar amplifiers which use only vacuum tubes (tubes) as electronic components are sought after for their sound when driven into distortion, but those amps are bulky, expensive, and inefficient. Lower-priced “hybrid” amplifiers, which try to combine the sound of tubes with the efficiency of transistors, tend to suffer from inferior sound when compared to tube amplifiers, as the role of tubes in the circuit is limited to preamplifier stages, with no effort to duplicate the sound of a tube power amplifier. The project is to design a hybrid amplifier head which better retains the sound of a vacuum tube amplifier, and which is extremely lightweight and efficient.

The project will also include a speaker cabinet to go along with the amplifier, which will be lightweight, with even sound dispersion at several angles of incidence. The cabinet will combine lightweight materials and acoustic design for enhanced low-frequency output.

1.1.2 Objectives

The goal of this design is to create a guitar amplifier head with output power between 35 W and 75 W, and a lightweight, matching speaker cabinet with good dispersion characteristics.

The amplifier head will include an entire low-power tube amplifier, and a solid-state class-D power amplifier for the speaker output, as well as a switching power supply. The amplifier will also have controls for gain, equalization, and volume. The speaker cabinet will use lightweight neodymium speakers, which will disperse in an even way at several angles of incidence and with a frequency response flattering to the guitar sound.

1.1.3 System Overview

An overall block diagram for the project is shown in Figure 1.

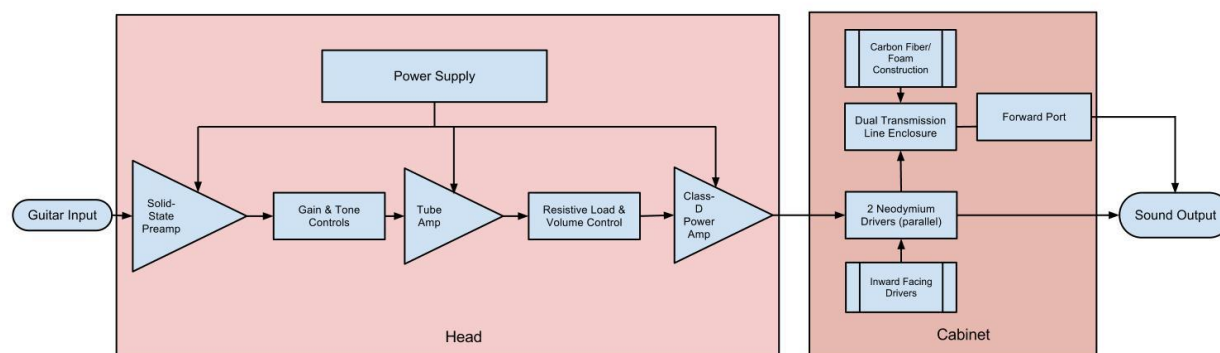


Figure 1 Block Diagram

The project is made up of two components: an amplifier head (head) which amplifies the electrical guitar signal and provides equalization and distortion, and a speaker cabinet (cabinet) which turns the amplified electrical signal into acoustic energy.

The center of the amplifier head is a complete vacuum tube amplifier module using a 12AT7 dual triode package. A solid-state preamplifier amplifies the input guitar signal to ensure that the tube amplifier will be driven into nonlinear operation. A module of gain and tone controls provides the user with the ability to adjust the sound

of the amplifier. The output of the tube amplifier leads to a module containing a resistive load for the amplifier, as well as a volume control to adjust the amount of voltage which proceeds to the solid-state power amplifier. The power amplifier is a class-D circuit with an output power of roughly 50 W with 1% harmonic distortion, which terminates in the output of the head. A switching power supply module provides the voltages needed for each of the amplifier modules.

The speaker cabinet connects to the output of the head. It has two 10-inch neodymium speakers, chosen for their low weight. The interior of the cabinet has a transmission line enclosure for each speaker, intended to extend the low-frequency response of the component. Each transmission line leads to ports at the front of the cabinet. Each driver is tilted 17° inward to reduce the horizontal directionality of the sound field emanating from the cabinet. The cabinet is constructed from carbon fiber and foam in order to provide great structural strength while being much more lightweight than the traditional choice of plywood.

2 Design

2.1 Design Procedure

2.1.1 Amplifier Head

The Power Supply Module of the Amplifier Head was chosen to implement a switching converter because of the lighter weight compared with a comparable classical power supply acting at 60 Hz, which would need a larger and heavier transformer. Additionally, this type of power supply allows for voltage regulation by feedback, which reduces the impact of varying supply voltage on the operation and longevity of the circuit. A quasi-resonant flyback converter was chosen over other flyback or forward converters because of the ease of design.

The Solid-State Preamplifier Module implements a non-inverting amplifier using an operational amplifier IC. This circuit was chosen over an inverting amplifier because of its high input impedance, which is vital for guitar inputs. A discrete preamplifier design using one or two transistors was considered but rejected for the sake of simplicity, linearity, and output voltage swing.

The Gain & Tone Controls Module imitates the design of a classic amplifier from the 1950s, the Fender Bassman. It is a very common choice for guitar amplifier tone controls because of its natural cut of midrange frequencies and easy adjustment of three frequency bands: bass, mids, and treble. A volume control, labeled "gain," is included before the tube amplifier stage to allow the user to control how much the signal is distorted in the tube amp stage.

The tube amplifier module implements two common-cathode amplifiers with a 12AT7 dual triode package. The 12AT7 was chosen for its availability, as well as its high gain and low plate resistance, which allow it to be used both in a preamplifier stage and a low-wattage power amplifier stage.

The Resistive Load & Volume Control module contains a resistor load for the tube amplifier and a voltage divider to limit the amount of voltage that proceeds to the power amplifier. A volume control is included after the tube amplifier for versatility of output volume, since the gain control mostly adjusted the sound timbre.

A Class-D power amplifier was chosen for the Solid State Power Amplifier module because of its power efficiency over Class-A and Class-AB designs, reducing the size and weight of needed heat sinks.

2.1.2 Speaker Cabinet

From the overall objective to develop a lightweight head and cabinet combo, the first consideration was the speaker weight. Typical high quality guitar speakers weigh approximately 10-12 pounds due to the large ceramic fixed magnets. By using neodymium magnets, each speaker is reduced in weight by 66% down to 4lbs. These drivers are mounted at an inward facing angle that increases the sound field dispersion at higher frequencies where beaming of the sound field occurs.

The circuit functions as follows: The AC voltage input is rectified with a diode bridge (D1 - D4), then filtered in C_DC. The IC periodically interrupts the DC current in the primary of the coupled inductor, which causes current to flow in the secondaries, through the secondary rectifier diodes D_A and D_r1 through D_R4. When the current flows through the secondaries, current goes through D_SY causing V_SYNC to have a significant voltage. This voltage lowers as the inductors dispel their energy. When it drops lower than 2.6 V, the MOSFET switch in the IC turns on, drawing more current into the coupled inductor. The frequency of this cycle is set by how long it takes for the inductor to charge and discharge with energy, so the frequency changes as a function of the input voltage and load current. Component values were chosen to keep the frequency above the audio range in the worst case, when the input voltage is low and the load current is high.

The voltage of the first output, Vo1, is fed back to the IC and modifies the duty cycle of the switching function to keep a steady 18 V. A simulation of the feedback loop's frequency response is provided by the software tool, and the results for this design are copied below in Figure 4.

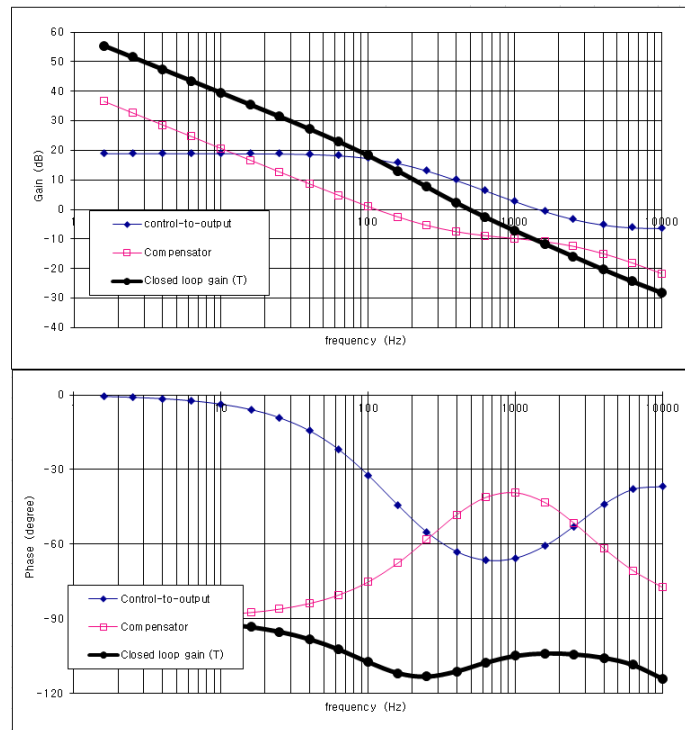


Figure 4 Power Supply Feedback Loop Frequency Response

The closed-loop gain rolls off at high frequencies to avoid having the IC react to its own switching action, and maintains high gain at low frequencies for good DC regulation.

2.2.1.2 Solid-State Preamplifier Module

The schematic for the Solid-State Preamplifier (Preamp) is shown in Figure 5.

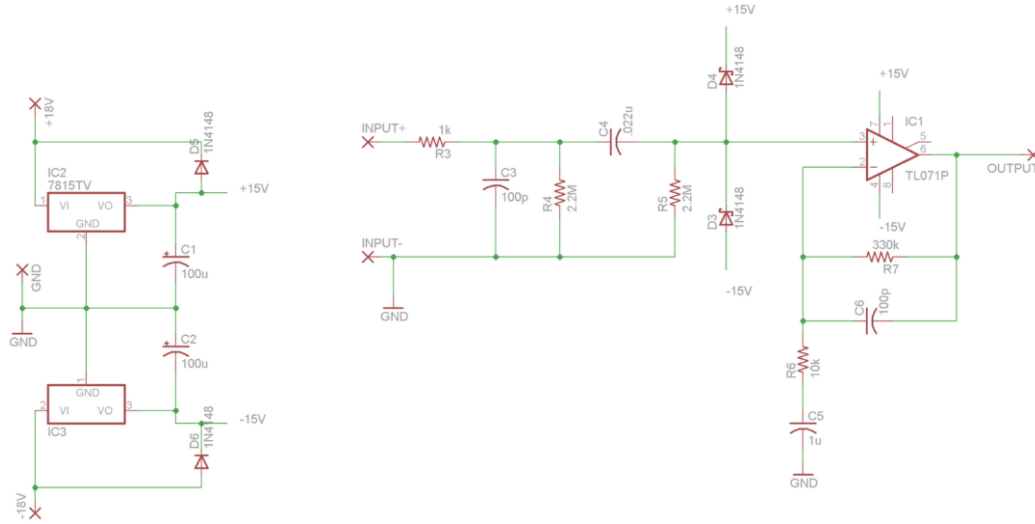


Figure 5 Solid-State Preamp Module Schematic

The subcircuit on the left is a pair of simple voltage regulators using 7815 and 7915 voltage regulator ICs to make sure that the TL071 op-amp has a safely limited bipolar voltage supply, while also ensuring that possible variations in the positive and negative 18 V supply rails caused by the power amplifier do not feed back to this earlier part of the circuit.

R3, in series with the impedance of the electric guitar, and C3 form a low pass filter to attenuate radio frequencies, or else demodulation may occur in the nonlinear tube amplifier. This would implement an AM radio. The maximum crossover frequency f_c is $12\pi \cdot R3 \cdot C3 = 1.6$ MHz. C6 and the parallel combination of R6 and R7 further reduce frequencies above 160 kHz.

At frequencies of interest for electric guitar, which is between 82 Hz and 5 kHz, the voltage gain of this circuit is calculated with (1) to be 34 V/V, or 30.6 dB.

$$A_v = 1 + R7/R6$$

(1)

Simulations of the frequency response and voltage gain of this circuit are shown in Figure 6.

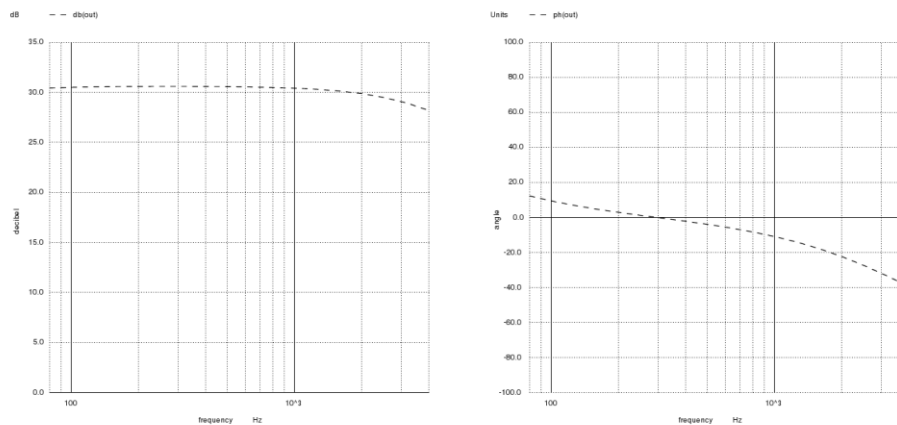


Figure 6 Amplitude (dB) and Phase (°) Simulations of Solid-State Preamp Circuit

The gain is very close to that calculated by (1) throughout the range of frequencies considered.

2.2.1.3 Gain & Tone Controls Module

The equalization circuit, often called a "tone stack," chosen for this amplifier is based on the one used in early Fender-brand tube amplifiers, but has been used in many other amplifiers. Its schematic is shown in Figure 7.

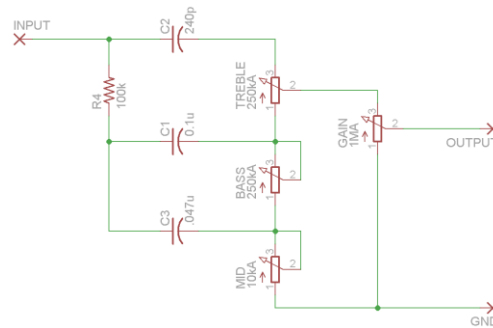


Figure 7 Gain and Tone Controls Module Schematic

Being a passive circuit, the tone stack results in some loss of signal. When its frequency response is set as flat as possible, with the gain knob and mid knob at full and treble and bass at minimum, the insertion loss of this circuit can be approximated as a voltage divider between R4 and R3. The voltage gain of this circuit, then, is

$$A_v = R_3 / (R_3 + R_4) = 0.091 \text{ V/V} \quad (2)$$

or -20.8 dB. Frequency response simulations for the condition described are in Figure 8.

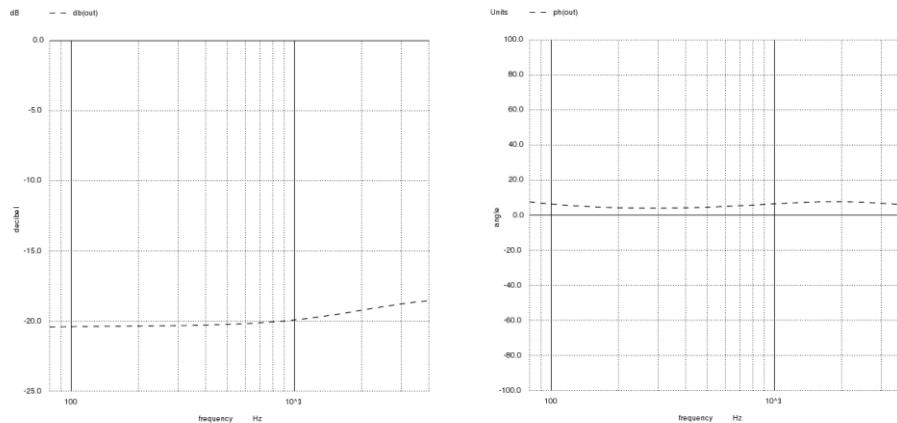


Figure 8 Amplitude (dB) and Phase (°) Simulations of Tone Control Circuit

2.2.1.4 Tube Amplifier Module

The schematic for the tube amplifier module follows in Figure 9.

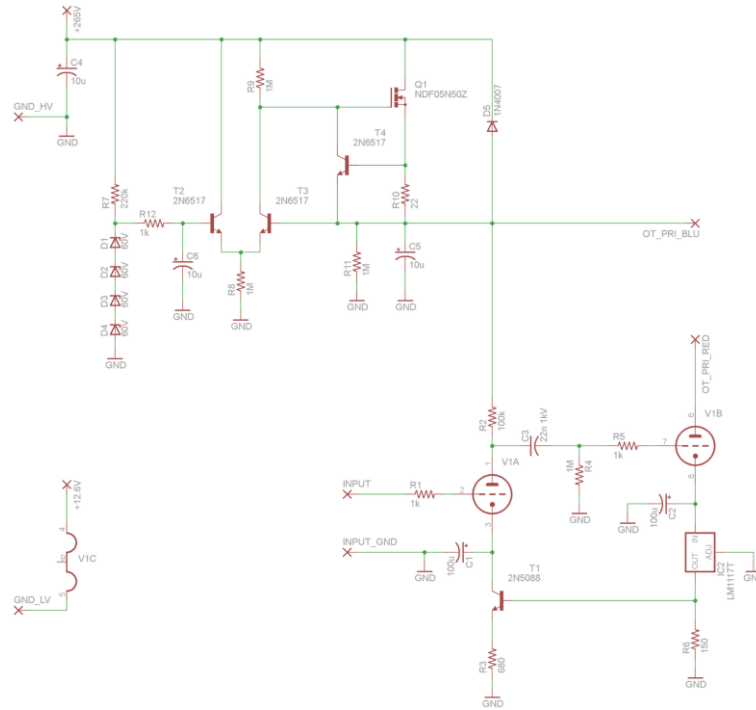


Figure 19 Tube Amplifier Module Schematic

A preliminary tolerance analysis of the amplifier showed that voltage ripple on the supply for the tube amplifier circuit exceeding 141 mV peak would be amplified enough to bring the noise above 1% at the amplifier's output. Since voltage regulators for high-voltage applications are expensive and difficult to find, a discrete series voltage regulator was designed to reduce power supply noise.

In this circuit, T4 in conjunction with R10 acts as a current limiting device for the voltage regulator; when the voltage across R10 exceeds the base-to-emitter voltage needed to turn T4 on, the transistor reduces the gate-to-source voltage of the pass MOSFET, Q1. This occurs when the current through the MOSFET reaches about $0.6 \text{ V}/22 \Omega = 27 \text{ mA}$.

V1A and V1B are both common-cathode amplifiers, similar in operation to common-source amplifiers using depletion-mode MOSFETs. The bias current is set in V1B by the low drop-out voltage regulator, which maintains 1.2V at its output. The bias current is then $1.2 \text{ V}/150 \Omega = 8 \text{ mA}$. Similarly, T1 forces the voltage at its emitter to be about 0.6V, so that the bias current of V1A is $0.6 \text{ V}/680 \Omega = 0.9 \text{ mA}$.

The load on the anode of V1B is the output transformer, which is not shown. It presents an impedance of about 11kΩ when its secondary is connected to the resistive load & volume control module. Therefore, the largest voltage swing at the plate of V1B is $8 \text{ mA} \cdot 11 \text{ k}\Omega = 88 \text{ V}$. If the input signal to the amplifier is a guitar with a peak voltage output of about 100 mV, and if the gain control is turned all the way up, then there is enough gain in this amplifier that the peak voltage swing at the plate of V1B ought to be 396 V. Being limited at 88 V, the amplifier distorts. This is a desirable effect because the distortion produced by this type of circuit is usually considered pleasant, when combined with taste.

The 12.6 V supply provides power for the heater filaments in the vacuum tube.

2.2.1.5 Resistive Load & Volume Control Module

Figure 10 shows the schematic for the resistive load and volume control.

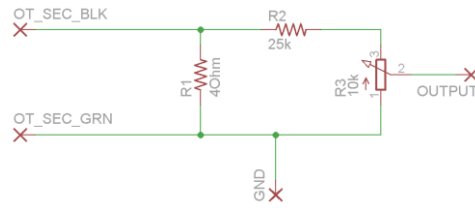


Figure 10 Resistive Load & Volume Control Module Schematic

At the secondary of the output transformer, the 4 Ohm resistor R1 serves as the load for the tube amplifier. R2 and R3 form a voltage divider to limit the amount of voltage that the input of the solid-state power amplifier will receive.

The result of a frequency response simulation done on the tube amplifier with the output transformer, the resistive load, and the volume control is shown in Figure 11.

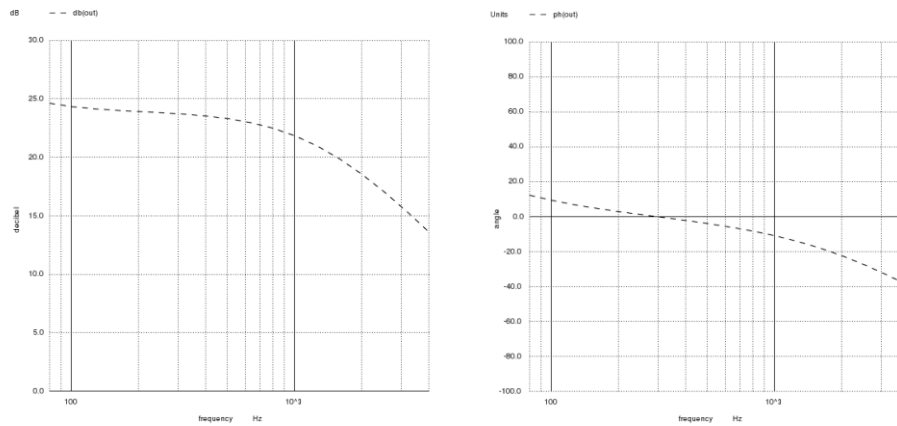


Figure 11 Amplitude (dB) and Phase (°) Simulations of Tube Amplifier Circuit

The gentle high-frequency roll off shown serves to reduce the “harshness” of the distorted sound.

2.2.1.6 Solid-State Power Amplifier Module

The schematic for the solid-state power amplifier module is shown in Figure 12.

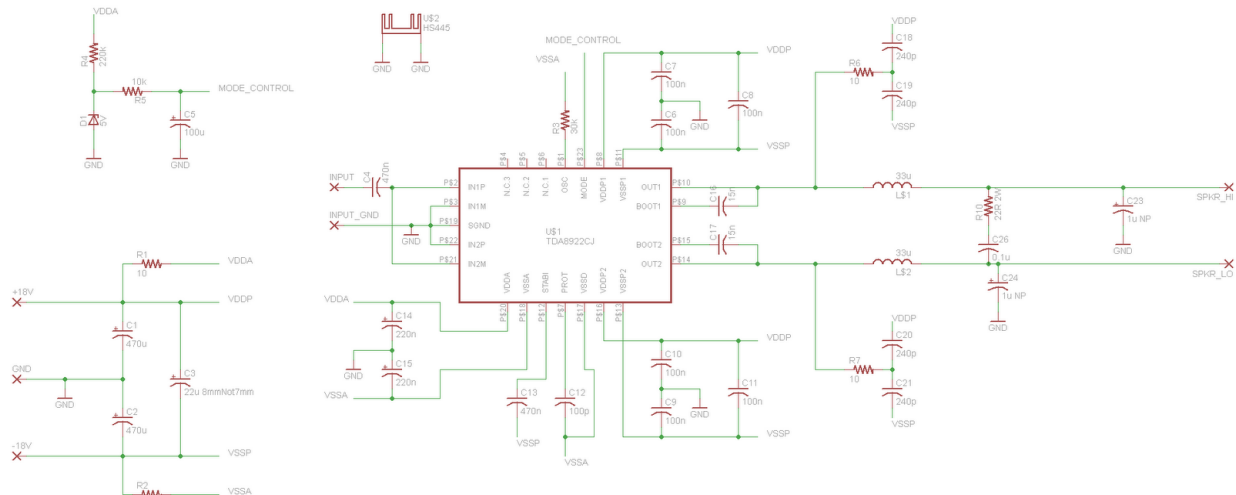


Figure 12 Solid-State Power Amplifier Module Schematic

The solid-state power amplifier was largely designed according to the application notes in the datasheet for the TDA8922CJ IC [3]. The MODE_CONTROL signal prevents the amplifier from popping upon startup; when the power supply voltage is applied, the MODE_CONTROL voltage raises toward 5 V with a time constant determined by R5 and C5. The application notes suggest a time constant of at least 500ms. The time constant of this circuit is $10\text{ k}\Omega \cdot 100\text{ }\mu\text{F} = 1\text{ s}$.

The IC outputs a PWM signal, switching at about 325kHz, which is filtered by the L-C lowpass filters made up of L\$1, C23, and C22; and L\$2, C24, and C25. The crossover frequency of this circuit can be calculated with

$$F_{lc} = 12\pi \cdot L \cdot C. \quad (3)$$

In this circuit, that is 27.7 kHz, well above the range of the electric guitar. Frequency response plots of a simulation of the solid-state amplifier and the output filter, along with the Boucherot cell and a model for a 10 inch speaker, are shown in Figure 13.

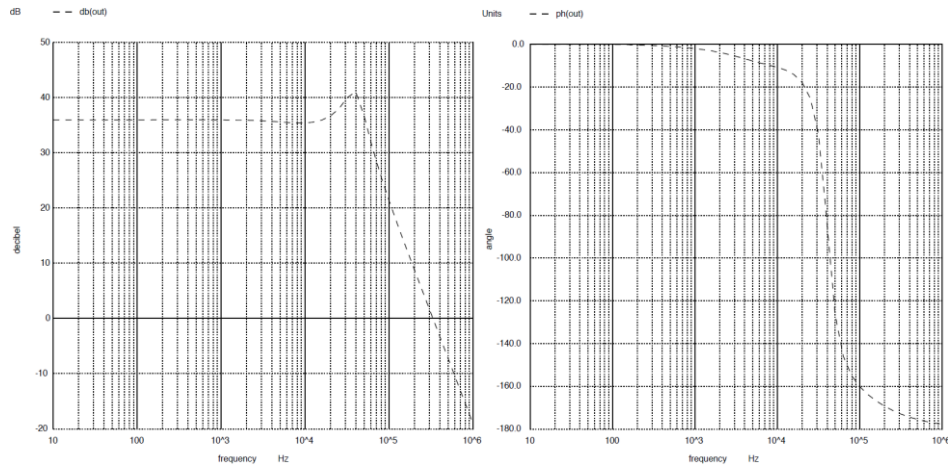


Figure 13 Amplitude (dB) and Phase (°) Simulations of Loaded Solid State Amplifier

The low-pass filter acting at about 28 kHz is evident.

2.2.2 Speaker Cabinet

2.2.2.1 Speakers

The cabinet speakers will be 2 Jensen Neo 10-100 guitar 10 inch guitar speakers[4] and are the only electrical component situated in the cabinet. These speakers were chosen based on their lightweight neodymium based design and moderate cost. For an input impedance of 8 Ohms, the 16 Ohm speakers will be mounted in parallel as shown in Figure 14. Both of the speakers will be mounted on separate baffle boards and positioned such that the directivity is directed inward at an angle of 17 degrees perpendicular to the cabinet front. Figure 15 shows the mounting configuration.

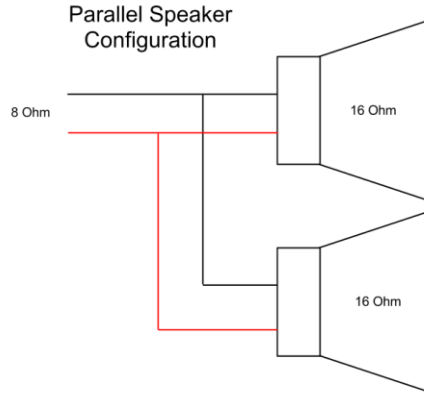


Figure 14 Speaker Wiring Scheme

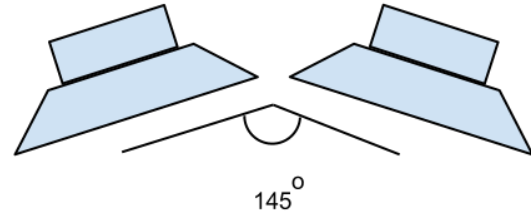


Figure 15 Mounting Configuration of the Two Loudspeakers

While the tilting of the speakers will not be of great effect at lower frequencies, when the sound begins to beam at the higher frequencies our design will facilitate a more even sound field. This is shown in figure 17 where a sound field is simulated using Mathematica with a sampling of frequencies. The equation (4) used is that of a baffled piston[5]:

$$p = j\rho c a^2 U_o \frac{k}{2r} e^{j(\omega t - kr)} \left[\frac{2J_1(ka \sin \theta)}{ka \sin \theta} \right] \quad (4)$$

where, $a=0.127$ m, $\rho=1.21$ kg/m³, $c=343$ m/s², $U_o=244$ m/s

This demonstrates how the sound field becomes more directional as the frequency increases and how this configuration aids in creating a more even sound field.

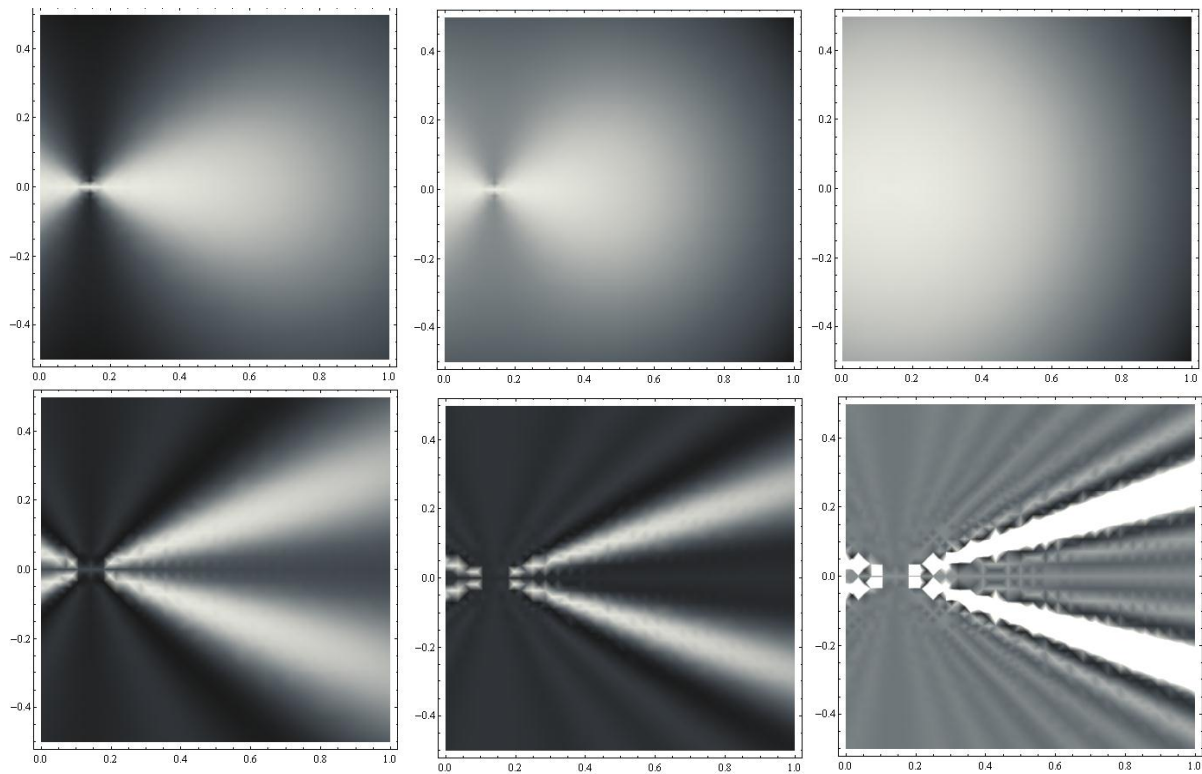


Figure 16 Directivity of Current Speaker Configuration using Frequencies of 1000(top left), 500(top middle), 80(top right), 5000(bottom left), 10000(bottom middle), 20000(bottom right).

2.2.2.2 Cabinet Construction

The cabinets design is that of a tapered transmission line cabinet, as shown in Figure 18. The typical application for this style of cabinet is for high fidelity home stereo systems. While a complicated and often mystified topology, when executed correctly the waves passing from the back of the speaker are absorbed along the tapered path and allows for a flat frequency curve[6].

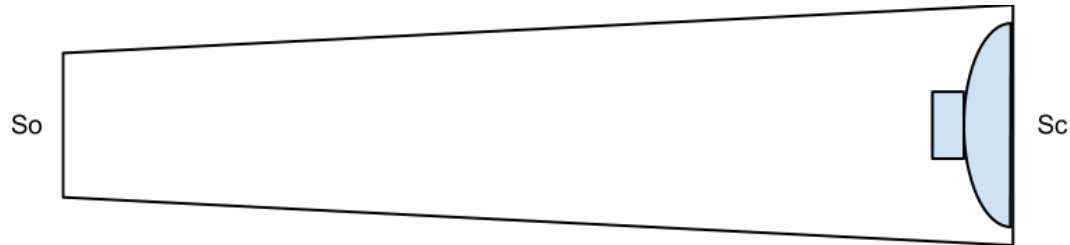


Figure 17 Transmission Line Topology

The design parameters for a transmission line are based around the resonant frequency of the drivers F_s and the driver's surface area S_d . A speaker baffle area, S_c , and port area, S_o , are devised through trial and error until an appropriate cabinet size is developed. For our design $S_c/S_d=1.68$ and $S_o/S_d= 0.6$. According to Martin King, these ratios should lie inbetween 2 and 0.5 [6]. To configure the transmission line, the resonant frequency is used to calculate the quarter wavelength, which will be the overall length of the line as shown in green in figure 19. Our transmission line cabinet has been folded to create a more compact cabinet as well as have a forward facing port, which will output sound waves in phase with the output of the speaker. This is used to increase the low frequency response of the drivers below their normal operating parameters.

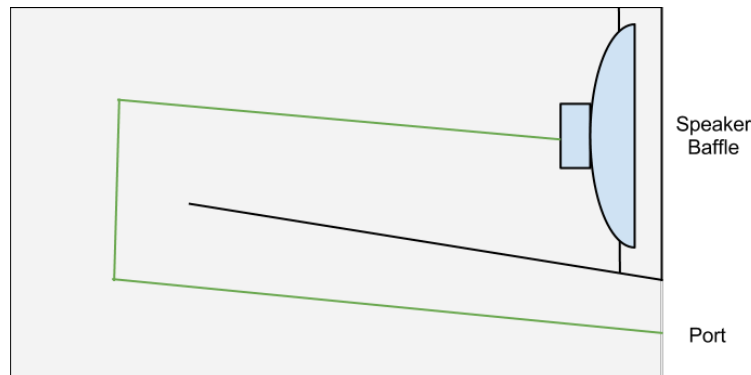


Figure 18 Folded Transmission Line Cabinet

The cabinet was constructed of carbon fiber wrapped around an extruded polystyrene core. From this method, the cabinet is lightweight, approximately 15 lbs, stiff and durable. Safety was taken into account with respirators, safety glasses, safety gloves and proper ventilation being used at all times of manufacturing.

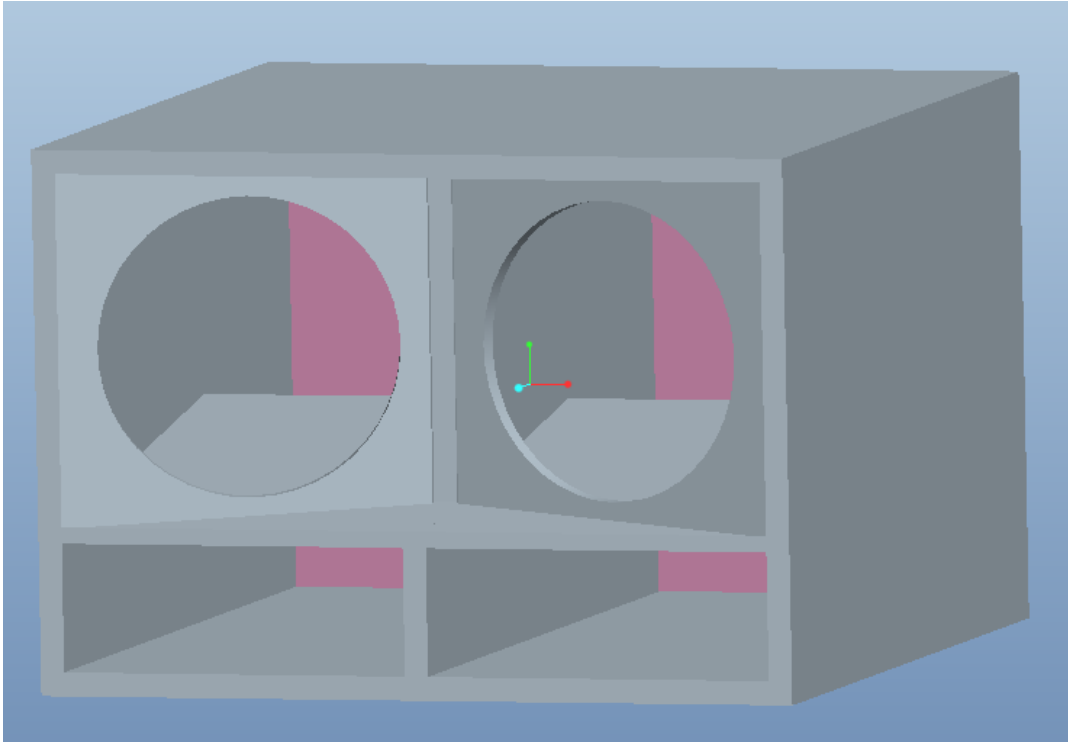


Figure 19 CAD Model of finalized Cabinet

CAD modeling was used to finalize spacing and determine surface area as well as volume.

3 Design Verification

3.1 Amplifier Head

Each sub-block of the amplifier head was tested similarly to the manner outlined in the verification table. When completed, the amplifier head was connected to the speaker cabinet and judged for audio quality, as well as for any other obvious problems.

3.1.1 Power Supply Module

The power supply module was tested with nominal loads of $18\ \Omega$ for each of the $+18\ \text{V}$ and $-18\ \text{V}$ outputs, $100\ \Omega$ for the $+12.6\ \text{V}$ output, and $18\ \text{k}\Omega$ for the $+250\ \text{V}$ output. The output DC voltages were monitored with DMMs, while the output voltage ripple was determined with an oscilloscope. Figure 15 shows the output voltages and ripple voltages.

Nominal Voltage	Acceptable DC Voltage	Actual DC Voltage	Acceptable Ripple (p-p)	Actual Ripple (p-p)
+250 V	(+245 V, +290 V)	+272 V	< 15 V	2.08 V
+18 V	(+13 V, +30 V)	+18.3 V	< 8 V	0.26 V
-18 V	(-30 V, -13 V)	-20.8 V	< 8 V	0.01 V

+12.6 V	(+11.3 V, +13.9 V)	+13.24 V	< 6 V	1.63 V
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Figure 20 Power Supply Verification Results

The requirements for this module were all met.

3.1.2 Solid-State Preamplifier Module

The Solid-State Preamplifier module was connected to a bipolar 18 V bench power supply. A 100 mV pk, 1 kHz sine wave was presented at the input. The output, seen in an oscilloscope, was a 3.44 V pk sine wave. This makes the gain for that module 34.4 V/V, or 30.7 dB, which verifies that module.

3.1.3 Gain & Tone Controls Module

A 10 V pk, 1 kHz sine wave was presented at the input of the module with the gain and mids controls turned all the way up and the treble and bass controls turned all the way down. The output, viewed in an oscilloscope, was a sine wave of 1 V pk. The gain is 0.1 V/V, or -20 dB, which verifies that module.

3.1.4 Tube Amplifier Module, Output Transformer, and Resistive Load & Volume Control Module

The input impedance of the Resistive Load & Volume Control module was checked with a DMM. It was found to be 3.9 Ω , which verifies the input impedance of that module.

After that, the tube amplifier module was connected to the +250 V and +12.6 V outputs from the Power Supply Module. Its output was connected to the output transformer primary. In turn, the output transformer secondary was connected to the Resistive Load & Volume Control Module, with the Volume control set at full. 1kHz sine waves of various amplitudes were presented to the input of the Tube Amplifier Module. The output of the Resistive Load & Volume Control Module was viewed in an oscilloscope to determine the character of distortion and the gain of the series of modules.

The gain was shown to be 2.6 V/V, or 8.3 dB. This was roughly a fourth of the expected value.

The amplifier module was driven into distortion by increasing the input signal voltage, as shown in the following figure.

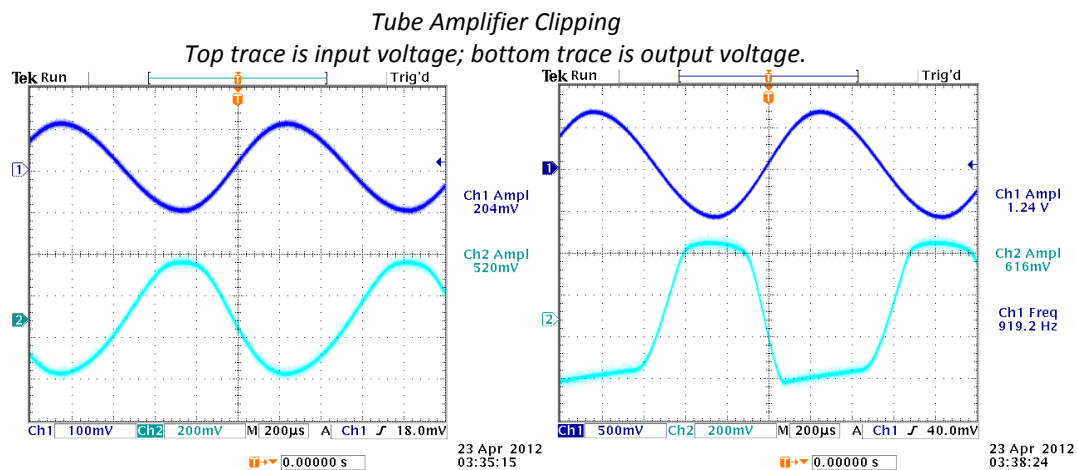


Figure 21 Tube Amplifier Clipping

The heavily clipped waveform on the bottom right of Figure 16 shows that even with a large amount of distortion, the clipped waveform has few sharp edges. This would translate into a distorted sound which does not emphasize buzzy, harsh-sounding high frequency harmonics.

The tube amplifier begins clipping at about 510 mV p-p. The expected value was 850 mV p-p. Because the gain of the Class-D amplifier is 36dB, this results in a maximum clean output power of 16.8 W instead of 44.9 W, which does not meet the specifications of the amplifier.

It was determined that the reduced gain and reduced clipping voltage of this sequence of modules could have been caused by a combination of two factors:

- Variations in characteristics of the vacuum tube from the specified values
- Lower plate current than expected in each triode

Vacuum tubes of the same manufacturer and model number often vary significantly in their characteristics, so that the former reason could play a role, especially in reducing the gain. The lowered plate current could be the cause of either problem.

The plate current of each triode stage was measured. The results are shown below.

Triode	Plate Current Expected	Plate Current Measured
V1A	1000 μ A	470 μ A
V1B	8 mA	6 mA

Figure 22 Plate Current

The results show that the plate currents were indeed less than expected. This is assumed to be because the LM1117 voltage regulator (IC2) did not have enough voltage at its input to operate correctly.

3.1.5 Solid-State Power Amplifier Module

The Solid-State Power Amplifier module was connected to the ± 18 V outputs of the Power Supply Module. A 1 kHz sine wave of varying amplitudes was presented to its input. A 7.1 Ω , 55W resistor was connected to its output. By inspection of the output voltage in an oscilloscope, the gain of the module was shown to be 60.5 V/V, or 35.6 dB. This is very close to the 36 dB specified in the documentation for the TDA8922CJ IC.

The highest output power data obtained was for 890 mV p-p input. This resulted in 50.8 W of output power, with no visible harmonic distortion. That verifies this module.

3.1.6 Completed Amplifier Head

After the amplifier head was assembled, it was connected to the speaker cabinet for subjective testing. The amplifier's sound is quite pleasant, both when played cleanly (with very little distortion) and when played with significant distortion. The amplifier was found to intermittently oscillate at low frequencies (less than 10 Hz), if the power supply wires were allowed to rest close to the PCBs in the amplifier.

3.2 Cabinet

The simplicity of the testing regime for the cabinet is indicative of the nature of the design. If the speakers are mounted properly and are undamaged, sound will be produced from the drivers regardless of the accuracy of the cabinet. Therefore most of the tests, save one, are simple and do not provide much in the way of concrete data feedback.

3.2.1 Speakers

Upon receiving the Jensen speakers, time was taken to physically inspect the drivers for damage. Once no physical damage was observed, each was hooked up to a frequency generator and small speaker driver and swept through frequencies ranging from 10 to 10,000 Hz. This was conducted to check that the voice coils were undamaged as well as the paper cones. Both speakers passed inspection and were stored until they could be mounted into the cabinet.

3.2.2 Cabinet

Once construction had been completed, the cabinet was wired and tested for structural stability as well as frequency response. To test stability, a person of approximately 150 lbs stood on the cabinet and minimal deflection was observed. Unfortunately, the structural rigidity is not as high as intended. This is particularly due to the type of carbon fiber used as well as the lack of extra material to finish the edges of the cabinet. Once the extra material can be used, the rigidity should increase.

The major test that determines the success of the cabinet design resides within the frequency response plot. This plot will demonstrate the major contributions the cabinet gives to the project, mainly the lowend frequency reinforcement and the minimal coloration of the sound due to standing waves within the cabinet. Figure 24 is the frequency response curve captured by measuring the Sound Pressure Level at 1 meter from the speakers using a spectrum analyser to generate the white noise required. When this plot is compared with Figure 25, the frequency response curve provided by the speaker manufacturer, it can be seen that the two plots reflect each other in all of the regions about 100 Hz. This proves that the cabinet does not color the sound above 100 Hz. Additionally, the low frequency response of the constructed cabinet is much greater than in figure 25 demonstrating that the transmission line topology accomplished its intention.

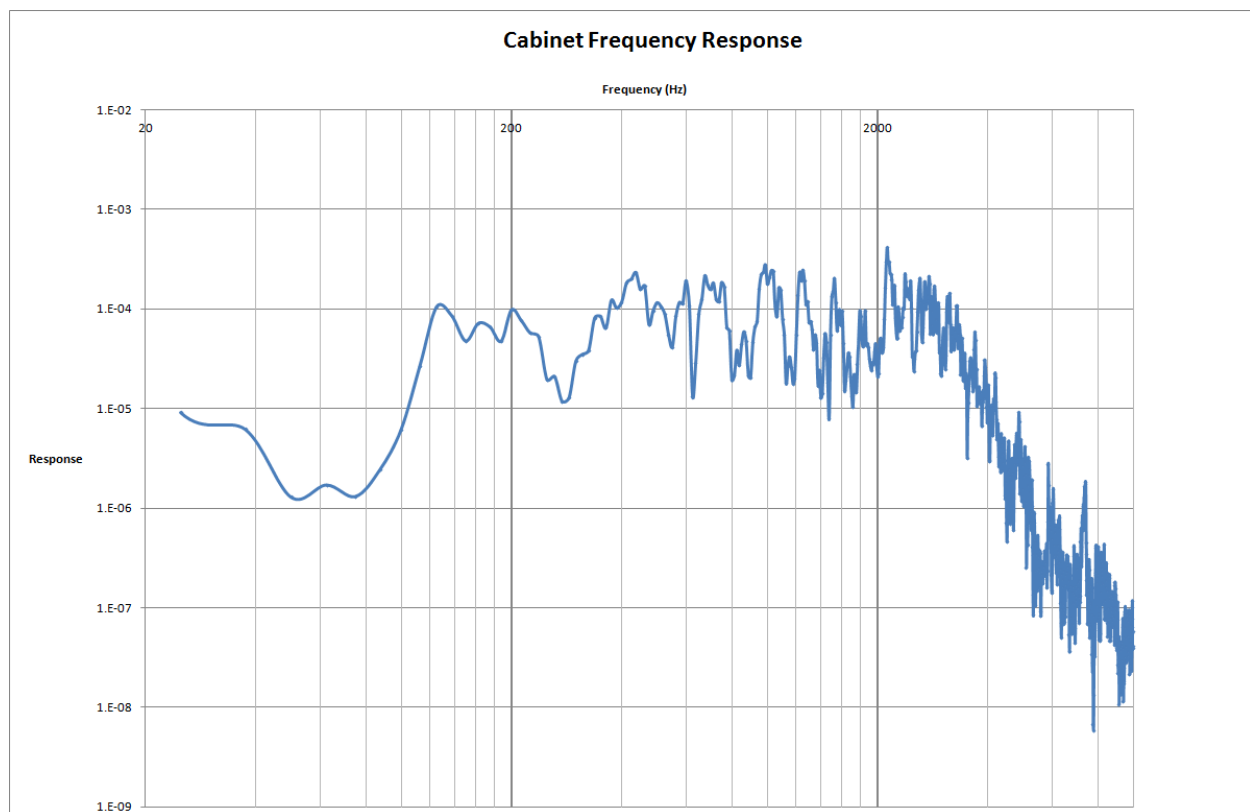


Figure 23 Frequency Response of the constructed 2x10 Cabinet from 20-10000 Hz.

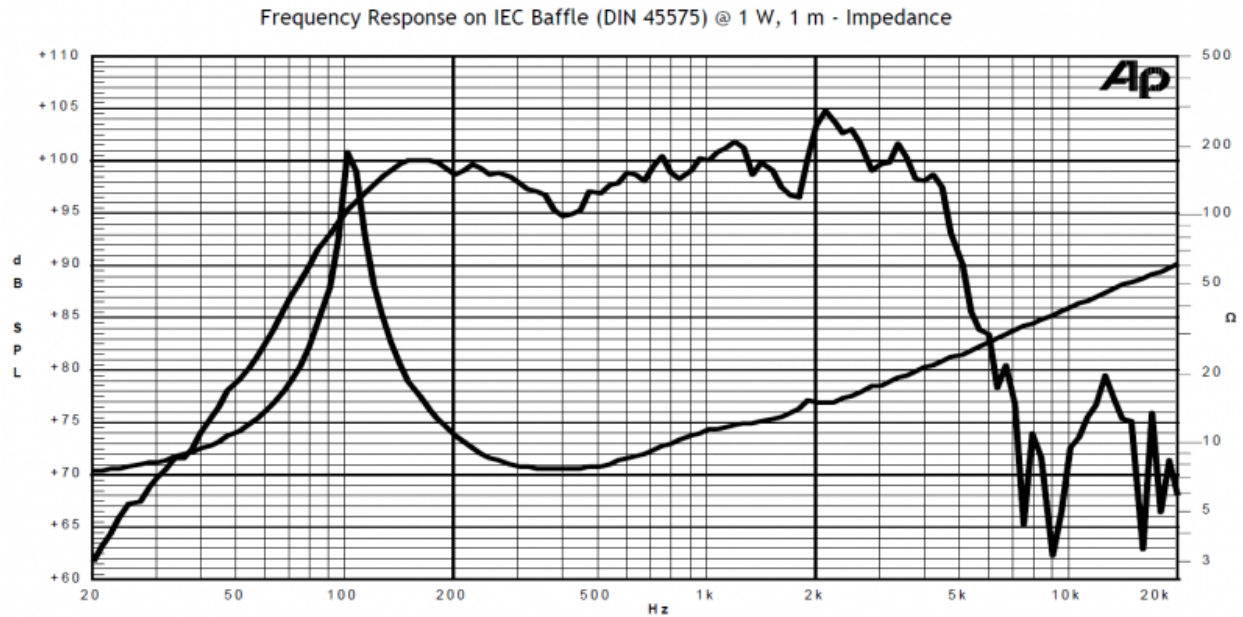


Figure 24 Frequency Response plot provided by Jensen for the NEO 10-100 speaker.

4 Costs

Labor

Dream Salary of each team member:		\$40 per hour
\$40 x 2.5 x 150 hours	=	\$15,000 per member
\$15,000 x 2 members	=	\$30,000

Material

Amplifier Head	:	\$150.49
Cabinet		\$469.34
Total		\$619.83

Overall Project Cost **\$30,619.83**

Manufacturing viability for mass production is simple for the head design due to its simplicity, part selection, and low number of components. The part cost would be further lowered from bulk costing of components while labor costs could be lowered by outsourcing labor. The mass manufacture of the cabinet would be difficult due to complexity of the shape, hazardousness of the materials and inability to use modern mass production techniques. Much of the current carbon fiber manufacturing business rests with smaller firms using a labor intensive and sophisticated process with limited product runs.

See overall budget in appendix 3.

5 Conclusions

5.1 Wrap-Up and Future Work

In the course of this project, a functional guitar amplifier head and cabinet were designed which were both lightweight and subjectively pleasant-sounding. The sound of the distortion from the vacuum tube and the bass frequency response of the cabinet were excellent, as it was intended from the beginning of the project.

Future work is largely in the area of the amplifier head. The lack of gain in the Tube Amplifier Module can be compensated for with an increase in gain in the Solid-State Preamplifier module, by decreasing the value of R6 in that module. The plate current of both triodes can be increased by connecting R4 of the Tube Amplifier Module to the output of the LM1117T IC instead of to ground, referencing the grid of V1B to a voltage higher than ground, resulting in more voltage available at that IC's input, which is the cathode of that triode. If this does not increase the maximum clean power of the amplifier to above 35 W, then R2 on the Resistive Load & Volume Control module can be changed to a lower value, letting more voltage proceed into the input of the Solid-State Power Amplifier. Careful rerouting of the power supply wires, in combination with twisting sets of wires together and shielding where possible, should fix the problem of low-frequency oscillation in the amplifier.

A 1x10 version of the cabinet will be developed to further lighten the overall weight and decrease overall size of the cabinet. Similar construction techniques will be used.

5.2 Ethical considerations

This design is affected by item 1 of the IEEE code of ethics. Item 1 instructs the engineer 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.” It should be noted that this design, like most vacuum tube amplifiers, has voltages within it which are potentially lethal, and care should be taken to discourage the end-user from opening the chassis, to avoid serious electric shock.

Additionally, the end user may, from time to time, need to replace the vacuum tube. A warning may need to be issued stating that the vacuum tube is very hot when the amplifier has been turned on, and it may be advisable to wait until it has cooled to touch it for removal.

Hazardous chemicals were used in the creation of the cabinet. Proper safety for anyone handling these chemicals as well as proper disposal is paramount to prevent contamination and will be followed at all times.

Finally, playing sound through this amplifier at high volumes may result in hearing loss. A commercially produced version of either the amplifier head or the cabinet should bear a warning to that effect.

References

1. *Application Note AN-4146*, Fairchild Semiconductors
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2. *FPS Design Assistant*; Fairchild Semiconductors
http://www.fairchildsemi.com/ShoppingExperience/action/redirect?type=designtool&url=/design_tools/fps_design_tool/qrc/FPS_Design_QRC_AN4146.xls
3. *TDA8922B Datasheet*; Phillips Electronics
http://www.nxp.com/documents/data_sheet/TDA8922B.pdf
4. *Neo 10-100*; Jensen Speakers
http://www.jensentone.com/sites/default/files/spec_sheets/Neo10-100_Specification_Sheet.pdf
5. *Fundamentals of Acoustics*; Kinsler, Frey, Coppens, Sanders
6. *Pearls from Martin J. King Quarter Wave Design*, Bjorn Johannesen
<http://www.t-linespeakers.org/design/MJK-for-dummies/index.html>

Appendix A

Design Verification Tables

The design verification tables for the amplifier head is shown below.

1 Amplifier Head

1.1 Solid-State Power Amplifier Module

Requirement	Verification																								
<p>The power amplifier's power output, when loaded with 8Ω at 1kHz, will exceed 35W with minimal distortion.</p> <ol style="list-style-type: none">1. Voltage is applied to power input pins2. Signal input is applied to input pins3. PWM signal is present at output pins4. Output power exceeds 35W5. Harmonic distortion at output is not visible in oscilloscope.	<p>The Solid-State Power Amplifier will be supplied power with a bench supply and loaded with an 8Ω, 50W or greater power resistor. With a 1kHz input signal of 400mV peak, checking for visible harmonic distortion of the output signal in an oscilloscope. If the output signal has no visible harmonic distortion, lower-level troubleshooting is unnecessary.</p> <ol style="list-style-type: none">1. With above setup, use DMM to check voltages at these pins, and expect these voltages: <table><tr><th>Pin Name</th><th>Pin Number</th><th>Voltage Expected</th></tr><tr><td>SGND</td><td>19</td><td>0V</td></tr><tr><td>VSSD</td><td>17</td><td>-18V</td></tr><tr><td>VDDP2</td><td>16</td><td>18V</td></tr><tr><td>VSSP2</td><td>13</td><td>-18V</td></tr><tr><td>VSSP1</td><td>11</td><td>-18V</td></tr><tr><td>VDDP1</td><td>8</td><td>18V</td></tr><tr><td>MODE</td><td>23</td><td>5V</td></tr></table> <p>Figure 1.1 Solid-State Power Amplifier DC Voltages</p> <ol style="list-style-type: none">2. With above setup, use oscilloscope to verify 400mV input signal at pins 2 and 21, zero voltage at pins 3 and 22.3. With above setup, use oscilloscope to verify PWM signal is generated at pins 10 and 14.4. With above setup, use power meter to verify power output of at least 35W.5. With above setup, use oscilloscope to verify no visible harmonic distortion.	Pin Name	Pin Number	Voltage Expected	SGND	19	0V	VSSD	17	-18V	VDDP2	16	18V	VSSP2	13	-18V	VSSP1	11	-18V	VDDP1	8	18V	MODE	23	5V
Pin Name	Pin Number	Voltage Expected																							
SGND	19	0V																							
VSSD	17	-18V																							
VDDP2	16	18V																							
VSSP2	13	-18V																							
VSSP1	11	-18V																							
VDDP1	8	18V																							
MODE	23	5V																							

Figure 1 Solid-State Power Amplifier Module Verification Table

1.2 Resistive Load & Volume Control Module

Requirement	Verification
<p>Resistive load & volume control module will have input impedance near 4Ω and will pass signal unless volume is at minimum.</p> <ol style="list-style-type: none"> 1. Input impedance is close to 4Ω. 2. Impedance from output to negative input is close to $7.15k\Omega$ with volume set to 	<p>The input impedance of the module will be tested with a multimeter. Then, a 2V pk 1kHz sine wave will be applied to the input of the module. An oscilloscope will be connected to the output. If the multimeter shows within 10% of 4Ω, and the output voltage measured with the oscilloscope is at least 400mV peak when the potentiometer is set to maximum, then no further testing is necessary for this module.</p> <ol style="list-style-type: none"> 1. With module disconnected from circuit, use DMM to measure impedance between the positive input and negative input. It should be within 10% of 4Ω. 2. With module disconnected from circuit and volume set to

<p>full.</p> <ol style="list-style-type: none"> Impedance from negative input to ground is less than 1Ω. Signal voltage gain should have a maximum of at least 0.2. 	<p>maximum, use DMM to measure impedance between the negative input and output. It should be within 20% of 7.15kΩ.</p> <ol style="list-style-type: none"> With module disconnected from circuit, use DMM to measure impedance between the negative input and ground pad. It should be less than 1Ω. A 2V pk 1kHz sine wave will be applied to the input of the module. An oscilloscope will be connected to the output. The output voltage with the volume set to full should exceed 400mV peak.
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Figure 2 Resistive Load & Volume Control Module Verification Table

1.3 Gain & Tone Controls Module

Requirement	Verification
Gain & Tone Controls Module will pass signal.	1kHz 10V pk sine wave will be presented to input. Output will be monitored with oscilloscope, and should be between 300mV and 3V pk when mids & gain are full, treble & bass are off.

Figure 3 Gain & Tone Controls Module Verification Table

1.4 Solid-State Preamplifier Module

Requirement	Verification
<p>Solid-State Preamp module will have voltage gain of about 34, or 30.5dB.</p> <ol style="list-style-type: none"> Voltage regulators will drop $\pm 18V$ bipolar supply to $\pm 15V$ bipolar supply, within 1V. Signal will pass through input filters to the IC input. Gain of module should be between 20 and 52.5. 	<p>Preamp will be removed from circuit and powered with a $\pm 18V$ bench supply. Input of preamp will be presented with a 1kHz, 100mV peak sine wave. Output will be monitored on an oscilloscope, and should be near 3.4V peak, between 2V and 5.25V peak. If this is verified, then no further testing is needed on this module.</p> <ol style="list-style-type: none"> Remove input signal. Use DMM to measure voltages at pin 7 and 4 of the TL071. They should be within 1V of +15V and -15V, respectively. Reapply input signal. Inspect voltage at pin 3 of the TL071 with an oscilloscope. It should have a value within 10% of 100mV. With input signal applied, inspect output voltage with an oscilloscope. Its peak value should be between 2V and 5.25V.

Figure 4 Solid-State Preamplifier Module Verification Table

1.5 Power Supply Module

Requirement	Verification																				
<p>Power Supply will provide the following voltages, with these tolerances and ripple requirements:</p> <table><tr><th>Output</th><th>Vmin</th><th>Vmax</th><th>Vripple ≤</th></tr><tr><td>+250V</td><td>+245V</td><td>+290V</td><td>15V p-p</td></tr><tr><td>-18V</td><td>-30V</td><td>-13V</td><td>8V p-p</td></tr><tr><td>+18V</td><td>+13V</td><td>+30V</td><td>8V p-p</td></tr><tr><td>+12.6V</td><td>+11.3</td><td>+13.9</td><td>6V p-p</td></tr></table> <p>Figure 5.1 Power Supply Specifications</p> <ol style="list-style-type: none">DC input voltage must be provided to switching circuitDC supply voltage must be provided to switching circuitSwitching supply circuit should be	Output	Vmin	Vmax	Vripple ≤	+250V	+245V	+290V	15V p-p	-18V	-30V	-13V	8V p-p	+18V	+13V	+30V	8V p-p	+12.6V	+11.3	+13.9	6V p-p	<p>Power supply will be loaded with nominal loads. Each output will be inspected in turn with a DMM to measure DC voltage and an oscilloscope to measure voltage ripple. Results will be checked against Table 5.1 at left. If this is verified, then no further testing is needed on this module.</p> <ol style="list-style-type: none">DC voltage at the positive terminal of C_DC should be between +130V and +170V, as read by DMMDC voltage at the positive terminal of C_A1 should be between +17V and +19V, as read by DMMWhen viewed in an oscilloscope, the waveform of the voltage at pin 5 of the FSCQ0965RT should have a frequency of at least 25kHzDC voltage at pin 4 of the FSCQ0965RT should be between 0V and +18V as measured with a DMM. It
Output	Vmin	Vmax	Vripple ≤																		
+250V	+245V	+290V	15V p-p																		
-18V	-30V	-13V	8V p-p																		
+18V	+13V	+30V	8V p-p																		
+12.6V	+11.3	+13.9	6V p-p																		

switching at frequency of at least 25kHz 4. Feedback voltage should be applied 5. The feedback optocoupler should be receiving input current 6. The output voltages should be as shown in Table 2 above.	should be close to +18V if 5b is verified and the +12.6V output has no voltage 5. The DC voltage between pin 1 and pin 2 of the CNY17 should be between 1V and 1.65V 6. Each output will be inspected in turn with a DMM to measure DC voltage and an oscilloscope to measure voltage ripple. Results will be checked against Figure 5.1 at left.
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Figure 5 Power Supply Module Verification Table

1.6 Tube Amplifier Module

Requirement	Verification																																													
<p>Tube Amplifier module with Resistive load & volume control module together should have maximum voltage gain at 1kHz of between 3 and 24.</p> <ol style="list-style-type: none">1. Heater filaments must work2. Quiescent voltages must be correct, according to the following table. <table><tr><th>Node</th><th>Vmin</th><th>Vmax</th></tr><tr><td>C4 +</td><td>245V</td><td>290V</td></tr><tr><td>T2 Base</td><td>235V</td><td>245V</td></tr><tr><td>C5 +</td><td>235V</td><td>245V</td></tr><tr><td>R8</td><td>234V</td><td>244V</td></tr><tr><td>Tube pin 1</td><td>+90V</td><td>+190V</td></tr><tr><td>Tube pin 2</td><td>-1V</td><td>+1V</td></tr><tr><td>Tube pin 3</td><td>+1V</td><td>+4V</td></tr><tr><td>Tube pin 4</td><td>0V</td><td>0V</td></tr><tr><td>Tube pin 5</td><td>+11.3V</td><td>+13.9V</td></tr><tr><td>Tube pin 6</td><td>+235V</td><td>+245V</td></tr><tr><td>Tube pin 7</td><td>-1V</td><td>+1V</td></tr><tr><td>Tube pin 8</td><td>+1V</td><td>+4V</td></tr><tr><td>R3</td><td>+340mV</td><td>+1V</td></tr><tr><td>R6</td><td>+1V</td><td>+1.4V</td></tr></table>	Node	Vmin	Vmax	C4 +	245V	290V	T2 Base	235V	245V	C5 +	235V	245V	R8	234V	244V	Tube pin 1	+90V	+190V	Tube pin 2	-1V	+1V	Tube pin 3	+1V	+4V	Tube pin 4	0V	0V	Tube pin 5	+11.3V	+13.9V	Tube pin 6	+235V	+245V	Tube pin 7	-1V	+1V	Tube pin 8	+1V	+4V	R3	+340mV	+1V	R6	+1V	+1.4V	<p>The Tube Amplifier module will be connected to the +250V and +12.6V outputs of the Power Supply module. The other outputs of the Power Supply module will be loaded with nominal loads. The output of the Tube Amplifier module will connect to the primary of the Output Transformer, whose secondary will connect to the Resistive Load & Volume control Module. A 10mV peak 1kHz sine wave will be presented to the input of the tube amplifier. With the volume knob turned up all the way, the output of the Resistive load and Volume Control module will be inspected with an oscilloscope. Its output should have a peak voltage between 30mV and 240mV. If this is verified, no further testing is needed on the Tube Amp module.</p> <ol style="list-style-type: none">1. The tube will be touched with a forefinger. If it is hot, the heater filaments are working correctly.2. With no input signal, DC voltages will be checked at nodes listed in Figure 6.1 with a DMM. Voltages should lie between Vmin and Vmax for each node.3. With 10mV pk-pk 1kHz input signal, the voltage at pin 7 of the tube should have a peak value of between 400mV and 700mV, when viewed in an oscilloscope.4. With 10mV pk-pk 1kHz input signal, the voltage at the input of the Resistive Load and Volume Control Module should have a peak value of between 75mV and 600mV, when viewed in an oscilloscope.
Node	Vmin	Vmax																																												
C4 +	245V	290V																																												
T2 Base	235V	245V																																												
C5 +	235V	245V																																												
R8	234V	244V																																												
Tube pin 1	+90V	+190V																																												
Tube pin 2	-1V	+1V																																												
Tube pin 3	+1V	+4V																																												
Tube pin 4	0V	0V																																												
Tube pin 5	+11.3V	+13.9V																																												
Tube pin 6	+235V	+245V																																												
Tube pin 7	-1V	+1V																																												
Tube pin 8	+1V	+4V																																												
R3	+340mV	+1V																																												
R6	+1V	+1.4V																																												

Figure 6.1 Tube Amp Quiescent Voltages

3. Gain of first tube stage should be between 40 and 70
4. Peak voltage at secondary should be between 75mV and 600mV.

Figure 6 Tube Amplifier Module Verification Table

2 Speaker Cabinet

2.1 Speakers

Requirement	Verification
7. Drivers are undamaged and work	7. Driver will be installed onto test baffle.

as intended a. Cone does not have defects b. No short or open circuit in voice Coil	a. Visually inspect cone with magnifying glass b. Connect speaker to separate amplifier and check for sound production
---	---

Figure 7 Gain & Tone Controls Module Verification Table

2.2 Cabinet Struture

Requirement	Verification
10. Cabinet will withstand hostile work environment. a. Capable of withstanding vertical compression without deflection.	10. Take Cabinet to Talbot and connect to compressive testing machine. a. Apply Loading characteristics of large human being of approximately 200 lbs.

Figure 8 Cabinet Structure Verification Table

2.3 Frequency Response

Requirement	Verification
9. Test Frequency Response of Speaker Cabinet a. No antiresonances at - 20dB of average SPL	9. Connect Speaker Cabinet to Spectrum Analyser with white noise output resulting in even frequency output and record output using lock in amplifiers. a. Compare output to average SPL

Figure 9 Frequency Response Verification Table

3 Budget

Item	Spec	Quantity	Unit Cost	Total
Head				
Vacuum Tube	12AT7	1	\$10.00	\$10.00
Output transformer	Hammond 1750A	1	\$19.01	\$19.01
Power Transformer				\$15.00
Chassis				\$20.00
Tube socket	9-pin, PC mount	1	\$2.45	\$2.45
Power Switch		1		\$15.00
Fuse Holder	Fender style, Conical	1	\$2.25	\$2.25
Power cable		1	\$8.95	\$8.95
Power cable strain relief		1	\$0.45	\$0.45
Jacks		3	\$2.50	\$7.50
Potentiometers		5	\$2.50	\$12.50
PCBs		4	\$0.00	\$0.00
Misc. Hardware		1	\$4	\$4
Metal Film Resistors - Through Hole 150Kohms 1% 100PPM	660-MF1/4DCT52R1503	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 221K 1% 100PPM	660-MF1/4DC2213F	3	\$0.06	\$0.18
Metal Film Resistors - Through Hole 240K 1% 100PPM	660-MF1/4DC2403F	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 330K 1% 100PPM	660-MF1/4DC3303F	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 1/4W 1M ohm 1%	660-MF1/4DCT52R1004	4	\$0.06	\$0.24
Metal Film Resistors - Through Hole 1/4W 2.21M ohm 1%	660-MF1/4DCT52R2214	2	\$0.06	\$0.12
Metal Film Resistors - Through Hole 10ohm 1% 100PPM	660-MF1/4DC10R0F	4	\$0.06	\$0.24
Metal Film Resistors - Through Hole 22ohm 1% 100PPM	660-MF1/4DC22R0F	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 150ohm 1% 100PPM	660-MF1/4DC1500F	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 680ohm 1% 100PPM	660-MF1/4DC6800F	2	\$0.06	\$0.12

Metal Film Resistors - Through Hole 1/4W 825 ohm 1% 826 OHM 1%	660- MF1/4DCT52R825C	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 845ohm 1% 100PPM	660- MF1/4DC8450F	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 1Kohms 1% 100PPM	660- MF1/4DCT52R1001	6	\$0.06	\$0.36
Metal Film Resistors - Through Hole 1/4W 1.5K ohm 1% 1.5K OHM 1%	660- MF1/4DCT52R1501	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 10K 1% 100PPM	660- MF1/4DC1002F	3	\$0.06	\$0.18
Metal Film Resistors - Through Hole 1/4W 22.1K ohm 1% 22.1K OHM 1%	660- MF1/4DCT52R2212	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 1/4W 24.3K ohm 1% 24.3K OHM 1%	660- MF1/4DCT52R2432	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 1/4W 24.9K ohm 1% 24.9K OHM 1%	660- MF1/4DCT52R2492	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 30K 1% 100PPM	660- MF1/4DC3002F	1	\$0.06	\$0.06
Metal Film Resistors - Through Hole 100K 1% 100PPM	660- MF1/4DC1003F	3	\$0.06	\$0.18
Audio Amplifiers 1CH Mono/2CH Stereo Audio Amp Speaker	771- TDA8922CJN1112	1	\$5.27	\$5.27
Metal Oxide Resistors 2W 22 5%	660- MOS2CT52R220J	1	\$0.13	\$0.13
Polyester Film Capacitors .47uF 50V 5%	667-ECQ- V1H474JL	2	\$0.4	\$0.8

Aluminum Electrolytic Capacitors - Leaded 50volts 22uF 8X7mm L/S=5.0mm Ammo Crmp	667-EEA- GA1H220B	1	\$0.65	\$0.65
Ceramic Disc Capacitors 20NF 1Kvolts 20%	594- S203M75Z5UN63JC	1	\$0.24	\$0.24
Transistors Bipolar (BJT) PNP Transistor General Purpose	512-2N4403TF	1	\$0.06	\$0.06
Transistors Bipolar (BJT) NPN Transistor General Purpose	512-2N5088TAR	2	\$0.08	\$0.16
Op Amps Single Lo-Noise JFET	511-TL071CN	1	\$0.52	\$0.52
Soft Switching PWM Controllers POWER_CONVERTER	512- FSCQ0965RTYDTU	1	\$2.32	\$2.32
Fuses SMALL DIM. FUSE	504-BK/GMD-1.5- R	1	\$0.78	\$0.78
Voltage & Current References Shunt Regulator 2.5V Programmable	512-KA431AZTA	1	\$0.14	\$0.14
Transistor Output Optocouplers 40- 80CTR 5000Vrms -55 to +110 Op Temp	638-CNY171M	1	\$0.21	\$0.21
Aluminum Electrolytic Capacitors - Leaded 16V 4700uF 20% 16x25mm	140- REA472M1CBK162	1	\$0.95	\$0.95
Aluminum Electrolytic Capacitors - Leaded 25V 220uF 20% 8x11.5mm	140- REA221M1EBK081	2	\$0.13	\$0.26
Diodes (General Purpose, Power, Switching) 1.0 Amp 1000 Volt	625-BA159-E3	1	\$0.06	\$0.06
Diodes (General Purpose, Power, Switching) Diode Ult Fast Recov Rectifier 600V 15A	771-BYT79- 600,127	2	\$1.49	\$2.98
Polyester Film Capacitors 100volts 0.0022uF	647- QYX2A222KTP	1	\$0.08	\$0.08
Zener Diodes Diode Zener Single 18V 5% 1W 2-Pin	771-1N4746A,133	1	\$0.04	\$0.04

Aluminum Electrolytic Capacitors - Leaded 50volts 10uF 5x11mm 85deg C	871- B41827A6106M000	2	\$0.06	\$0.12
Diodes (General Purpose, Power, Switching) 100V	833-1N4448-TP	3	\$0.05	\$0.15
Polyester Film Capacitors 1000volts 0.001uF 10% LS 5mm	80- MMK5102K1000J0	1	\$0.2	\$0.2
Aluminum Electrolytic Capacitors - Leaded 200Volts 330uF 18X35.5 20%	647- UCS2D331MHD	1	\$2.62	\$2.62
Diodes (General Purpose, Power, Switching) 1.0 Amp 400 Volt	625-BA157-E3	4	\$0.06	\$0.24
Aluminum Electrolytic Capacitors - Leaded 100volts 0.33uF Radial	647- UFW2AR33MDD	4	\$0.08	\$0.32
Polyester Film Capacitors 50V 0.015uF 5%	647- QYP1H153JTP	2	\$0.15	\$0.3
Aluminum Electrolytic Capacitors - Leaded 50V 0.22 uF 20% 5x11mm	140- REAR22M1HBK051	2	\$0.06	\$0.12
Multilayer Ceramic Capacitors (MLCC) - Leaded . 1uF 50volts Z5U 20% 2.5mm L/S	21RZ310-RC	7	\$0.08	\$0.56
Aluminum Electrolytic Capacitors - Leaded 16V 10uF 20% 5x11mm	140- REA100M1CBK051	1	\$0.06	\$0.06
Zener Diodes VREG 500MA 5%	771-1N4733A-T/R	1	\$0.04	\$0.04
Aluminum Electrolytic Capacitors - Leaded 25volts 470uF 10x12.5mm 85deg C	871- B41827A5477M000	2	\$0.17	\$0.34
Metal Oxide Resistors MOSX2 3.9 5% 2W	660- MOSX2CT52A3R9	1	\$0.13	\$0.13
Rectifiers Vr/1000V Io/1A	512-1N4007	1	\$0.09	\$0.09
Transistors Bipolar (BJT) NPN Si Transistor Epitaxial	512-2N6517CTA	3	\$0.06	\$0.18
MOSFET NFET T0220FP 500V 5A 1.5R	863-NDF05N50ZG	1	\$0.69	\$0.69

Zener Diodes 60 Volt 0.5 Watt	78-1N5264B	4	\$0.07	\$0.28
Aluminum Electrolytic Capacitors - Leaded 350V 10uF 20% 10x20mm	140-REA100M2VBK102	3	\$0.31	\$0.93
Low Dropout (LDO) Regulators 800MA LDO LINEAR REG	926-LM1117T-3.3 /NOPB	1	\$1.49	\$1.49
Polyester Film Capacitors .047uF 50V 5%	667-ECQ-V1H473JL3	1	\$0.13	\$0.13
Ceramic Disc Capacitors 50V 240pF SL 5% Tol	140-50S5-241J-RC	5	\$0.07	\$0.35
Polyester Film Capacitors .022UF 100V STACK METAL FLM	667-ECQ-V1223JM	4	\$0.31	\$1.24
Polyester Film Capacitors ECQVStack Met Poly Film Cap Lead	667-ECQ-V1H104JLW	1	\$0.14	\$0.14
Aluminum Electrolytic Capacitors - Leaded 1uF 25Volt 85C	539-SN010M025ST	1	\$0.31	\$0.31
Diodes (General Purpose, Power, Switching) 100V Io/150mA T/R	78-1N4148	4	\$0.08	\$0.32
Ceramic Disc Capacitors 50V 100pF SL 5% Tol	140-50S5-101J-RC	3	\$0.06	\$0.18
Aluminum Electrolytic Capacitors - Leaded 25volts 100uF 6.3x11mm 105deg C	871-B41828A5107M000	4	\$0.08	\$0.32
Zener Diodes 16 Volt 0.5W 10%	78-TZX16A	2	\$0.07	\$0.14
Power Inductors 22UH RADIAL COIL CHOKE	667-ELC-18B220L	2	\$1.7	\$3.4
			TOTAL	\$150.49
Cabinet				
High Density Insulation Foam	8'x4'x3/4"	2	\$12	\$24
Jensen NEd 10-100	10" -16 Ohm	2	\$112.65	\$225.3
Neutrik Locking jack	black	1	\$6	\$6
carbon fiber part kit	3 yard kit	1	\$196	\$196
10-32 Machine Screws with T-nuts	50	1	\$18.04	\$18.04
			TOTAL	\$469.34
			GRAND TOTAL	\$619.83

Figure 10

Budget