Wild Stallion Distortion Pedal

A SENIOR PROJECT
PRESENTED TO
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Acknowledgements

To my loving mother - Thank you so much for the unbounded love, support, and guidance you have given me throughout the years. Without your incredible example I wouldn’t be half the man I am today.

To my wonderful and dearly missed father - Thank you for the wisdom and lessons you taught me while still on this earth. I miss you and wish you could be here for this. I am still trying to make you proud.

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To all the friends I have made while here at Cal Poly - Thank you for the great times and shoulders to lean on. You made this journey a blast.

To my God and Savior Jesus Christ – Thanks for watching out for me, believing in me, and giving me everything I needed to get through this crazy journey- Joshua 1:9.

Abstract

The Wild Stallion Distortion Pedal project encompasses the research, design, implementation, PCB layout, and packaging of a distortion effect pedal for the electric guitar. This project aims to use analog circuitry in order to replicate the effect of vintage tube amplifiers to create a distortion effect. The procedure includes research, design, simulations, and prototype testing in order to produce a quality distortion effect built as a stomp pedal for the electric guitar.

Chapter I: Introduction

Having studied and performed on the piano and guitar for over 17 years, it has been a dream of mine to understand and explore the sonic characteristics and designs of my favorite musical devices. Throughout the entirety of my electrical engineering studies at Cal Poly, I have sought to understand and perceive certain concepts taught, from a musical stand point. With my senior project, it is my desire to incorporate the education I have received to facilitate the creation of an effect pedal for the electric guitar.

This project aims to create a quality distortion pedal that models a vintage tube-like distortion sound similar to the widely used Ibanez Tube Screamer. By using analog circuitry, qualities can be induced in the signal that model sounds as though interacting with a vacuum tube amplifier. Tube amplifiers work in such a way that as the amplitude of the input signal from a guitar increases to overload the tube amplifier's preamp, the signal becomes distorted in such a way that sustain, edge, and harmonic qualities affect the signal, while leaving the tonal characteristics of the guitar and the player dynamics intact [2]. For this project, the design goal aims at distorting the signal asymmetrically like a vacuum tube amplifier would, to create a stylish and quality sounding distortion effect. With this basic design goal in mind, modification possibilities will be explored to produce a more custom and unique final product tailored to my own aesthetic tastes as well as customer needs.

Chapter II: Product Design - Engineering Requirements

Customer Needs Assessment

Engineering requirements necessary for design of the Wild Stallion Distortion Pedal are partially derived from customer need assessments. The primary customer base mainly includes electric guitar players. However, keyboard players, singers, hobbyists or anyone who has a ¼” TRS audio cable and wants Wild Stallion distortion in their signal chain can use it. Assessments of customer needs, determined by conducting interviews and doing market research, yielded the most useful information. While demographic characterization of potential customers includes players of all skill levels, ages, and ethnicities, brief interview questions posed to musicians having more significant experience with guitar effect pedals yielded the best results. Questions during interviews included:

1. What features and qualities do you like concerning distortion pedals?
2. What are some of your favorite distortion pedals and why?
3. What concerns do you have when considering purchasing a distortion pedal?
4. What might be a nice or novel additional feature to a distortion pedal?

These interviews yielded a strong bias towards a more “vintage” distortion quality with a couple mentions of JFET technology and the Ibanez Tube Screamer circa the mid eighties design. Overall, of the customers interviewed, four prominent product needs emerged: quality sound, ease of use, product durability, and product affordability.

Requirements and Specifications

The Wild Stallion’s requirements and specifications derive primarily from the previous customer needs assessment. The expected design follows several customers’ aesthetic preference as well as my own in that the design attempts to model the ever popular “vintage” tube amplifier sound by performing asymmetrical soft clipping. The expected durability for performing guitarists requires devices that can withstand possible high external pressures applied during a live stage performance as indicated by the common name “stomp pedal” for such devices. Customer needs also indicate a desire for simple and easy to use controllability. As the use of the Wild Stallion Distortion pedal includes live performances as well as at-home practice sessions, the device must accommodate a portability feature via an optional autonomous battery supply. Finally, the product’s retail price must cap at a per-unit cost of $175 to retain affordability. The previously mentioned needs promote requirements for device sound quality, device durability, device portability, and affordability. A complete list of the Wild Stallion’s marketing requirements and engineering specifications appears in **Table 2.1**.

Table 2.1 Requirements and Specifications

Related Marketing Requirements*	Engineering Specifications	Justification
6	**1** Product uses ¼” TRS input and output jacks	Input and output connectivity for a standard ¼” TRS guitar cable.
1	**2** Circuit contains a distortion stage that produces asymmetrical soft clipping of the waveform	Asymmetrical soft clipping models the popular vintage tube amplifier sound.
2, 5,3	**3** Cast alloy enclosure within dimensions of: 5” (L) x 3” (W) x 2” (H)	Small cast alloy architecture allows for portability and added durability.
6, 3	**4** On/Off (bypass) Pedal Control	A sturdy 3PDT stomp pedal switch activates the device.
4	**5** Product’s battery life lasts for approximately 15 hours (with continuous use).	The product operates for the duration of several lengthy performances or practice sessions.
7	**6** Per unit purchase cost of approximately $175	This device’s price point sits in a competitive location amongst similar distortion pedals.
1,2	**7** Final Circuit contained on a printed circuit board.	High quality and professional looking final circuit layout.
1,8	**8** The device incorporates three level adjustment knobs.	Adds controllability for the amount of distortion, tone, and volume.
2	**9** High quality paint job and decal logo.	The final product includes a high quality paint finish and stylish decal of a custom logo.
3	**10** Device must withstand 300 lbs of external pressure.	Durable enclosure and able to withstand rigorous performances.
5	**11** Fully assembled unit weighs less than 5 lbs	Lightweight design for increased portability.

***Marketing Requirements**

1. Quality sounding
2. Aesthetically pleasing
3. Durable
4. Long battery life
5. Portable
6. Easy to use
7. Affordable
8. Adjustable

Level 0 Decomposition

On the most abstracted level, the Wild Stallion Distortion Pedal accepts an audio signal and introduces distortion (or clipping) to the signal then passes the signal out. **Figure 2.1** presents the device's level 0 black box diagram. The inputs and outputs shown represent abstract information transmission rather than electrical signal transmission. **Table 2.2** further explains the inputs and outputs of the diagram. It also describes the functionality of the box itself.

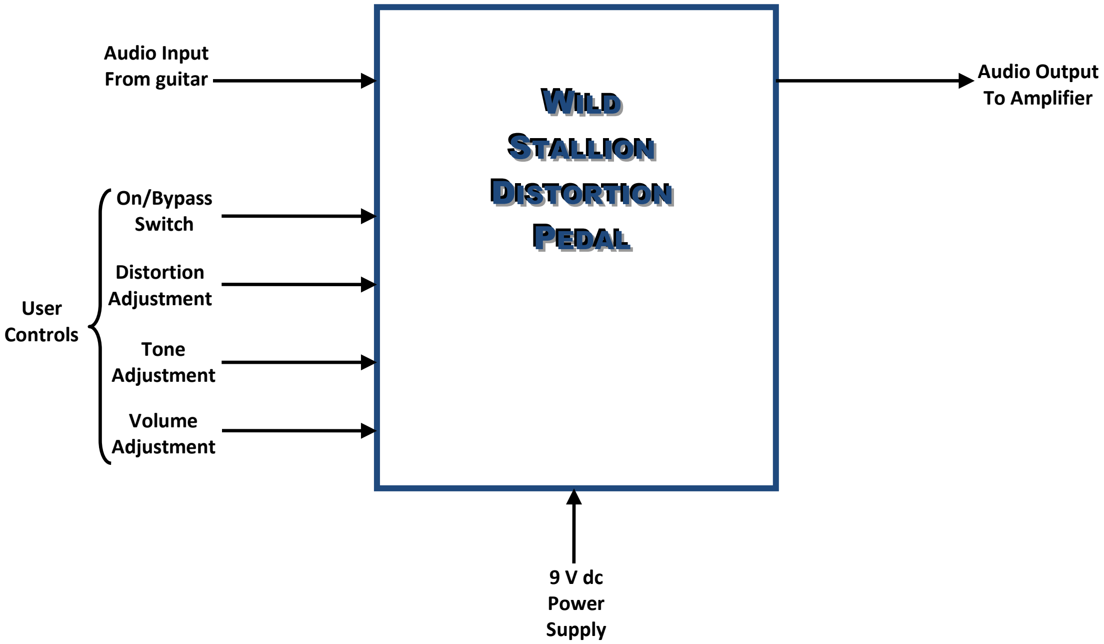


Figure 2.1: Wild Stallion Distortion Pedal Level 0 Black Box Diagram

Table 2.2 Level 0 Functionality

Module	Signal Description
Inputs	Audio Signal - ¼" male stereo TRS cable socket (from guitar) On/Off Switch - Physical 3PDT push button stomp switch Power Supply - 9 V dc supply for circuit (battery alternative) Distortion - Distortion amount adjustment knob Tone – Adjustment knob controlling cutoff frequency Volume - Adjustment knob controlling gain
Outputs	Audio Signal - ¼" male stereo TRS Cable socket (to amplifier)
Functionality	The distortion pedal utilizes analog circuitry to introduce clipping to an audio input signal, effectively producing a desirable distortion quality on the output waveform. The pedal is equipped with a foot switch that when pressed, activates the circuit that otherwise remains bypassed. The pedal has three user control knobs; one controls the level of distortion on the output signal, one controls an RC network to adjust the tone, and the third controls the overall gain in the signal.

Chapter III: System Design - Functional Decomposition

Level 1 Decomposition

The level 1 box diagram presented in **Figure 3.1** further deconstructs the information shown previously in **Figure 2.1**. As seen below, the circuitry performs specific functions on the audio signal through various stages. The input buffer takes in the audio signal from a guitar via a ¼“male stereo TRS Cable creating a high input impedance to preserve the signal’s integrity and avoid high frequency loss [6]. The signal then passes to the clipping amplifier stage for clipping/distortion of the signal. A tone/volume stage is implemented to give user variability over the effect’s loudness and filtering provisions. Finally, the manipulated signal is passed to an output buffer circuit that ensures low output impedance for delivery to an amplifier. **Table 3.1** goes into greater detail on the Wild Stallion’s level 1 functionality.

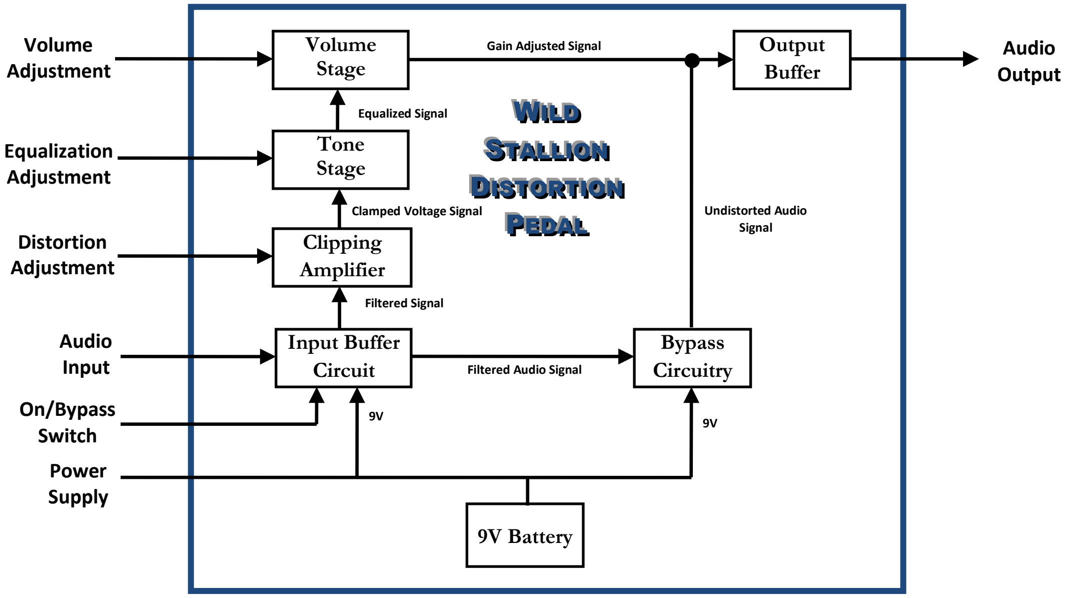


Figure 3.1: Wild Stallion Distortion Level 1 Functional Block Diagram

Table 3.1 Level 1 Functionality

Input Buffer Circuit	Inputs	- ¼” Male TRS audio signal input - 9V Battery/power supply voltage for TRS cable - Switch for accessing bypass circuitry
	Outputs	- Filtered voltage Signal
	Functionality	Creates a high input impedance to preserve signal integrity and aids in avoiding high frequency signal loss.
Clipping Amplifier	Inputs	- User set distortion adjustment knob position - Filtered voltage signal
	Outputs	- Asymmetrically clipped voltage waveform
	Functionality	Shapes the amount of clipping performed on the voltage signal and the frequency at which it occurs.
Tone Stage	Inputs	- User set tone adjustment knob position - Clipped voltage signal
	Outputs	- Adjusted cut-off frequency waveform
	Functionality	Adjusts the cut-off frequency allowing more or less treble/bass frequencies to pass in the signal.
Volume Stage	Inputs	- User set gain adjustment knob position - Equalized voltage signal
	Outputs	- Voltage signal with desired gain
	Functionality	Provides gain adjustment to the incoming voltage signal.
Output Buffer Circuit	Inputs	- Distorted voltage signal - Unaltered audio signal from bypass circuitry
	Outputs	- Audio signal via ¼” Male TRS audio output
	Functionality	Provides low output impedance to preserve signal integrity.
Bypass Circuit	Inputs	- Buffered audio input voltage signal - User controlled pedal switch
	Outputs	- Unaltered audio signal
	Functionality	Generates a bypass path for the signal via pedal push to allow the effect to be in an off state.

Chapter IV: Design Approach Alternatives

The primary choice in designing this distortion pedal lies in how the clipping of the incoming signal is performed in order to achieve the desired distortion sound. Many design approaches exist in introducing distortion to a guitar signal. One way is to overdrive one of the amplifiers to its supply rails somewhere in the signal chain in order to clip the audio signal. Similarly by cascading gain stages, the input signal can be driven to the supply rails of the op-amps in order to clip the waveform yielding a harsher sounding clipping quality [3].

Another simple way involves clamping the signal with diodes. By choosing the diode clipping route, numerous opportunities for waveform shaping alternatives exist. A preliminary design choice included diode clipping located at the output of the amplification stage as shown in **Figure 4.1**

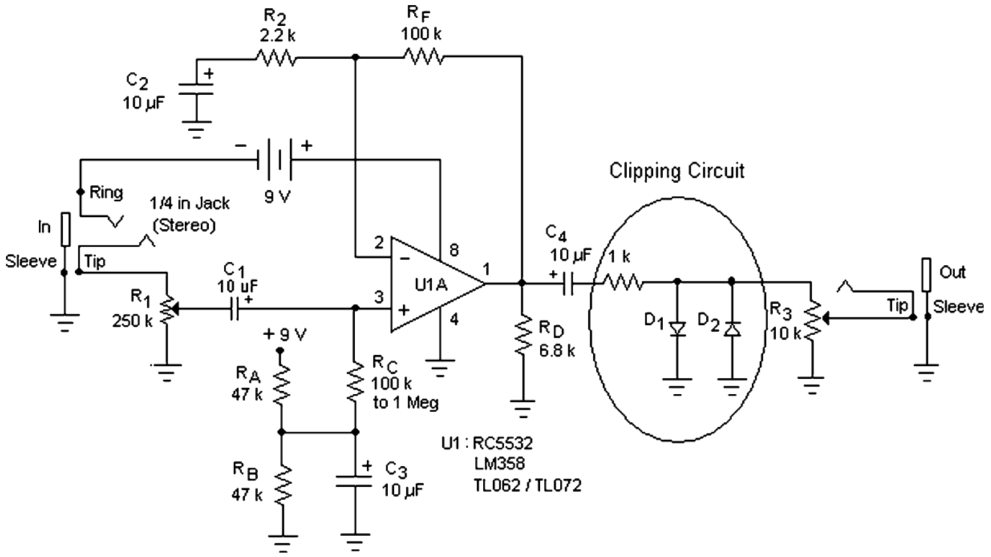


Figure 4.1: Distortion Circuit with Post-Amplification Diode Clipping [3]

This configuration results in what is typically known as hard clipping [8]. With a shunt diode configuration at the output, the voltage waveform becomes clamped at the forward voltage specification of the diodes causing a sharp or "hard" clipping of the output waveform.

Conversely a "soft" clipping of the waveform can be produced by placing diodes in the feedback network of the chosen op amp as shown in **Figure 4.2**.

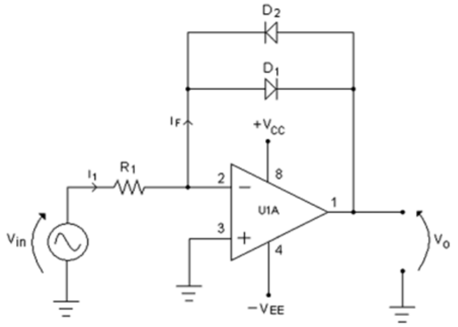


Figure 4.2: Distortion Circuit with Soft Diode Clipping [3]

This type of soft clipping affects the waveform more gradually than the hard clipping counterpart resulting in less harsher sounding tonal characteristics. Diode D_1 of **Figure 4.2** becomes forward biased during the positive swing of the AC input signal allowing current to flow while diode D_2 acts like an open. Conversely, during the negative half swing of the input the diode's roles are reversed. The typical output waveform due to soft clipping is represented in **Figure 4.3** where the edges observed take on a softer slope during clipping.

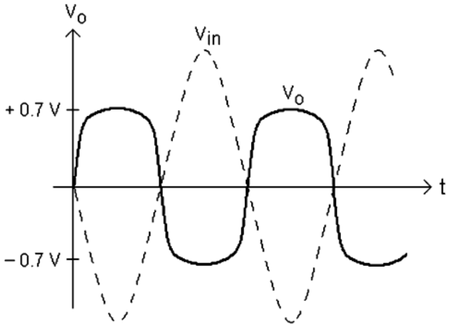


Figure 4.3: Output Waveform typical of "Soft" Diode Clipping [3]

For this project, diode soft clipping is the chosen approach to produce distortion. This is done by using diodes oriented in an anti-parallel configuration in the feedback of the gain stage similar to those shown in **Figure 4.2**. By using a mix of both germanium and silicon diodes in an anti-parallel configuration, the output waveform can be tailored to produce unique asymmetrical soft clipping to suit the design goal of vintage tube amp emulation.

Chapter V: Project Design

Circuit simulation software LTSpice was used to simulate the preliminary design layouts. A circuit was built modeling a basic dual op-amp distortion circuit similar to the Boss DS-1 or Ibanez Tube Screamer topology. The circuit consists of an input buffer, clipping stage, a tone and volume stage, and finally an output buffer. Values were swept, adjusted, and evaluated to produce reasonable results. Resistor networks were used to simulate the three potentiometers used in actual physical design. **Figure 5.1** displays the finalized overall schematic of the topology used for simulating the distortion circuit.

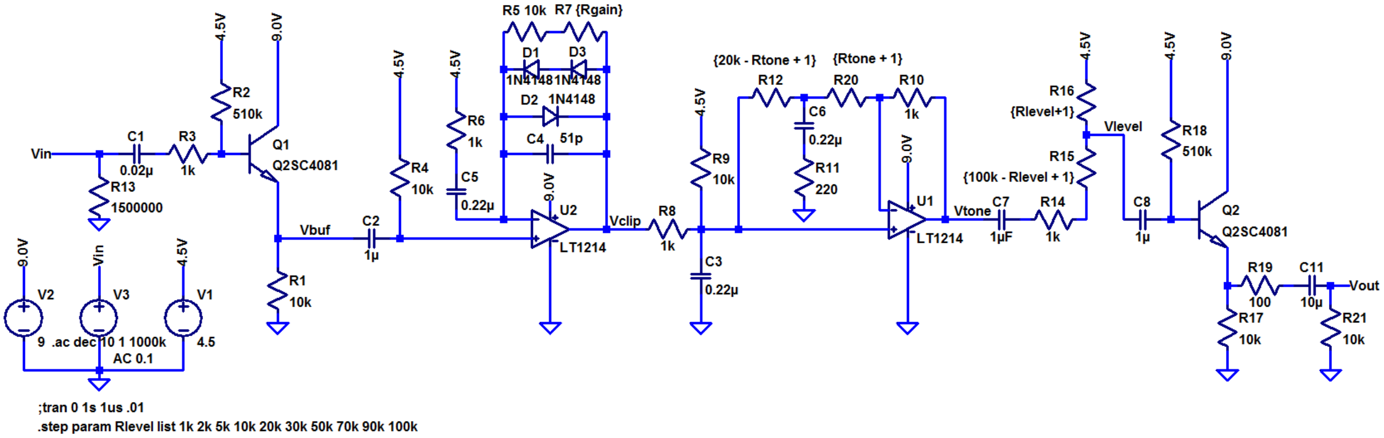


Figure 5.1: Final Schematic of the Distortion Circuit Used for Simulation

The overall circuit comprises several stages, each performing various modifications to the input signal sent from the guitar. These stages will be discussed in detail starting with the first stage of the overall circuit consisting of an input buffer.

The Input Stage

Before the guitar's small output signal (in the mV range) is sent to the clipping stage, the signal is sent through an emitter-follower (common collector) amplifier which serves as a voltage buffer to the guitar's signal [3]. By using a capacitor to inhibit the guitars lower frequencies and presenting a high input-impedance at the transistor base, noise (low frequency hum or popping) from the guitar signal is buffered. The schematic shown in **Figure 5.2** displays the circuit diagram of the unity gain input buffer used for the input of the design.

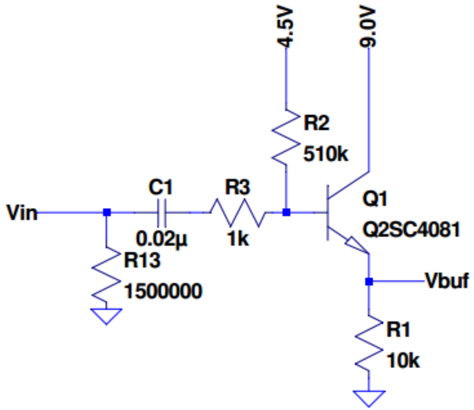
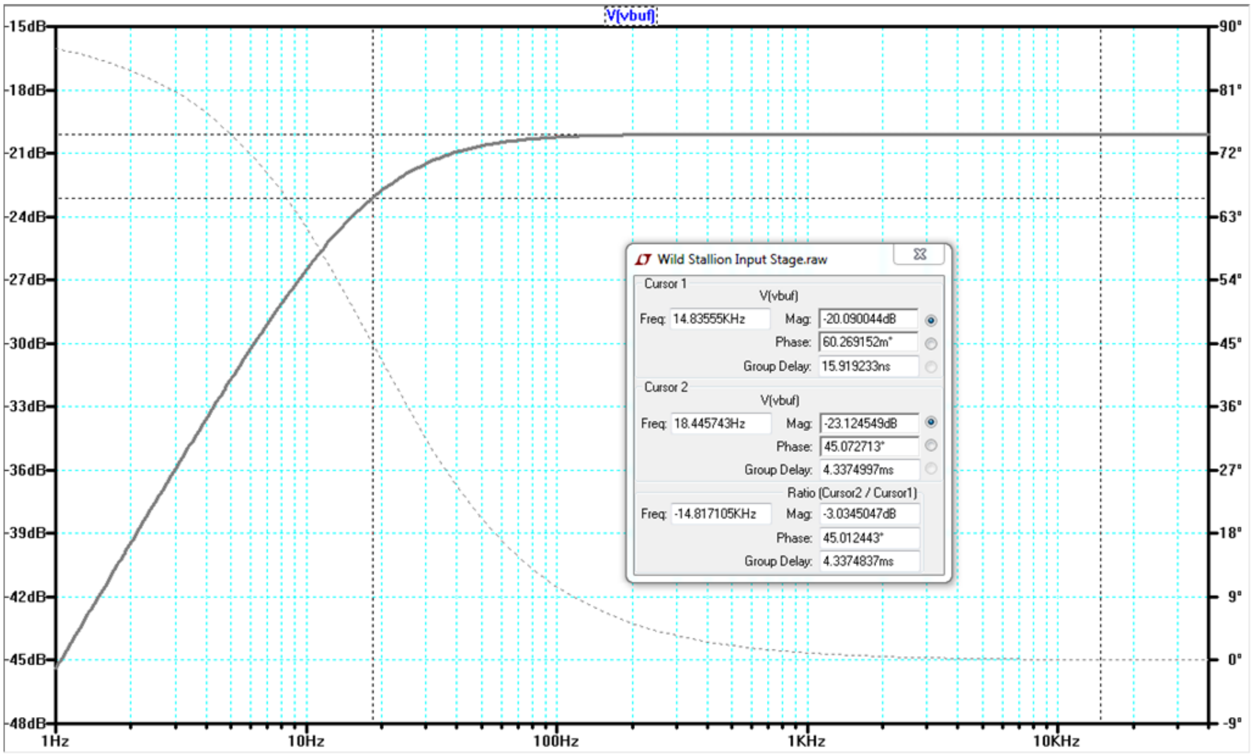


Figure 5.2: Distortion Circuit Input Stage

The input capacitor C_1 is used as a DC blocking capacitor separating direct current from the guitar. The input stage also serves as a high pass filter to prevent noise at low frequencies. Circuit loading is prevented by transforming the high input impedance to low output impedance through the NPN common collector for delivery to the clipping stage [4]. The resulting frequency response of the input stage shown in **Figure 5.3** exhibits that of a high pass filter.



Cursor 1
V(vbuf)
Freq: 14.83555KHz
Mag: -20.090044dB ●
Phase: 60.269152m° ○
Group Delay: 15.919233ns ○

Cursor 2
V(vbuf)
Freq: 18.445743Hz
Mag: -23.124549dB ●
Phase: 45.072713° ○
Group Delay: 4.3374997ms ○

Ratio (Cursor2 / Cursor1)
Freq: -14.817105KHz
Mag: -3.0345047dB
Phase: 45.012443°
Group Delay: 4.3374837ms

Figure 5.3: Frequency Response of the Input Stage

Figure 5.3 displays the Bode plot simulation results for the input Stage. The pass-band begins at approximately 18.45 Hz with the -3dB point, and the stop-band containing the lower frequencies. Simulation results indicate a successful unity gain input buffer acting as high pass filter effectively tapering off frequencies below 100Hz.

The Distortion Stage

The second stage of the design is the most significant portion of the circuit and is used to satisfy the required distortion specification to the signal. A non-inverting operational amplifier configuration is used as the basis for controlling the gain. The voltage signal from the input stage is routed to the positive terminal of the op-amp with the anti-parallel diode configuration comprising the feedback network that feeds into the negative terminal of the op-amp as shown in **Figure 5.4**.

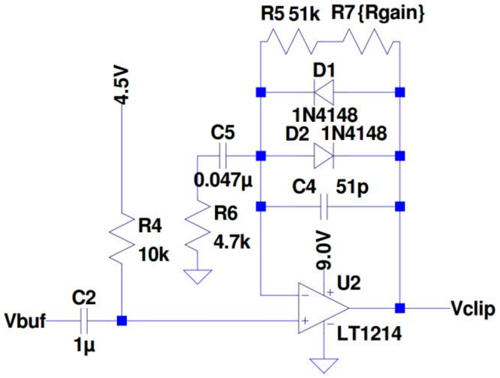


Figure 5.4: Distortion Circuit Clipping Stage

The feedback network consists of the anti-parallel diode configuration and contributes to the filter created by the addition of capacitor C_4, which contributes to setting the gain and responds like a short at higher frequencies to further inhibit lower frequencies.

The gain of the non-inverting op amp configuration is set for the design by increasing or decreasing the feedback resistance with a 500k potentiometer. For simulation purposes the R_{Gain} variable is used.

Figure 5.5 shows a simplified non-inverting operational amplifier.

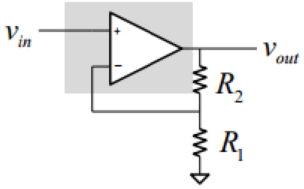


Figure 5.5: Non-inverting Amplifier [5]

Neglecting the diodes and the frequency dependant capacitors in the feedback network of **Figure 5.4**, the gain of this simplified non-inverting op-amp configuration can be derived from the transfer function and is mathematically related with the formula:

$$Gain = A = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1} \qquad \text{eq. 5.1}$$

Where R_1 and R_2 represent the values indicated in **Figure 5.4** as R_6 and R_5. By adding in a variable resistor in series with R_2 this equation becomes:

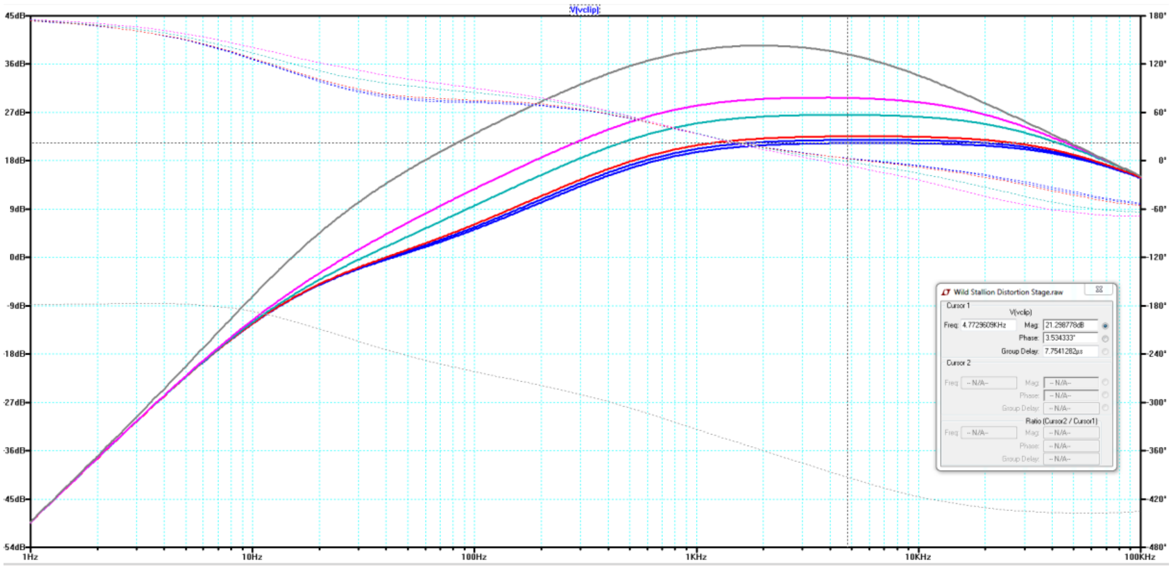
$$A = 1 + \frac{R_2 + R_{Gain}}{R_1} \qquad \text{eq. 5.2}$$

By substituting the chosen values of 4.7 kΩ and 51kΩ for R_1 and R_2 respectively and 500 kΩ for R_{Gain}, approximate values for the maximum and minimum gain can be estimated as follows:

$$A_{max} = 1 + \frac{51k\Omega + 500k\Omega}{4.7k\Omega} = 118.23 \rightarrow 20log(A_{max}) = 41.46\ dB$$

$$A_{min} = 1 + \frac{51k\Omega}{4.7k\Omega} = 11.85 \rightarrow 20log(A_{min}) = 21.48\ dB$$

Figure 5.6 shows a Bode plot for the simulated results, generated by sweeping the R_{Gain} variable. The resulting A_{max} and A_{min} are respectively close to 41 dB and 21 dB as shown.



Cursor 1
V(vclip)
Freq: 4.7729609KHz
Mag: 21.298778dB
Phase: 3.534333°
Group Delay: 7.7541282µs
Cursor 2
Freq: -- N/A--
Mag: -- N/A--
Phase: -- N/A--
Group Delay: -- N/A--
Ratio (Cursor2 / Cursor1)
Freq: -- N/A--
Mag: -- N/A--
Phase: -- N/A--
Group Delay: -- N/A--

Figure 5.6: Gain Sweep of the Distortion Stage Output

Further increasing the value of the 500kΩ potentiometer to 1MΩ and decreasing the value of R_6 and R_5 to 1kΩ and 10kΩ yields:

$$A_{maxNew} = 1 + \frac{10k\Omega + 1M\Omega}{1k\Omega} = 1010 \rightarrow 20log(A_{maxNew}) = 60.09\ dB$$

Figure 5.7 shows the frequency response of sweeping the R_{Gain} variable with the revised values. The new values yield an increased maximum gain approaching 60 dB and a broader dB range.

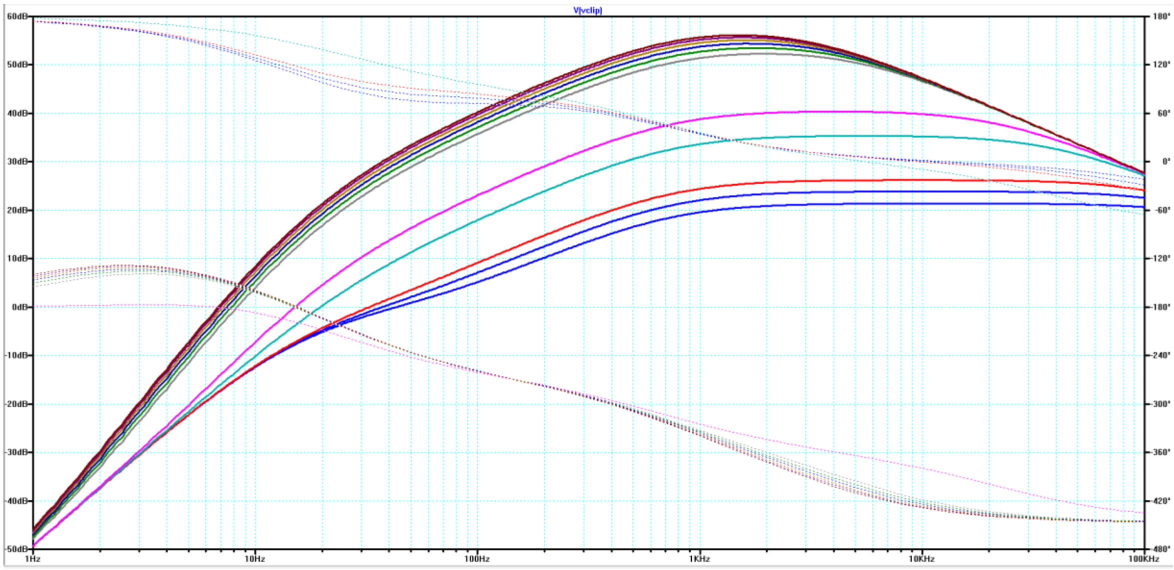


Figure 5.7: Gain Sweep of the Distortion Stage Output with revised values

Figure 5.8 shows the transient response for sweeping the R_{Gain} variable of the circuit with a .50 mV sinusoidal input at 200 Hz.

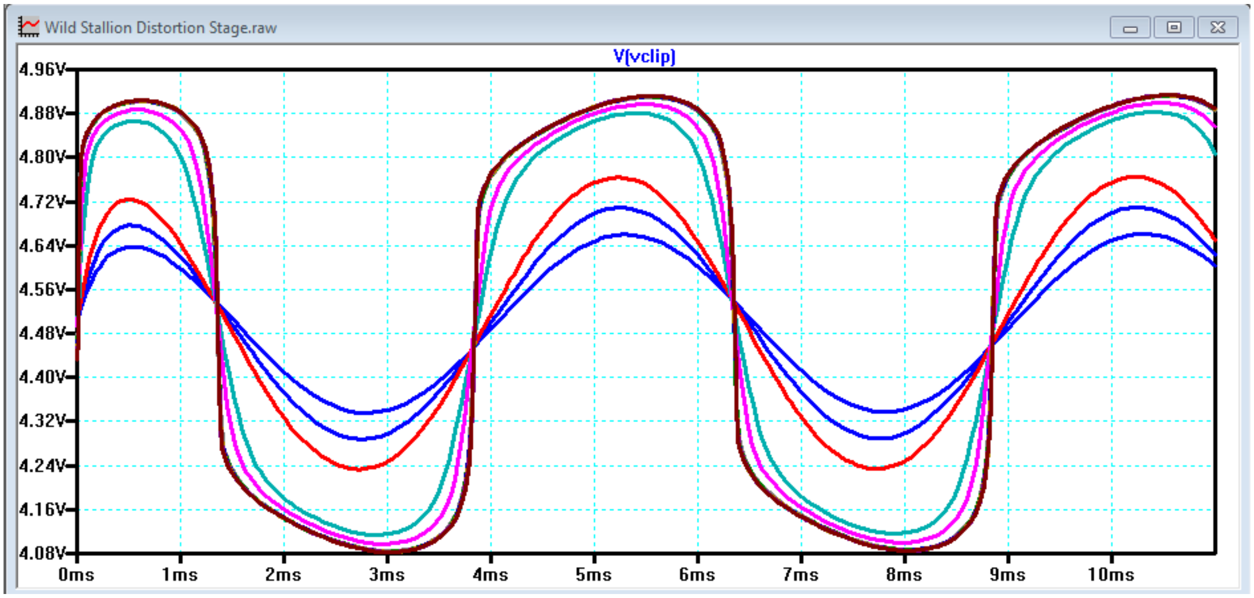


Figure 5.8: Transient Response of the Distortion Stage Output

The waveform in **Figure 5.8** depicts a soft clipped waveform that is symmetrical about the x and y axes.

By placing another diode in series in one of the parallel feedback pathways as shown in **Figure 5.9**, the waveform becomes asymmetrical and better produces a unique tube amplifier sound to satisfy requirements set forth in the engineering specifications.

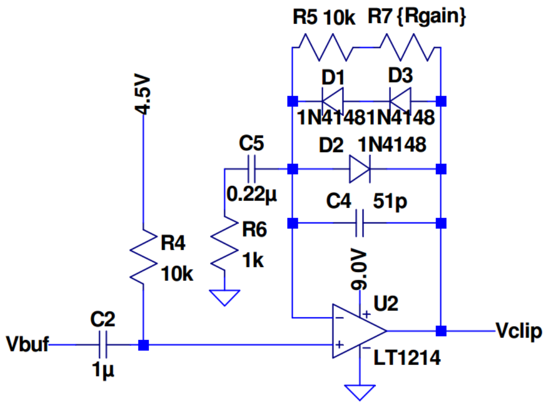


Figure 5.9: Distortion Circuit Clipping Stage with Added Diode and Revised Values

As shown in **Figure 5.10**, the added diode yields an asymmetrical waveform where the positive half swing of the AC output varies significantly from the lower portion. The result during the bread-boarding and audible testing phase is a tone with a fuller sound, more warmth and a seemingly increased bass response.

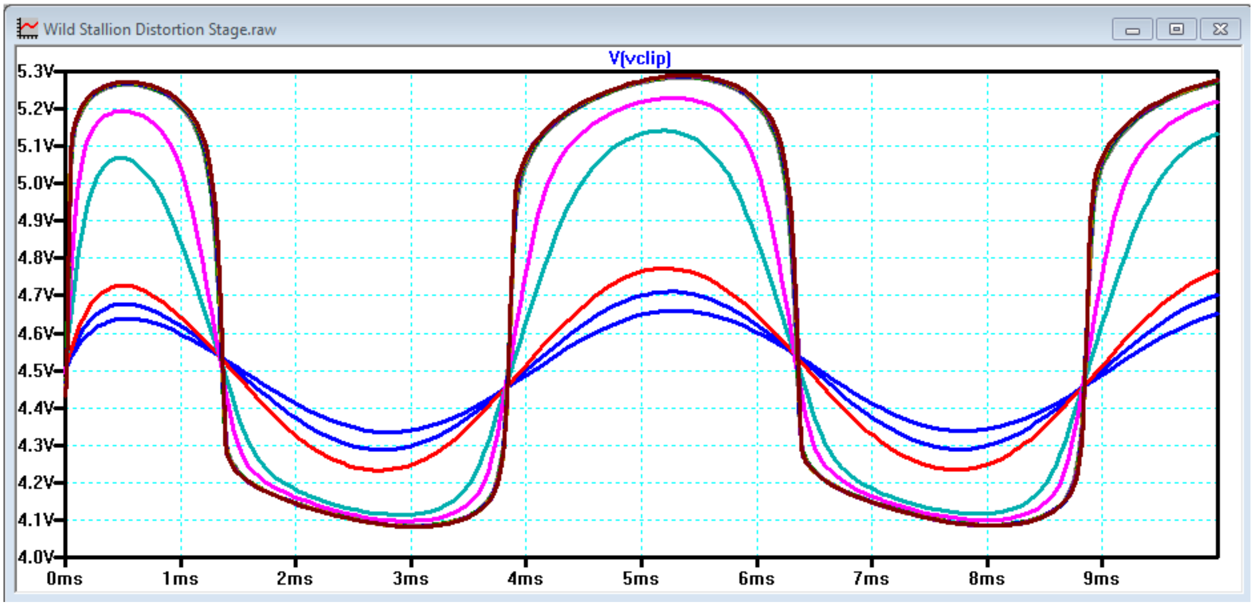


Figure 5.10: Transient Response of Distortion Circuit with Added Series Diode

The Tone and Volume Stage

The tone circuit displayed in **Figure 5.11** is modeled similarly to the Ibanez Tube Screamers TS808 model **[14]**.

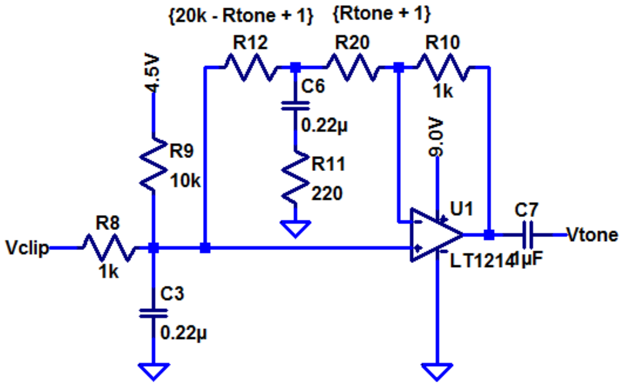


Figure 5.11: Distortion Circuit's Tone Stage

R_{12} and *R_{20}* are used in simulation to model a 20 kΩ potentiometer .The input to the tone stage contains a passive low pass filter consisting of R_8 and C_3 with a cutoff frequency of 723.43 Hz.

$$f_{cutoff} = \frac{1}{2\pi R_8 C_3} = \frac{1}{2\pi * 1000\Omega * .22\mu F} = 723.43\ Hz$$

The R_{11} and C_6 network create another low pass filter or a high pass filter to limit frequencies depending on the 20 kΩ potentiometer's position. With the potentiometer rotated to both extremes, the circuit's outputs yields that of **Figure 5.12**.

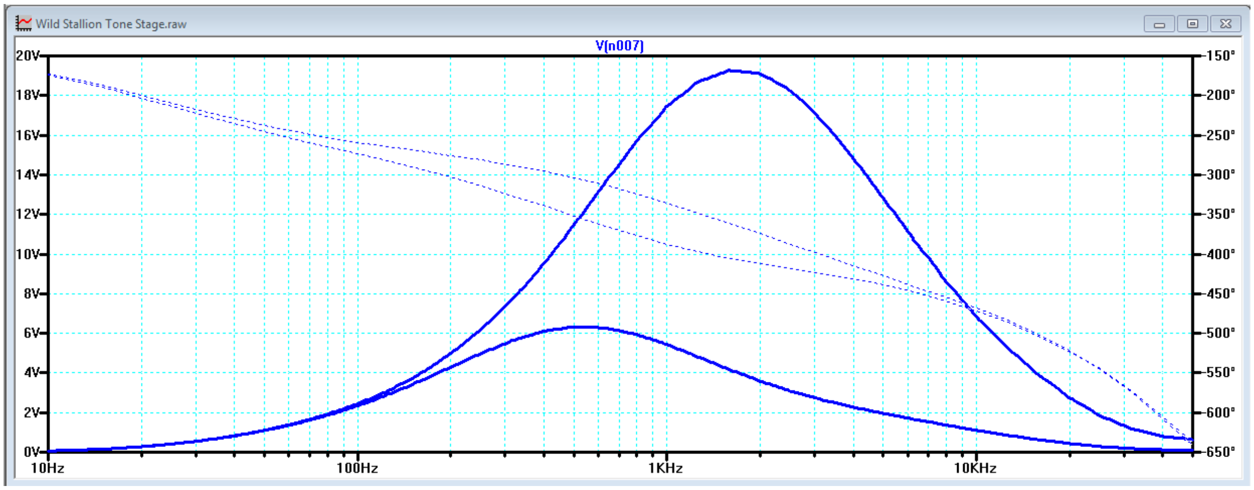


Figure 5.12: Extremes of the 20 kΩ Potentiometer for the Tone Stage

With the potentiometer rotated fully counter clockwise (brown trace of **Figure 5.13**), the R_{11} and C_6 network act as a low pass filter inhibiting higher frequencies .With the potentiometer rotated fully clockwise (red trace of **Figure 5.13**), the network results in a band pass type filter as shown in **Figure 5.12** and **Figure 5.13**. The full parametric sweep for the potentiometer from 1k to 20 kΩ is shown in **Figure 5.13**. A dB scale is shown for reference in **Figure 5.14**.

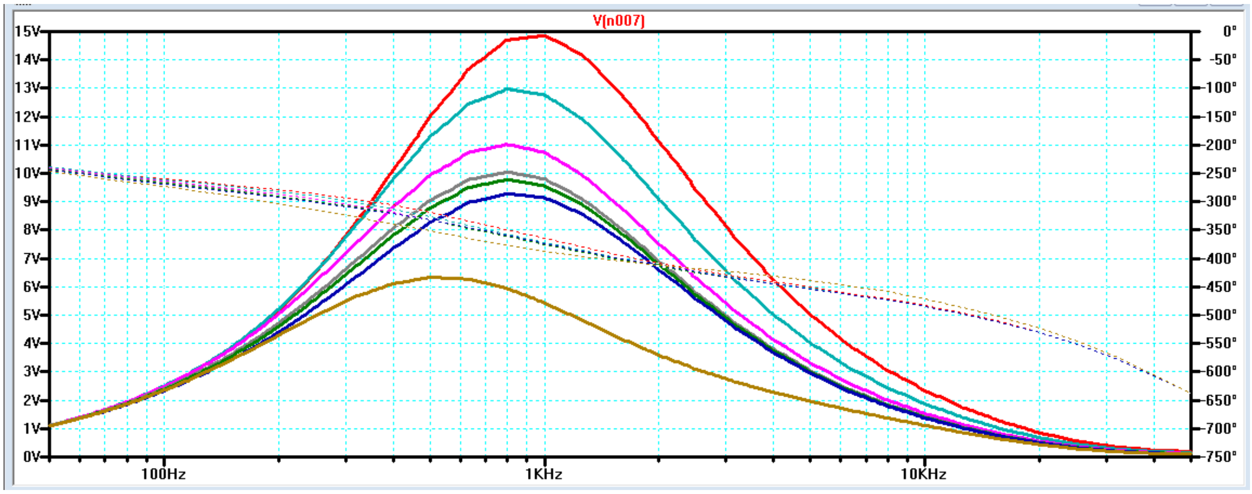


Figure 5.13: Full Parametric Sweep of the 20 kΩ Potentiometer for the Tone Stage

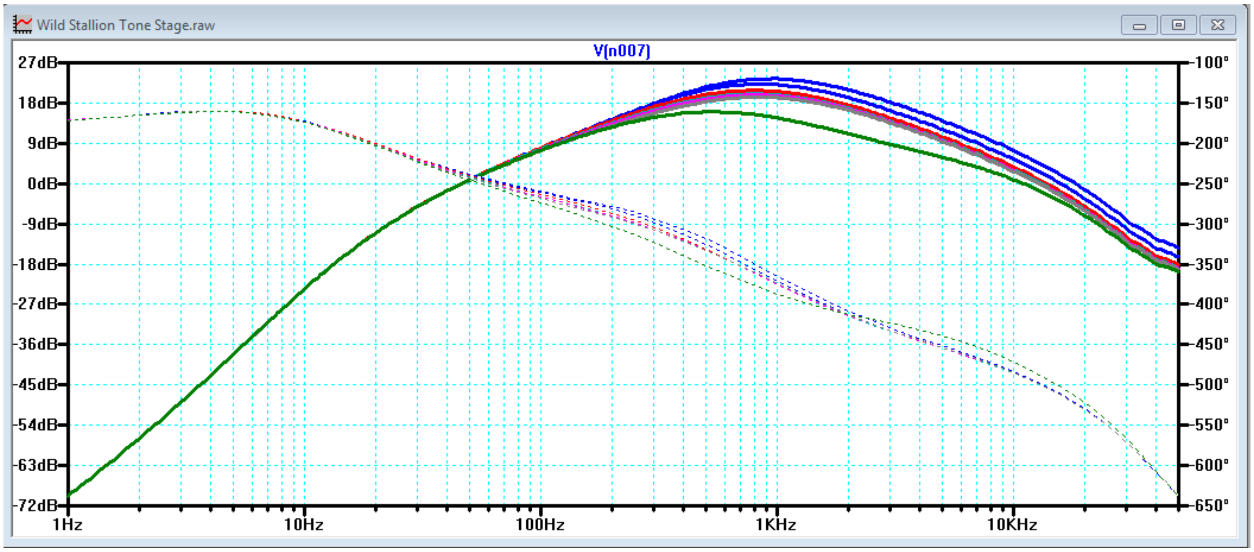


Figure 5.14: Full Parametric Sweep of the 20 kΩ Potentiometer in dB scale

The Volume stage shown in **Figure 5.15** is controlled by a 100 kΩ linear potentiometer that inhibits a portion of the input signal depending on the potentiometer's position.

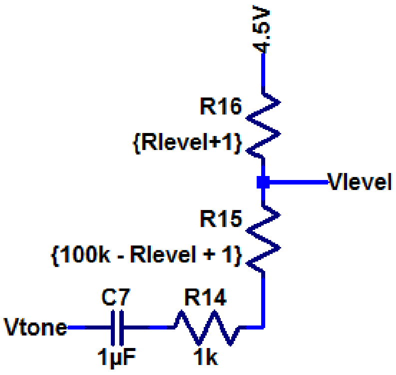


Figure 5.15: Distortion Circuit's Volume Stage

Figure 5.16, **Figure 5.17**, and **Figure 5.18** display output results of the volume stage. R_{15} and R_{16} are used in simulation to model the 100 kΩ potentiometer in a fashion similar to the tone stage. By sweeping the values for R_{15} and R_{16}, the 100 kΩ potentiometer is modeled and results are produced as shown.

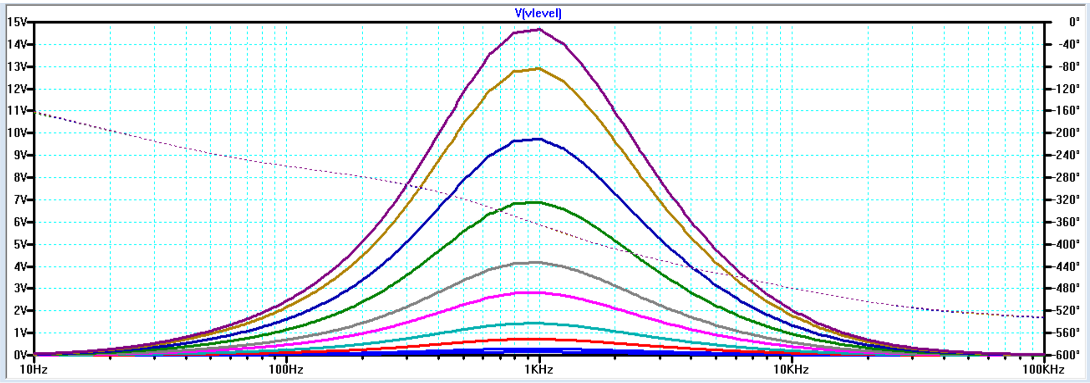


Figure 5.16: Parametric Sweep of the Volume Stage (in Volts)

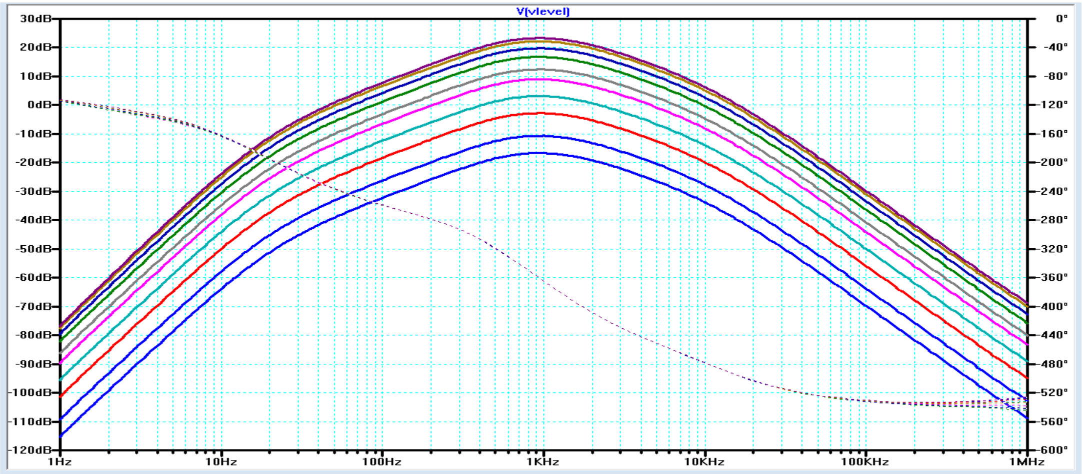


Figure 5.17: Parametric Sweep of the Volume Stage (in Db)

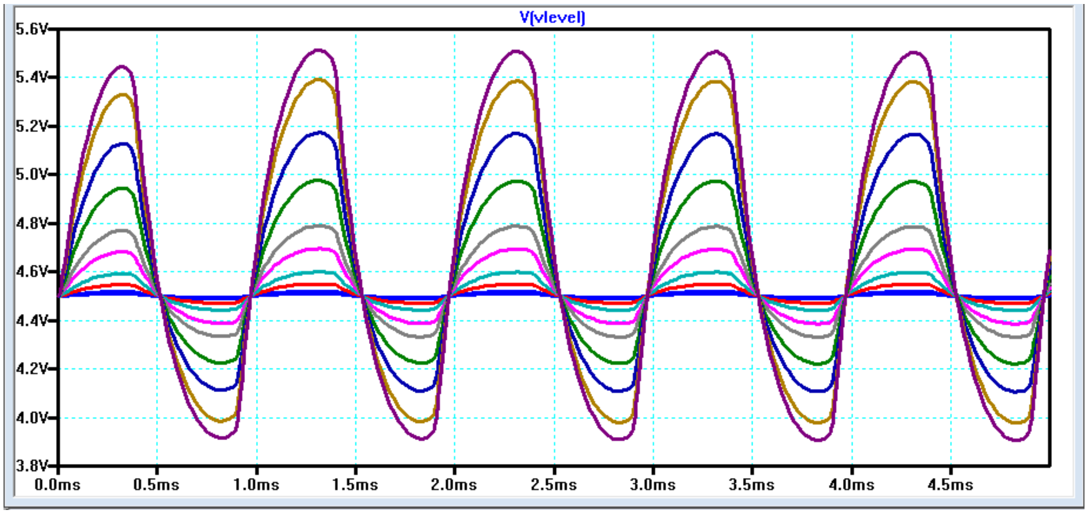


Figure 5.18: Transient Response of the Volume Stage Output

The Output Stage

Similar to the input stage, the output stage of **Figure 5.19** consists of an emitter follower that serves as a high pass filter and provides unity gain [21]. Conditioning of the signal and a low output impedance aid to preserve the signal and set up for delivery to an amplifier.

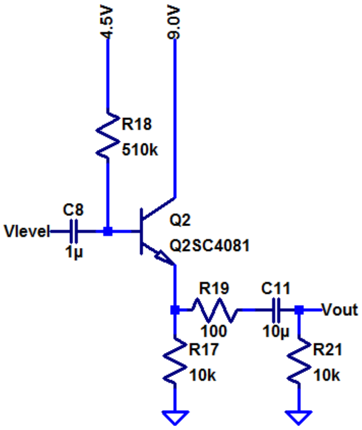


Figure 5.19: Distortion Circuit Output Buffer

The low output impedance of the NPN common collector also serves to prevent circuit loading [4], producing a well-conditioned signal upon delivery to an amplifier.

Simulations were conducted along with the breadboard design phase in Chapter VI. Topologies and values were updated in simulation concurrent with any changes in the breadboard design process to ensure consistency and reflect the final circuit as shown in **Figure 5.1**.

Chapter VI: Physical Construction and Integration

To facilitate development of the Wild Stallion Distortion Pedal, preliminary designs were physically constructed onto a breadboard to enable audible testing of the circuit and allow for ease-of-use in changing component values. **Figure 6.1** and **Figure 6.2** show the early developmental stages of the pedal's design.

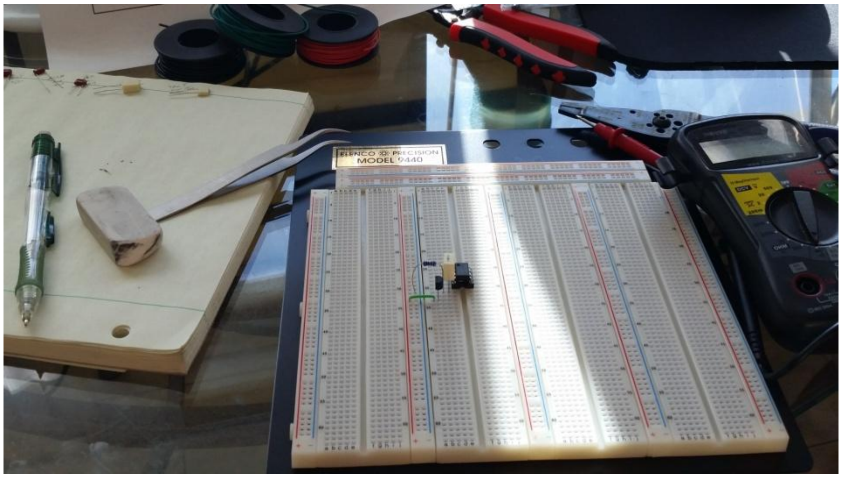


Figure 6.1: Preliminary Breadboard Design

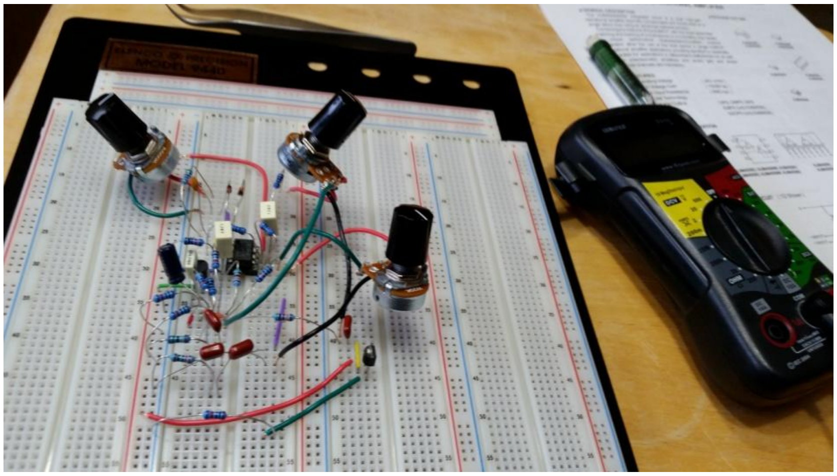


Figure 6.2: Intermediate Breadboard Design

For physical construction, potentiometers were used in place of the resistor networks utilized in simulation and a 9V battery was used as the 9V DC source with a resistor divider network (10kΩ and 10kΩ) used to obtain the reference voltage of approximately 4.5V to bias the circuit. By-pass capacitors [19] were used to remove unnecessary AC ripple present on the DC supply signal. **Figure 6.3** represents the power supply network used in physical implementation.

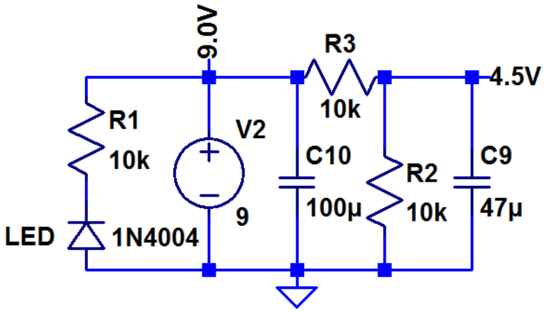


Figure 6.3: Schematic of the Power Supply Network

Figure 6.4 displays the schematic used for wiring the 3PDT switch and the TRS ¼" input (stereo) and output (mono) jacks [3]. With the circuit design implemented onto a breadboard shown in **Figure 6.5**, audible testing was performed to evaluate the sound of the circuit in its intended application.

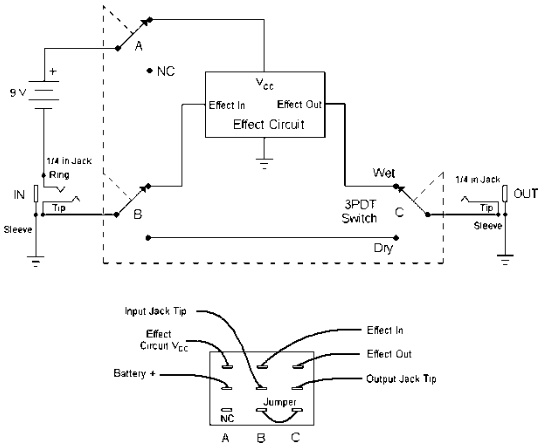


Figure 6.4: Schematic for the 3PDT Switch, Input, and Output Jacks [3]

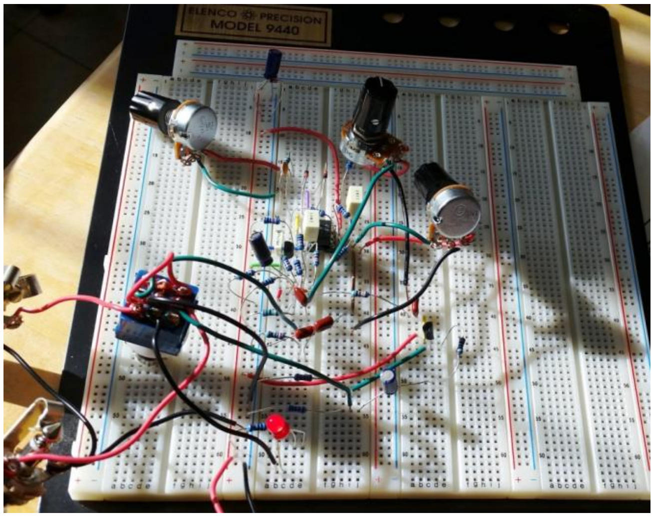


Figure 6.5: Functional Breadboard Design

Audible testing was conducted using a Fender Stratocaster electric guitar and a small Crate KX-15 amplifier shown in **Figure 6.6**.

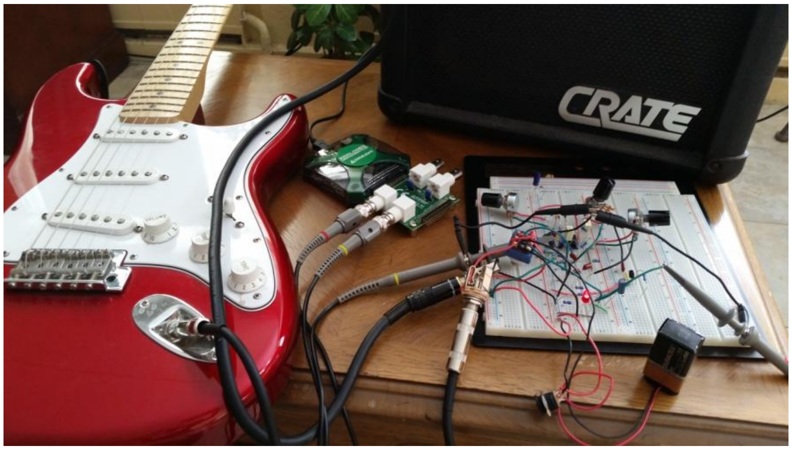


Figure 6.6: Application Testing Using a Fender Stratocaster and Crate KX-15 Amplifier

Audible results with the initial design yielded acceptable sound quality. However, design revisions were made during this stage of the design process to produce a warmer and fuller sound quality. Changes included adding a series diode to one of the diode feedback branches (discussed in Chapter V) and swapping values of C_5, R_5 and R_6 to achieve a more unique sound. Changing the values of R_5 and R_6 from 51 kΩ and 4.7 kΩ to 10 kΩ and 1 kΩ and lowering the capacitance of C_5 to .22 µF from .047 µF suppressed the brittle sounding and higher tonal qualities and produced more bass and mid-range sounding tonal characteristics as a result. The addition of the series diode gave the design a far more unique sound quality.

The next phase of the design process required the Wild Stallion Distortion pedal's final circuit layout to consist on a printed circuit board (PCB). Eagle PCB design software was used to facilitate transfer of the design to a PCB. **Figure 6.7** displays the design made in the Eagle's Schematic software.

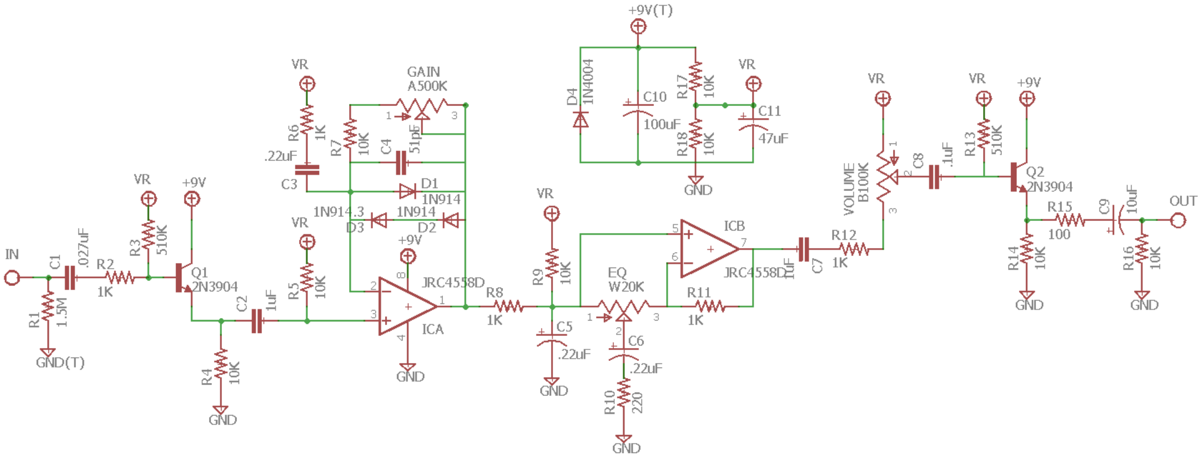


Figure 6.7: Design Layout in Eagle Schematic

With the design laid out, carefully inspected, and tested using the software's analysis, the schematic was transferred to a board layout. Elements were arranged to allow proper spacing of the traces and to exist within the confines of the chosen board dimensions. The board's dimensions of 1.4" x 2.5" ensure the PCB to fit inside a chosen enclosure. **Figure 6.8** shows the PCB layout in the Eagle CAD software.

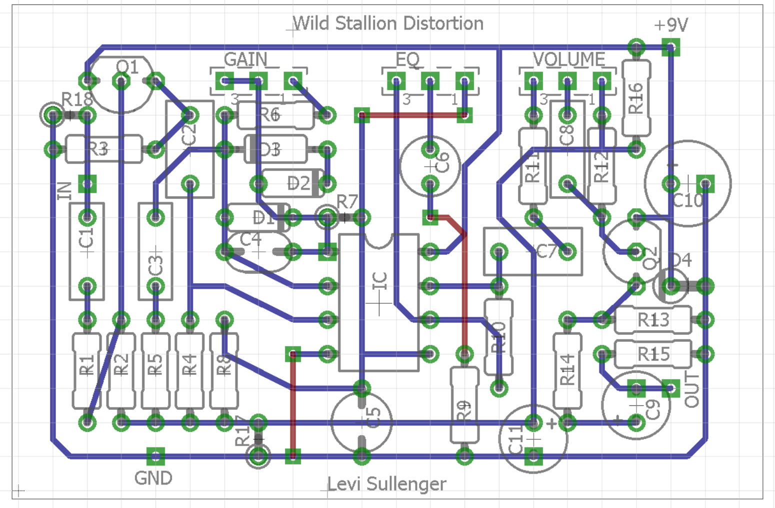


Figure 6.8: PCB Layout in Eagle Schematic

Gerber files were then generated and sent to printed circuit board manufacturer Advanced Circuits at www.4pcb.com for the PCB's assembly [22]. Three boards were ordered in case of manufacturing defect or the event of soldering error. **Figure 6.9** shows the printed circuit board upon arrival.

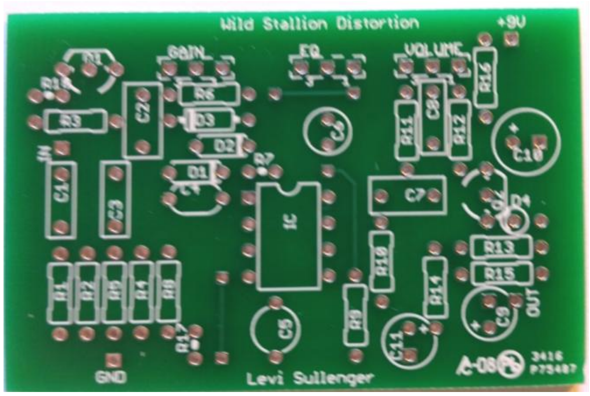


Figure 6.9: Printed Circuit Board From Advanced Circuits

Once the PCB's arrived, the routes were verified using a multi-meter to check the conductivity of the traces **Figure 6.10**.

Figure 6.10: Verifying Conductivity of Printed Circuit Board Assembly

Components are then soldered into respective places and cross referenced using **Figure 6.11**. **Figure 6.12** shows the PCB with elements soldered in place during the assembly and build phase.

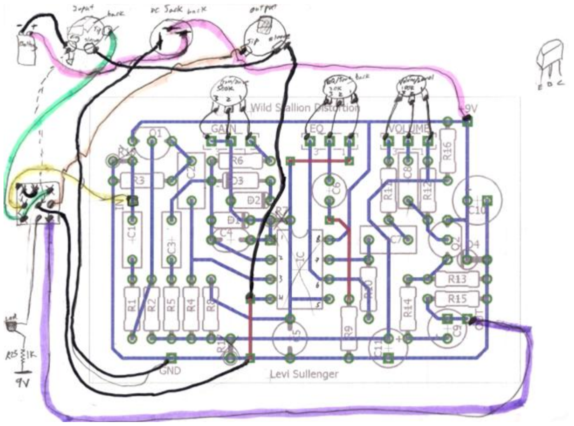


Figure 6.11: Diagram Used for Soldering and Wiring Components

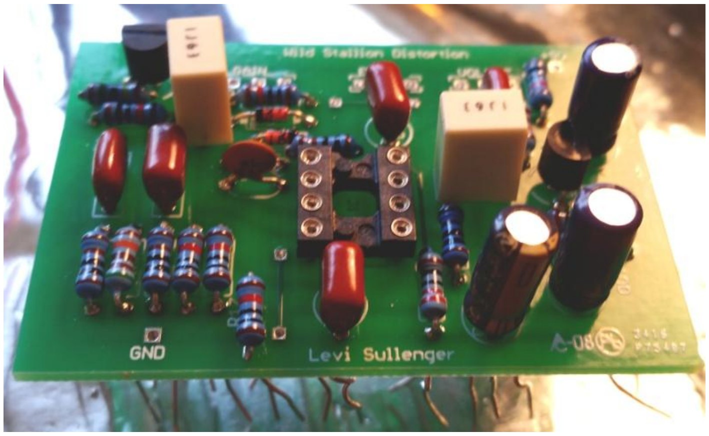


Figure 6.12: PCB with Soldered Components

Figure 6.13 shows the enclosure with drilled out holes marked and ready for assembly. With the PCB Components soldered into place, the 3PDT switch, LED, Jacks, Potentiometers, and battery cables are mounted and secured inside the enclosure as shown in **Figure 6.14**.

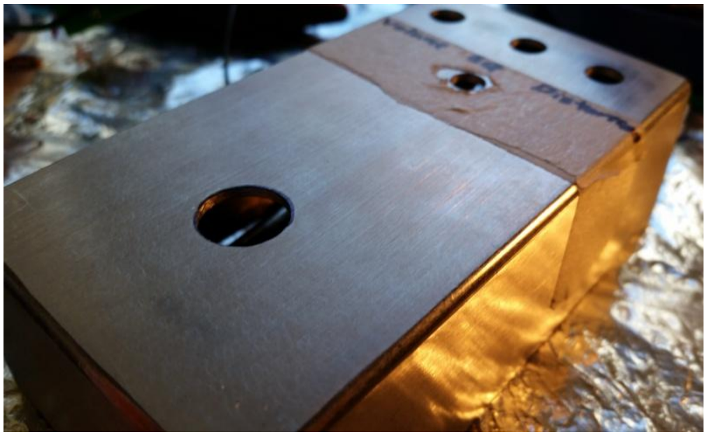


Figure 6.13: Drilled Enclosure Ready for Assembly

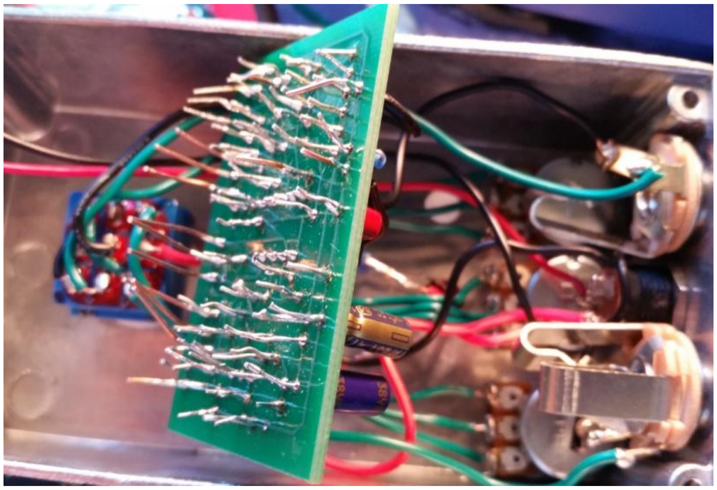


Figure 6.14: Components Mounted and Assembled Inside Enclosure

A high-gloss, green, metallic automotive paint was selected to stylize the enclosure. Potentiometers, jacks, and the switch were masked off and the paint was applied. Note: In future builds, the enclosure needs the paint application prior to component installation in order to expedite the process and to prevent uneven coating of the paint. **Figure 6.15** displays the enclosure upon completion of the paint application.

Figure 6.15: Enclosure with Paint Applied

A decal of a horse and a Cal Poly logo was used for the pedal’s exterior design. Decals were placed onto the pedal along with the Wild Stallion Distortion title and user control indicators. Finally a clear coat is applied to the pedal to enhance the gloss and protect the decals. The pedal in finished form is shown in **Figure 6.16**.

Figure 6.16: The Wild Stallion Distortion Pedal

Chapter VII: Integrated System Tests and Results

To ensure proper functionality for each stage, the circuit outputs are tested at necessary stages. Circuit measurements are made using the Analog Discovery2 oscilloscope and instrumentation system. Transient and frequency response characteristics are examined to confirm proper behavior of the circuit.

At the output of the clipping stage, the Analog Discovery 2 is connected and the drive Potentiometer is evaluated at its high and low extremes. The output results shown in **Figure 7.1** and **Figure 7.2** are for a sinusoidal input of 100 mV amplitude and 1 kHz frequency.

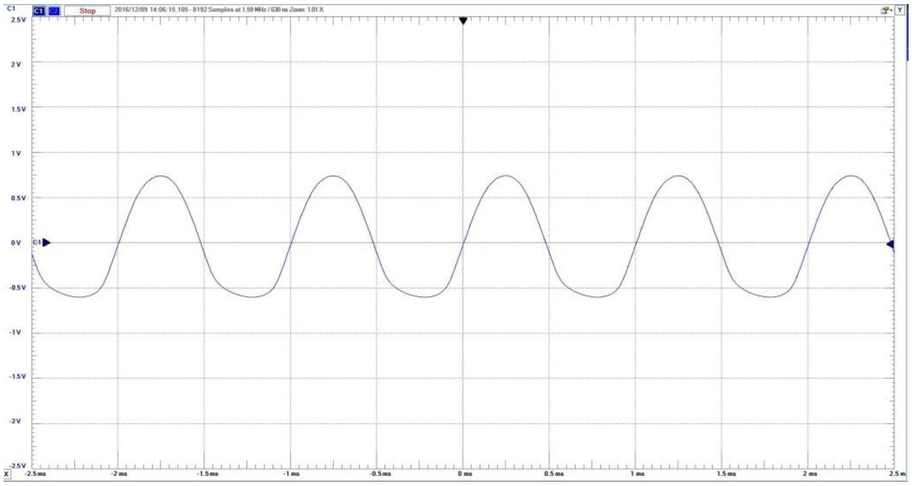


Figure 7.1: Output of the Clipping Stage with Drive Pot at Minimum

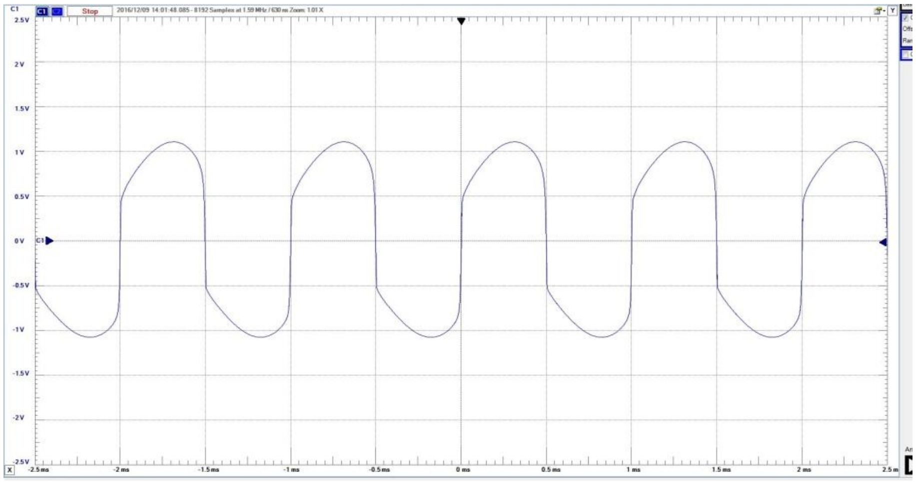


Figure 7.2: Output of the Clipping Stage with Drive Pot at Maximum

Figure 7.1 and **Figure 7.2** contrast the effects of the potentiometer's position. **Figure 7.1** displays a more symmetrical sinusoid when the potentiometer is completely down. **Figure 7.2** displays a more asymmetrical sinusoid with the drive potentiometer at its max. The results are similar to the transient response performed during simulations (**Figure 5.8**) indicating a successful Clipping stage.

When tested using the low E-string of an actual guitar as the input, the asymmetrical results of the added diode of (**Figure 5.10**) become more apparent as shown in **Figure 7.3**.

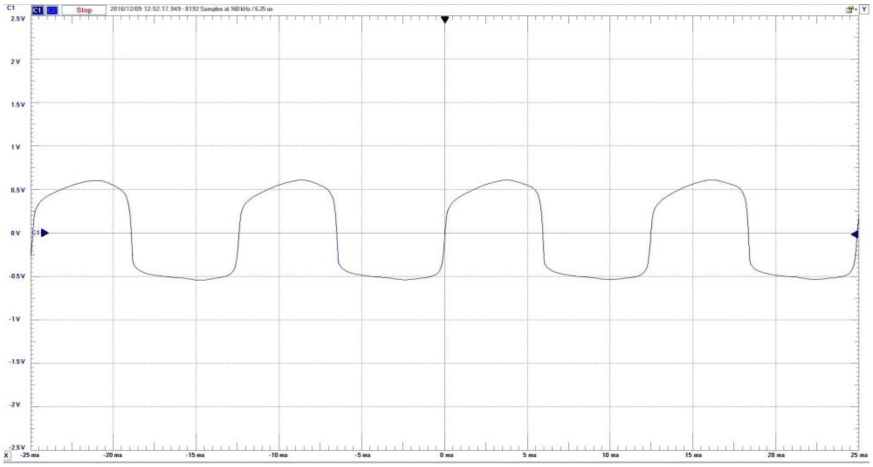


Figure 7.3: Output of the Clipping Stage Using a Guitar Input with the Drive Pot at Max

Figure 7.4 shows the output results of the guitar's low E-string input with the drive potentiometer at its minimum.

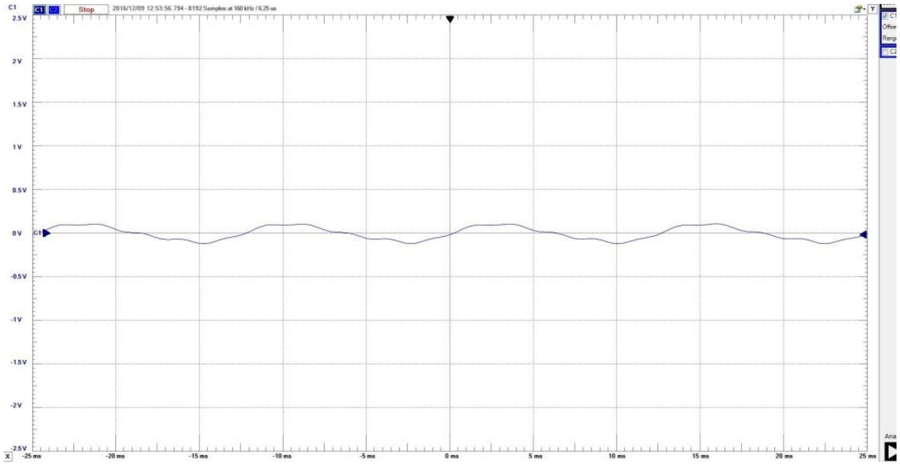
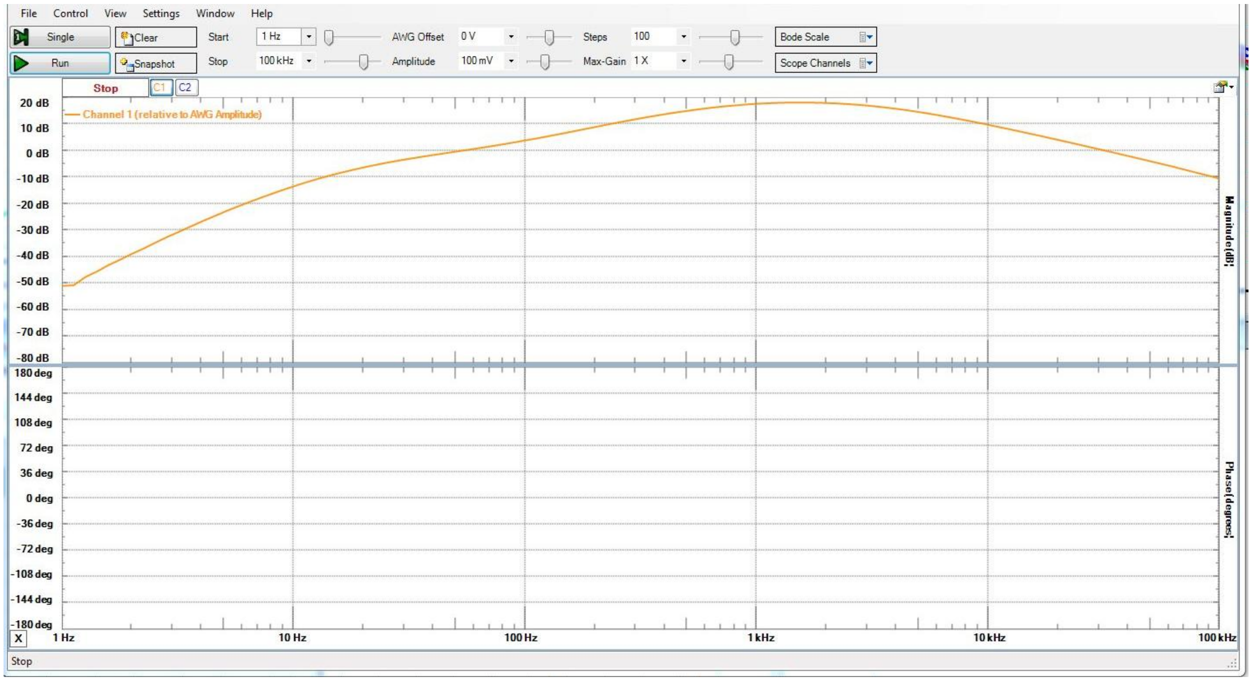


Figure 7.4: Output of the Clipping Stage Using a Guitar Input with the Drive Pot at Min

The output of the tone stage is tested next to verify its proper response to the tone control potentiometer. The output results are shown for the potentiometer at both extremes in **Figure 7.5** and **Figure 7.6**. The input again is a sinusoidal input of 100 mV amplitude and 1 kHz frequency.



Start 1 Hz

Stop 100 kHz

AWG Offset 0 V

Amplitude 100 mV

Steps 100

Max-Gain 1 X

Figure 7.5: Output of the Tone Stage with the Tone Potentiometer at Max

The frequency response in **Figure 7.5** shows a maximum approaching 20 dB with the tone potentiometer at its highest position. **Figure 7.6** shows a minimum of 10 dB with the tone potentiometer at its lowest position.

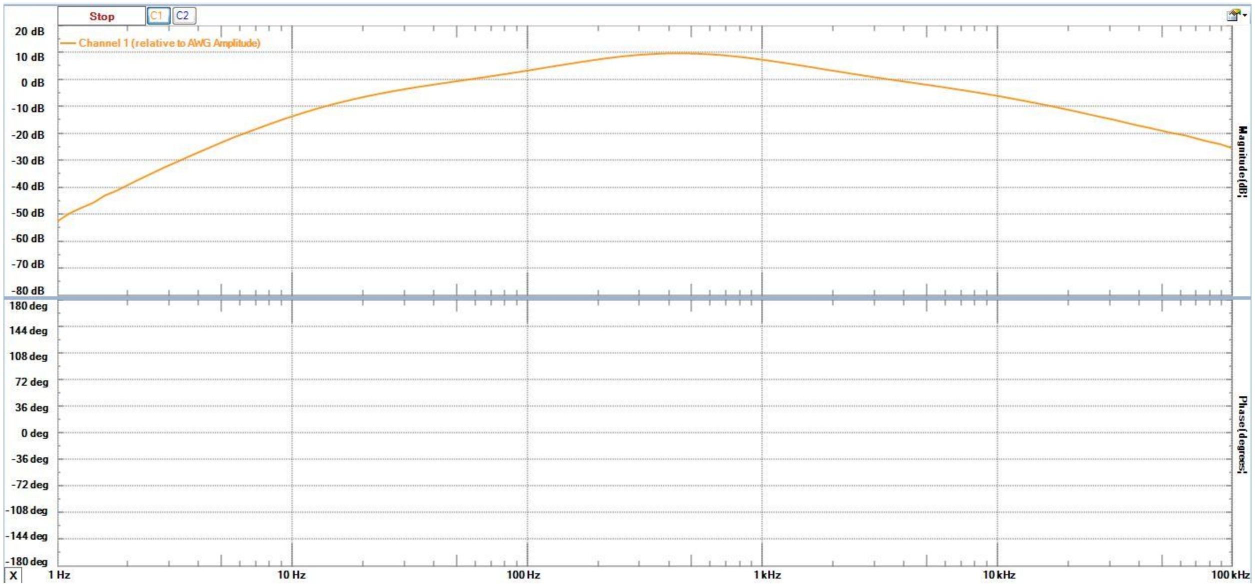


Figure 7.6: Output of the Tone Stage with the Tone Potentiometer at Min

The output results of the tone stage correspond well with the simulation results of Chapter V (**Figure 5.14**) indicating a correctly implemented tone response circuit.

The transient response for the output of the volume stage is shown in **Figure 7.7** and **Figure 7.8**. The same sinusoidal input of 100 mV amplitude and 1 kHz frequency is used again.

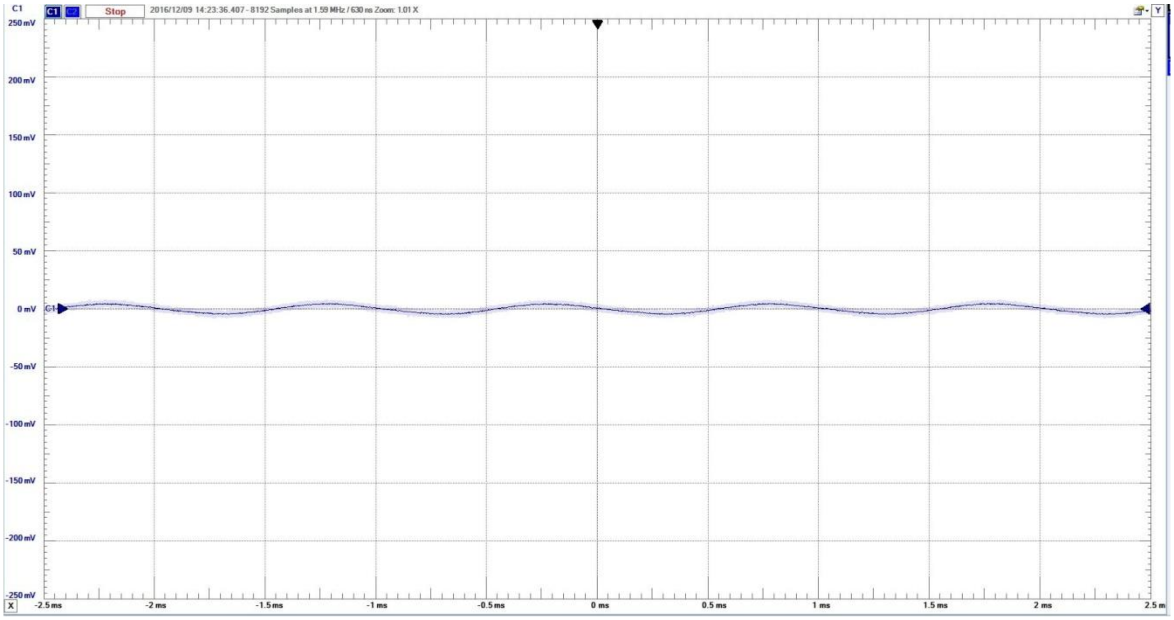


Figure 7.7: Output of the Volume Stage with the Volume Potentiometer Approaching Minimum

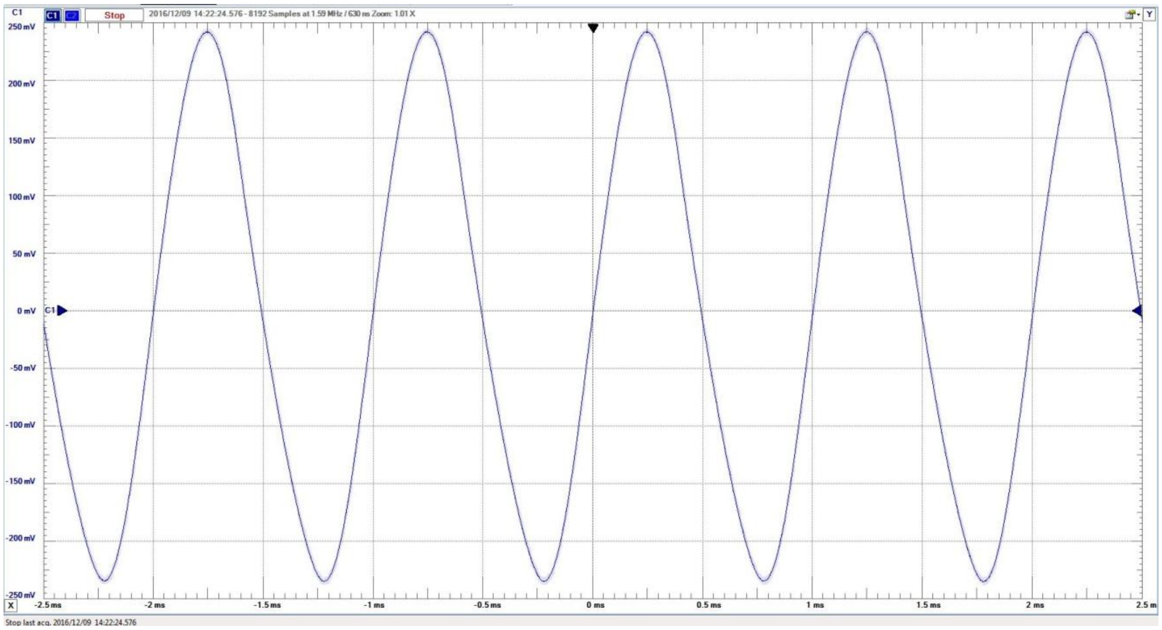


Figure 7.8: Output of the Volume Stage with the Volume Potentiometer at Maximum

Figure 7.9 displays the output of the entire circuit for the low E-string of the guitar with all the potentiometers at their maximum positions.

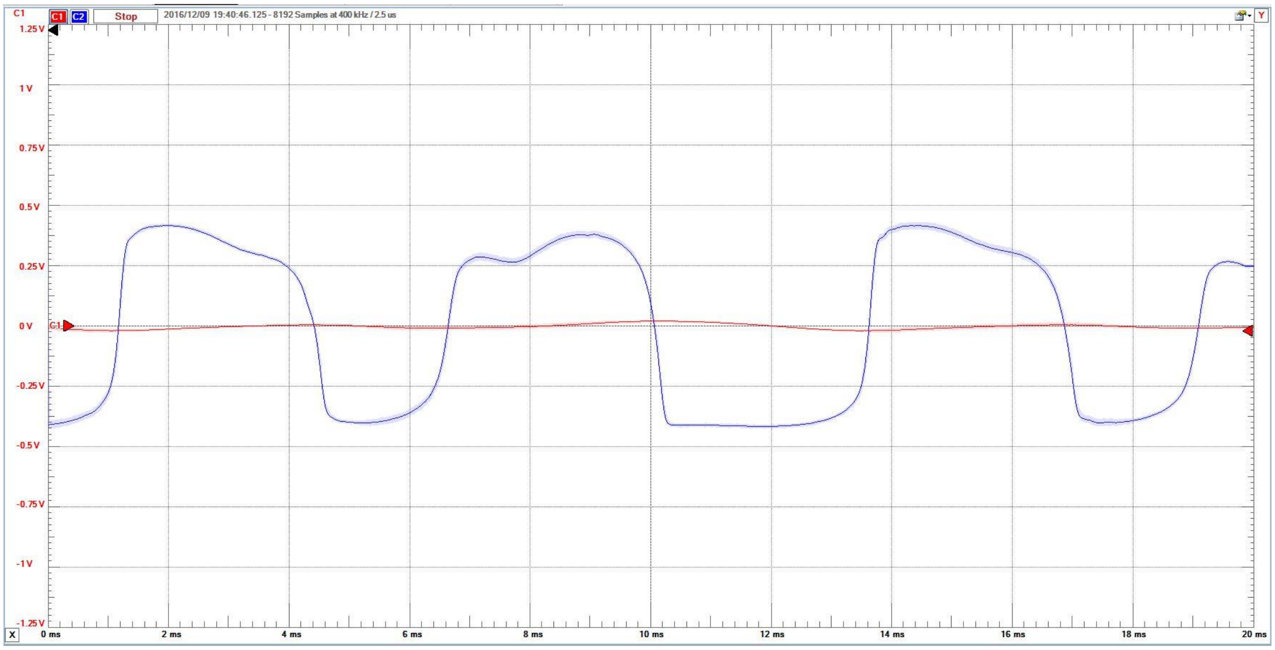


Figure 7.9: Circuit Output with All Potentiometers at Maximum Positions

The input (shown in red) in **Figure 7.9**, is the guitar signal read directly from the guitar cable. The output (shown in blue) is the output of the overall circuit. The waveform produced is asymmetrical about the x and y axes satisfying design criteria and producing a desirable sound reminiscent of a tube amplifier.

Current Draw and Battery Life

By connecting a multi-meter in series with the battery negative terminal the current draw is measured for the pedal for both its active mode and bypassed mode of operation in order to determine the total runtime of the effect pedal. The values found were: 8.48mA for the active mode's current draw and 4.75 mA for the bypass mode's current draw. The rated battery capacity at 580 mAh is found from the battery's datasheet [18]. The total runtime (*TR*) for the pedal in bypassed mode is then determined as follows:

$$\boldsymbol{TR_{Bypass\ Mode}} = \frac{\boldsymbol{Rated\ Battery\ Capacity\ (mAh)}}{\boldsymbol{Measured\ Current\ Draw\ (mA)}} = \frac{\mathbf{580}\ \boldsymbol{mAh}}{\mathbf{4.75}\ \boldsymbol{mA}} = \mathbf{122.11}\ \boldsymbol{hours} \cong \mathbf{5}\ \boldsymbol{days}$$

Similarly for the active mode:

$$\boldsymbol{TR_{Active\ Mode}} = \frac{\mathbf{580}\ \boldsymbol{mAh}}{\mathbf{8.48}\ \boldsymbol{mA}} = \mathbf{68.40}\ \boldsymbol{hours} \cong \mathbf{2.85}\ \boldsymbol{days}$$

While the results fully satisfy the engineering specifications presented in Chapter II, the parasitic current draw of 4.75 mA in bypassed mode is something to be addressed in future designs to allow the circuit to be more efficient during bypass mode and conserve power.

Product Specifications

Table 7.1 displays the Wild Stallion Distortion Pedal's product specifications.

Table 7.1 Product Specifications

Power Supply	1 x 9V Battery or external AC adapter
Battery Type	9V
Battery Life	68.40 hrs (active) 122.11 hrs (bypass)
Active Mode Current Draw	8.48 mA
Bypass Mode Current Draw	4.75 mA
Enclosure Dimensions	4.75 in x 2.5 in x 1.5 in
Max Gain	+ 26 dB
Weight	2.6 lbs

Test Plan

The following test plan is used to determine that the final product satisfies the major design goals and requirements set forth in **Table 2.1**.

TC1 - Verify conductivity of PCB traces.
TC2 - Power the circuit using a 9V battery and external AC adapter to ensure unit is powered correctly.
TC3 - Test and evaluate controllability of all potentiometers.
TC4 - Conduct audible testing to ensure a desired sound.
TC5 - Evaluate current draw in active and bypass modes of operation.
TC6 – Perform visual inspection to satisfy aesthetic features and to ensure secure connections.
TC7 – Weigh the pedal on a scale to ensure a weight of less than 5 lbs.
TC8 – Stand on the pedal for approximate durability to withstand external pressure.
TC9 – Evaluate production cost to ensure per unit price of less than $175.00

The testability matrix of **Table 7.2** displays the results of testing the product to ensure all requirements are met in the incorporated design.

Table 7.2 Testability Matrix

Requirements		**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
Test Cases	**Total**	2	2	4	2	3	2	1	2
TC1	2	X		X					
TC2	2				X	X			
TC3	2						X		X
TC4	6	X	X	X		X	X		X
TC5	1				X				
TC6	2		X	X					
TC7	1					X			
TC8	1			X					
TC9	1							X	

The testability matrix of **Table 7.2** displays the results of testing the product to ensure all requirements are met in the incorporated design.

Chapter VIII: Conclusions

The Wild Stallion Distortion Pedal in its current state is a working and successful design. However, the process involved in creating the pedal revealed several areas of improvement for future design endeavors.

While the device succeeds in meeting the basic functionality in the requirements section of this report, the current draw of 4.75 mA for the device in its bypass mode of operation is something to be improved upon. To access the battery and change it every several days is inconvenient from a user stand point as it involves unscrewing the enclosure. Along these lines, future improvements would be to reduce this parasitic current draw to conserve power and also make the battery more accessible for replacement.

An important lesson learned from minor oversight is that the painting of the enclosure should be done prior to assembly. Masking off the various potentiometers and jacks to apply the paint added a significant amount of time and effort to the project and the resulting paint application was imperfect to say the least. Also, multiple coats of paint require ample time to dry in between coats and need the right non-humid environment to produce a quality paint job.

Care should also be taken with assembly of components and the right tools should be used. Stripped out threads on a potentiometer, an oversized drilled hole, and multiple diode replacements were the result of rushing and improper preparation. These missteps will consequently be avoided in future endeavors.

In future design builds, the 1 MΩ logarithmic potentiometer used for the distortion control, could be changed to a linear potentiometer for future revisions. This would potentially produce a smoother gain adjustment and aid in avoiding leaps in the gain as shown in **Figure 5.7**.

As far as the cost of the unit goes, the total project cost was more than the anticipated selling point of $175.00. The projects total cost, approaching $250.00 with shipping and handling, tax, and miscellaneous trips to RadioShack for part replacement, doesn’t account for the costs of tools required, such as a soldering iron or testing equipment such as an oscilloscope. The PCB assembly was the most expensive portion of the overall cost adding a significant amount to the overall project. With Bulk production of the unit, manufacturing costs could be reduced significantly.

Overall, the project was a success and I am happy to have been a part of it. The Wild Stallion Distortion Pedal will be a part of my musical arsenal for years to come and the knowledge I have acquired throughout the process is even more valuable.

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Appendix A: Senior Project Analysis

1. Summary of Functional Requirements

The Wild Stallion Distortion functions as a guitar effect pedal. By taking a ¼“ TRS cable output of a guitar as its input, a distorted waveform results on the output due to diode clipping implemented through analog circuitry. The signal then routes to a ¼“ TRS connected output. The pedal comes equipped with a foot switch that when pressed, activates the distortion circuit that otherwise remains bypassed. The three control knobs give user control over the level of distortion on the output signal, the tone of the signal, and the amount of gain or overall volume of the signal.

2. Primary Constraints

The constraints surrounding The Wild Stallion Distortion unit and its development primarily include economic and social constraints. Limited funding exists for the project. In order to remain competitive in market, the developmental costs per unit excluding labor should not exceed $250. This limits the possibility of numerous design revisions during development thereby making quality design practices imperative. Possible legal constraints could potentially exist since the product’s initial design piggybacks on previous known and successful designs which would require a thorough patent search and legal consult before the product to become commercialized.

3. Economic

Upon comparison with large scale projects, the Wild Stallion Distortion pedal requires minimal capital. The required human capital, encompass the electrical engineering student, academic advisor, and those involved with testing procedures.

Financial capital accrues upon successful design and marketing efforts. The expected financial capital required to build one unit is projected at $6209.72. This value accounts for anticipated component and labor costs the project requires and incorporates the possibility of multiple design revisions, build, and test cycles. The labor costs for research and development account for the majority of the cost estimated at $4.515.00, representing a fixed cost [12]. The manufacturing, labor, and component costs represent variable cost estimated at $1,694.72. This cost would likely decrease with the use of bulk reproduction and streamlined manufacturing processes. Principal funding for the project, provided primarily by the Cal Poly electrical engineering department’s Senior Project Fund and the project developer, finances the build. Large scale production of the unit would require investment for manufacturing facilities, labor force, and marketing.

Testing equipment and testing facilities are required for the project’s successful completion including: guitars, guitar amplifiers, power supplies, oscilloscopes, function generators, and simulation software. These represent real capital and are used to aid in the characterization of various stages of the product.

Environmental costs accumulate through various forms including: the silicon used in the production of the components as well as any toxic materials possibly contained in the components. The requirement of electricity for the product’s use has environmental implications as well. Environment costs remain minimal with development of one unit. However, the costs would increase at a linear rate with increase in production.

4. Manufacturing on a Commercial Basis

The estimated number of Wild Stallion Distortion pedals sold per year depends largely on final design quality and successful marketing tactics. A baseline estimate provided simplistic marketing efforts, might include 200 units conservatively. The per-unit cost of the final device, not including labor, is tentatively projected at \$150.00. With a sale price of \$175 to the consumer, a projected profit of about \$5000 per year minus labor cost appears. The production scale may rise if presented with quick market success. In this case, projected profits rise in relation to decreasing per unit development costs. When considering an estimated production labor cost of \$2,500.00 associated with the project as fixed costs, a break-even point appears at 249 units according to the following equation:

$$Break\ Pt. = \frac{Total\ Development\ Cost}{Market\ Price\ per\ Unit - Manufacturing\ Cost\ per\ Unit} \quad \textbf{eq. 3}$$

5. Environmental

The Wild Stallion Distortion pedal contributes to the depletion of natural resources including metals such as gold and silver, and materials such as silicon. Due to anticipated low power consumption and limited number of components, the environmental impact becomes modest.

6. Manufacturability

Manufacturing challenges arise when considering making production autonomous. The more larger scale the production, the more labor involved; printed circuit board production as well as metal fabrication of the product's enclosure, involve monetary and safety concerns when dealing with manufacturing thereby increasing with increased production. In current stages, the Wild Stallion pedal aims at hand construction involving the use of solder. This places limitations on mass production. In order to increase both the speed and size of manufacturing, investments in manufacturing equipment and facilities would have to occur for circuit board fabrication, assembly, testing, and soldering.

7. Sustainability

Maintainability of the product becomes a small concern provided that the product is used as intended. Factors such as degradation of materials due to corrosion wouldn't concern the consumer for many years into the product's lifespan.
This project impacts the sustainable use of resources in its limited use of electrical components. A slight negative impact presents itself as the components and materials used appear in nature on a finite basis; however, the expected limited production of the device makes this impact nearly negligible.

8. Ethical

Adherence to ethical standards according to the frameworks of the IEEE code of ethics and ethical principlism are strived for throughout the course of this project. Safety and responsibility become key concerns in the design and implementation of this project; for all who use it as well as the environment as a whole. Non-toxic materials are used whenever possible to lessen environmental impacts. The development of the device features no conflict of interests since few third parties have direct financial stake in the device.

Any claims about the product's functionality, asserts support from empirical data. The IEEE code leads in that developers accept no forms of bribes for the project. Through analysis of the social and ethical effects, the developers aim at improving the understanding of the device's technology and its consequences. The developer of the device claims qualifications to create such a device from electrical engineering education and experiences obtained at Cal Poly San Luis Obispo. The product development of the Wild Stallion Distortion pedal seeks to accept honest criticism and critique through faculty advisement and customer feedback.

The project supports the ethical principlism function of autonomy by allowing users the freedom of implementation through a wide variety of means. The device aims at benevolence and non-maleficence by subjecting to safety tests, avoiding toxic materials, and striving to give due credit throughout the entirety of production when considering existing design concepts.

9. Health and Safety

Health and safety concerns may arise with the use of the product. Being an electrical device, a power supply is needed for operation and may pose a risk if not used as intended or proper precautions are not taken when electrical connection occurs. Any sharp edges on the enclosure are beveled and sanded off too protect handling of the device. Non-toxic materials are used during construction whenever and wherever there's reasonable opportunity to do so. During the device's design and manufacturing processes, the health and safety of those building the device requires consideration. The potential for accidents can arise when working with electrical and manufacturing equipment used for product development.

10. Social and Political

The developer stands as the primary beneficiary and stakeholder concerning the Wild Stallion Distortion project. With successful completion of the project, not only is a good grade received for Cal Poly courses EE 460, EE 461, and EE 462, but financial gain becomes possible with the result of a successfully packaged and commercially available product. A failed project however potentially affects academic success and possibly the outlook future employers may have when making hiring decisions. Cal Poly faculty and students appear as stakeholders in this project. Wild Stallion Distortion's future success possibly relates to the school's reputation as well.

Social and political organizations associated with music and guitar players could potentially consider themselves stakeholders in this project. Though, little potential harm exists for these organizations as a failed project would not release publicly.

11. Development

Project planning and design analysis tools including Gantt chart development and Monte Carlo analysis techniques are a useful resource and continue as an aid through product finalization. The ability to analyze the economic, social, and political considerations associated with product development was achieved. This included finding the projected fixed and variable costs of the project and developing a timeline to meet successful completion. The project's development required research into past and present analog distortion designs as well as strategies involved in the design process itself. A literature search was conducted as a result thereby yielding quality information to provide a starting point for this project. Finally, the project furthered understanding of processes used and considerations to make when manufacturing an electrical product. Overall, electrical engineering abilities improved as this serves as a solid starting point for future endeavors.

Appendix B: Parts List and Costs

The Wild Stallion Distortion unit requires many hours for design and manufacturing. These hours account for design, build, and test phases of the device's hardware and layout, as well as documentation of the work involved with the device. **Table B.1** lays out estimated hours associated with each task, resulting in a total time exhausted of 208.75 hours. The time shown for task completion within the Gantt chart appears longer than the hours represented in **Table B.1** allowing for a division of labor time into multiple days. Each time estimate derived for the table relies upon the PERT method of estimation [12]. The following equation (**eq. b.1)** shows the method's implementation procedure:

$$T_{estimated} = \frac{T_{optimistic} + 4T_{realistic} + T_{pessimistic}}{6} \qquad \textbf{eq. b.1}$$

Table B.1 Total Wild Stallion Distortion Time Estimate

Category	Task	Time (hr.)
Research & Development	Hardware Design	30
	Hardware Prototyping and Revisions	40
	Project Planning Documentation	55
	Final Project Documentation	25.50
	Total	**150.50**
Manufacturing and Testing	Hardware Building	15
	Hardware Testing	25
	Product Packaging and Layout	18.25
	Total	78.25
Total		**208.75**

The Wild Stallion project's costs include a combination of labor and component costs. **Table B.2** presents a breakdown of these costs. Research and Development represent the largest portion of the total project cost, with subsequent costs falling close to $200.00 and likely to be less. Similar to the time estimates, cost estimates in **Table B.2** are derived from the PERT estimation method [12] where applicable. Similar to before, **eq. b.2** appears as follows:

$$C_{estimated} = \frac{C_{optimistic} + 4C_{realistic} + C_{pessimistic}}{6} \qquad \textbf{eq. b.2}$$

Table B.2 Total Wild Stallion Distortion Cost Estimates

	Item	**Cost/Unit**	**Quantity**	**Total**	**Explanation**
Labor Cost	Research & Development	$30/hr.	150.50 hr.	$4,515.00	The labor costs accrued from time spent developing and documenting the Wild Stallion project. An hourly wage of $30/hr. applied to the time represents a standard wage paid to an intern within an R&D position.
	Manufacturing and Testing	$25/hr.	58.25 hr.	$1,456.25	The labor costs accrued from time spent building and testing the distortion pedal. An hourly wage of $25/hr. applied to the time represents the average wage paid to an intern within a manufacturing position.
Part Cost	Diecast Aluminum Enclosure	$9.50	1 unit	$15.49	Price taken from 3 different electronic websites for the guitar pedal's enclosure.
	Boss 9V power supply	$21.99	1 unit	$21.99	Standard cost for the Boss PSA-120s adapter taken from guitarcenter.com, zzounds.com, and sweetwater.com used as an alternative source to the product's battery supply.
	PCB Fabrication	$60.00	1 unit	$65.99	Price determined by quote from sunstone.com plus shipping.
	Active and Discrete Components and Parts	$80	1 unit	$80	Estimated cost of components needed for the device including: resistors, capacitors, diodes, transistors, switches, potentiometers, and operational amplifiers.
	Miscellaneous Costs	$55	x unit	$55	Cost of paint, jacks/sockets, knobs, decals, as well as any unanticipated costs required.
Total Estimated Cost				**$6209.72**	
Total Estimated Cost – (Labor & Testing)				**$238.47**	

Bill of Materials

Table B.3 Wild Stallion Distortion Bill of Materials

Part Description	Manufacturer	Distributor	Quantity	Unit Price	Total Price
Yobett Resistors Pack	Yobett	Amazon	1	14.99	14.99
E-Projects 36 Value Capacitor Kit	E-Projects	Amazon	1	19.99	19.99
Alpha 500k & 1M Audio (Log) Taper	Alpha Electronics	Amazon	2	1.40	2.80
Alpha B20k Potentiometer	Alpha Electronics	Amazon	1	3.99	3.99
Alpha 100k Linear Potentiometer	Alpha Electronics	Amazon	1	1.40	1.40
JRC 4558D DIP Dual Op Amp	Mammoth Electronics	Mammoth Electronics	2	0.40	0.80
RC 4558P DIP Dual Op Amp	Texas Instruments	Mouser	1	0.37	0.37
LF353P DIP Dual Op Amp	Texas Instruments	Mouser	1	0.57	0.57
1N914 Zener Diode 20Pack	NTE Electronics	Amazon	1	7.17	7.17
5mm Red LED	RadioShack	RadioShack	2	1.99	3.98
Stereo ¼” TRS Jack	Switchcraft	Amazon	1	6.39	6.39
Mono ¼” TRS Jack	Switchcraft	Amazon	1	1.55	1.55
2N4401 NPN BJT	Central Semiconductor Corp.	Mouser	2	0.39	0.78
JK-101DC Round DC Power Jack	Mammoth Electronics	Mammoth Electronics	1	0.80	0.80
9-Pin Latching 3PDT Footswitch	Uxcell	Amazon	1	7.78	7.78
3 x Spool Solid Core 20AWG Hookup Wire	RadioShack	RadioShack	1	8.99	8.99
9V DC 1A Power Supply Cable	Mr. Power	Amazon	1	10.99	10.99
3 Pack Duracell Quantum 9V Battery	Duracell	Walgreens	1	12.99	12.99
JK-9VSNP Battery Snap Connector	Mammoth Electronics	Mammoth Electronics	1	0.45	0.45
4S1590B Enclosure	Mammoth Electronics	Mammoth Electronics	1	5.75	5.75
PCB Assembly	Advanced Circuits	Advanced Circuits www.4pcb.com	3	33.00	99.00
1900 H Series Knob	Mammoth Electronics	Mammoth Electronics	3	0.80	2.40
Total Cost			**$213.93**		

Appendix C: Project Schedule

The project plan formed at the beginning of the Wild Stallion Distortion project assists to provide organization and accountability. When planning a project, two main resources require accounting. These resources appear as time and money**. Figure C.1**, **Figure C.2**, and **Figure C.3** show Gantt charts representing the expected timeline of the project. The chart exists, split into three figures for the reader's convenience.

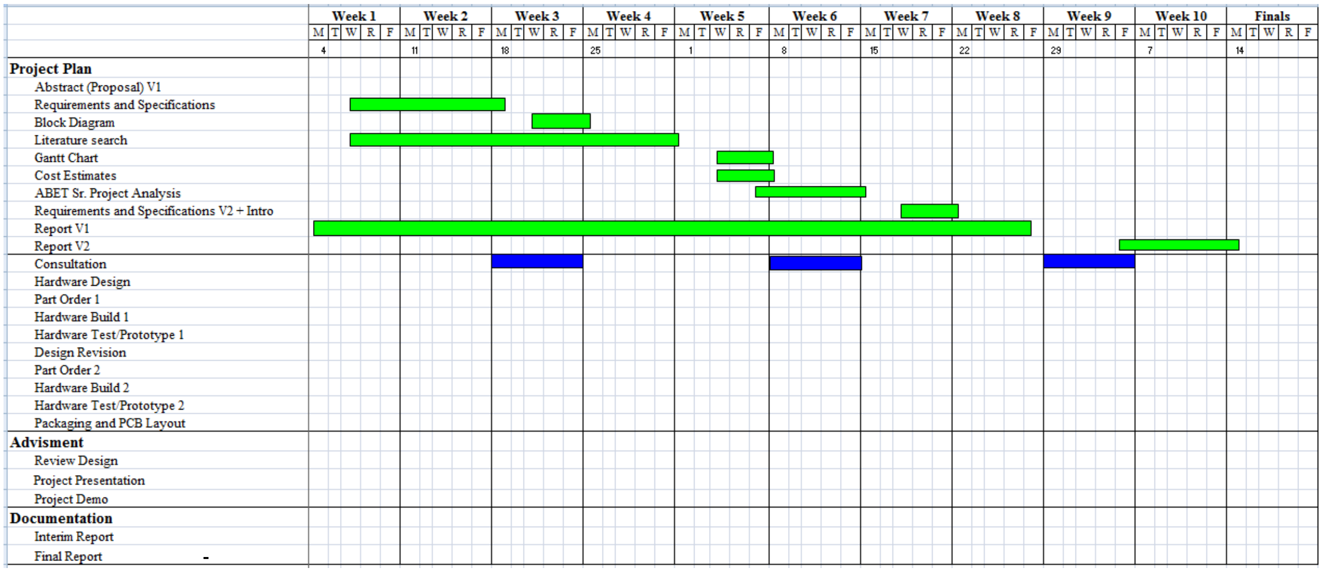


Figure C.1: Gantt chart through EE460

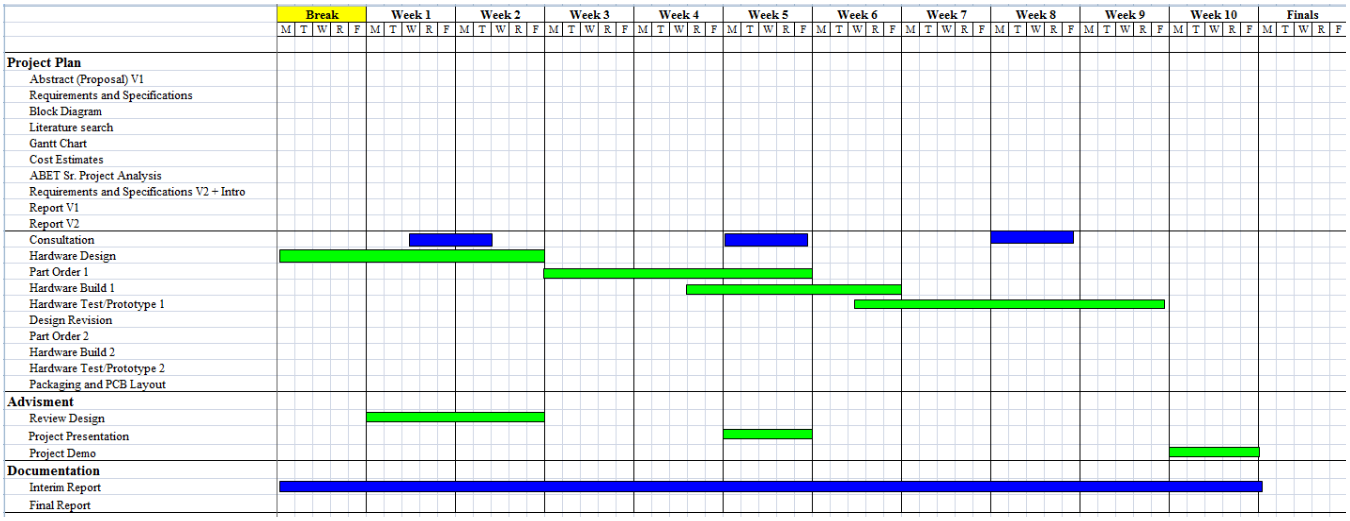
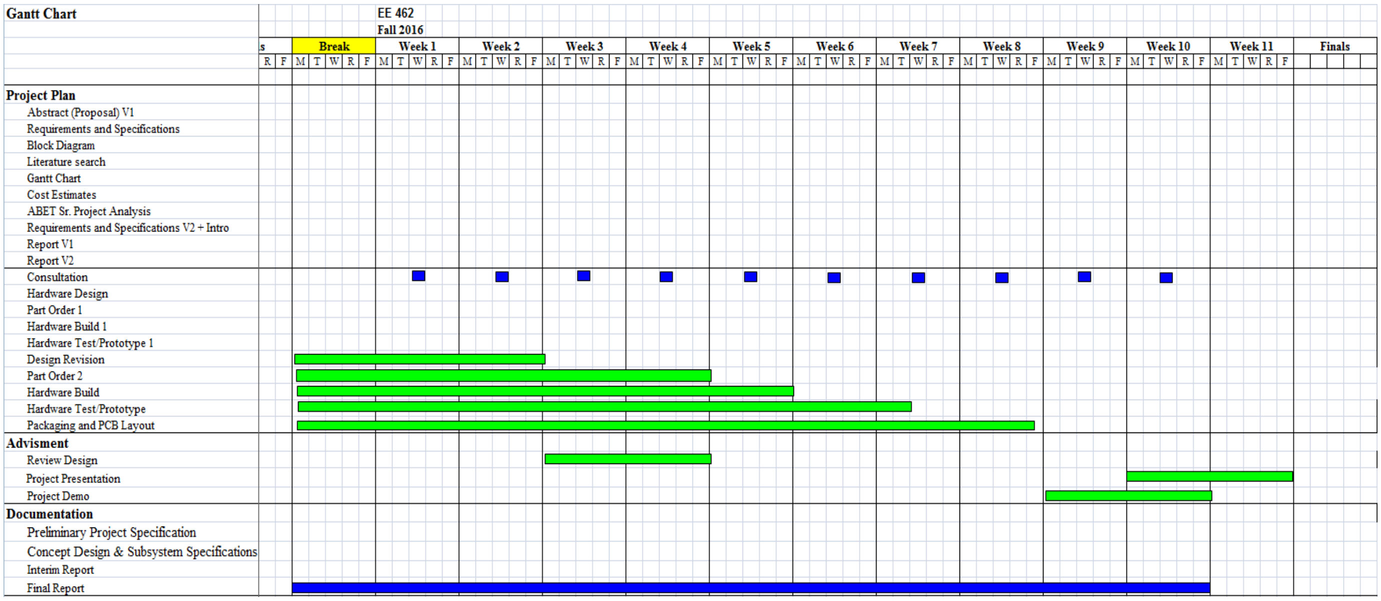


Figure C.2: Gantt chart through EE461



EE 462
Fall 2016

Gantt Chart	s	Break	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Finals
Project Plan														
Abstract (Proposal) V1														
Requirements and Specifications														
Block Diagram														
Literature search														
Gantt Chart														
Cost Estimates														
ABET Sr. Project Analysis														
Requirements and Specifications V2 + Intro														
Report V1														
Report V2														
Consultation			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
Hardware Design														
Part Order 1														
Hardware Build 1														
Hardware Test/Prototype 1														
Design Revision		🟩	🟩	🟩										
Part Order 2		🟩	🟩	🟩	🟩	🟩								
Hardware Build		🟩	🟩	🟩	🟩	🟩	🟩							
Hardware Test/Prototype		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩					
Packaging and PCB Layout		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
Advisment														
Review Design					🟩	🟩								
Project Presentation												🟩	🟩	
Project Demo											🟩	🟩		
Documentation														
Preliminary Project Specification														
Concept Design & Subsystem Specifications														
Interim Report														
Final Report		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		

Figure C.3: Gantt chart through EE462

Appendix D: Printed Circuit Board Layout

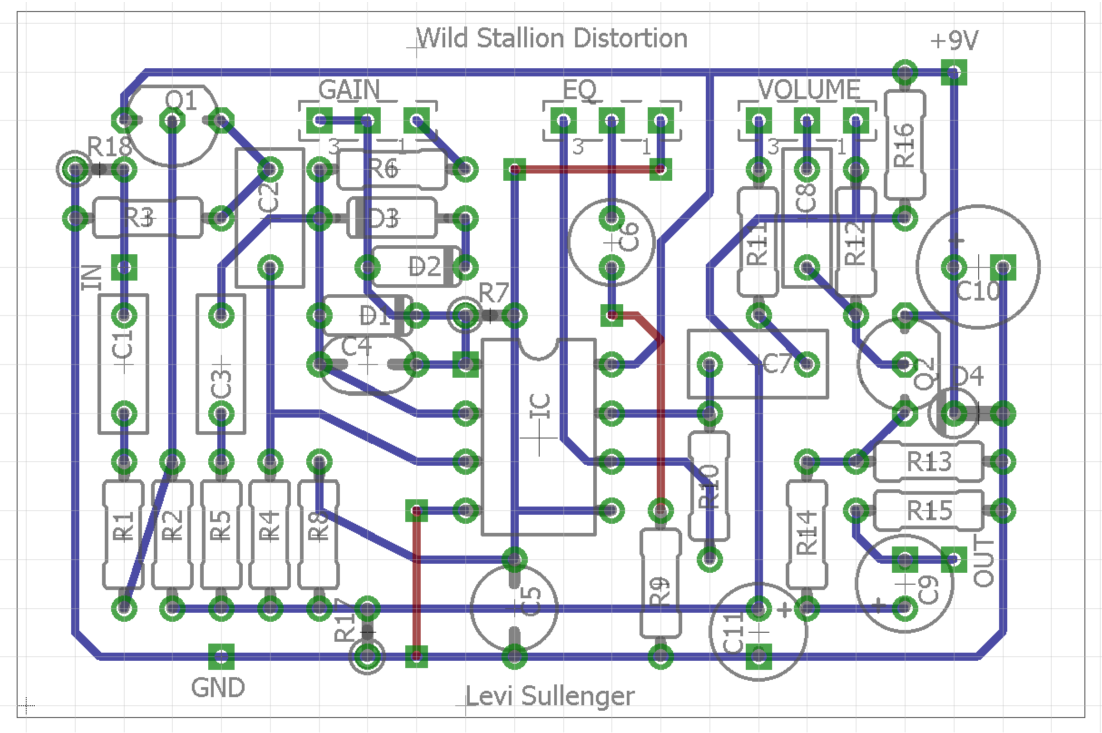


Figure D.1: PCB Layout