Analog Electric Guitar Distortion Effects and Headphone Amplification

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June 2010

Abstract

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The goal of this project was to create an electronic system which integrates popular audio processing effects as well as headphone amplification circuitry for use with an electric guitar. By implementing a system which fits natively inside the body of an electric guitar, the need for numerous external accessories relating to a standalone amplifier system is eliminated, improving device versatility and portability.

TABLE OF CONTENTS

List of Figures and Tables

Acknowledgements

I would first like to thank my parents for their continued support and dedication to helping me receive the best education allowed to me. I would also like to thank Professor Bryan Mealy for encouraging me to work on a project that fulfills both technical goals and personal ambitions. I am grateful to the rest of the Cal Poly faculty who I have had the pleasure of experiencing the educative process with first hand. Their wisdom and support have helped me achieve the knowledge and tools necessary for completing this work.

I. Introduction

Playing the electric guitar can often be a burdensome process due to the amount of accessories and equipment required to actually play. Besides the guitar itself, an amplifier is required to boost the audio signal to necessary levels to drive a speaker, as well as a patch cable to connect the guitar to the amplifier. In order to diversify the sound output of the guitar, players often rely on numerous standalone effects pedals such as the *MXR Distortion Plus* or the *Line 6 Liqua-Flange* which perform analog or digital signal processing techniques to manipulate the audio signals before they are sent to the amplifier.[1] These effects pedals also require numerous patch cables as well as individual power supplies to function. Maintaining all of this equipment can prove difficult in situations where space is limited and portability is an issue. The goal of this project is to create an electronic system which integrates popular audio processing effects as well as headphone amplification circuitry which will fit natively inside the body of an electric guitar, eliminating the need for numerous external accessories.

Enabling the electric guitar for standalone use with a pair of headphones can provide numerous options for playability. An external amplifier is no longer required to hear sound from the guitar, and the ability to practice at a personal volume is simplified while maintaining the functionality of effects processing units. Having onboard audio circuitry also improves portability, allowing one to travel and play with an electric guitar without having to bring several accessories besides a pair of headphones.

II. Background

An electric guitar produces sound through the use of one or more electromagnetic pickups. When the strings of a guitar vibrate near the pickup, small changes in the magnetic field of the pickup coil create an oscillating signal.[2] Due to the high output impedance of these pickup coils, the power of the output signal is too low to drive a low impedance speaker or pair of headphones and must be amplified in order to do so.

Since the electric guitar became a popular instrument in the 1950’s, players have been seeking methods of altering their tone in order to add variety and diversify themselves from other players. Electronic effects processing units including phasers, delays, and overdrives are often used to help achieve this diversity.[3] One of the most common effects currently used is referred to as distortion, which adds a crunchy tone to a clean guitar signal.

Through the use of active electronic components such as operational amplifiers, the guitar signal can be amplified as well as manipulated to apply these popular signal effects and to drive a speaker load such as a pair of headphones. A high input impedance operational amplifier solves the problem of impedance matching to achieve near maximum power transfer from the guitar source to the speaker load. A desired range of frequencies within the audible range of 20Hz-25,000Hz can be emphasized through the implementation of filtering techniques, while dampening unwanted frequencies such as RF interference and noise.[4]

III. Requirements

The system must perform two main functions: apply a distortion audio effect, and amplify the guitar signal to provide enough power to drive a pair of headphones. The circuitry should also allow for true bypass functionality, allowing multiple modes of operation. LED's will be used to indicate the status of each mode. A control will also be present to adjust the amount of distortion applied to the guitar signal. The guitar has a volume control present, so a second will not be needed for headphone use. The system should contain a low part count due to space constraints in the body of an electric guitar. The entire circuit should be powered by a single 9V battery to minimize space consumption.

Summarized Feature List

- Distortion Audio Effect
- Headphone Amplification
- Bypass Functionality (Allowing use with headphones or guitar amplifier)
- Gain Control
- LED Status Indication
- Single 9V Battery Powered
- Small Form Factor for Electric Guitar

Two main stages of circuitry will be used to perform the functions of distortion and headphone amplification:

Distortion Stage: Processes the signal from the output of an electric guitar and applies signal processing techniques to implement distortion. This stage will have bypass functionality so that it can be turned on or off as well as variable gain control for sound variety. An LED will display the on/bypass state of this stage.

Headphone Amplification Stage: Provides an amplification stage to the output signal of the Distortion Stage or to the clean signal from the guitar. This amplification stage will be designed so that headphones can be used directly with a guitar without the need of a standalone amplifier system. It will also have bypass functionality so that the guitar can be used with a standalone amplifier. Volume control will be provided by the native volume control of the guitar. This stage will provide output from the guitar. An LED will display the on/bypass state of this stage.

System Block Diagram

The system block diagram is visualized in Figure1. All input controls are present as well as output LED indicators. Dotted lines represent alternate signal paths when switches are set to bypass mode.

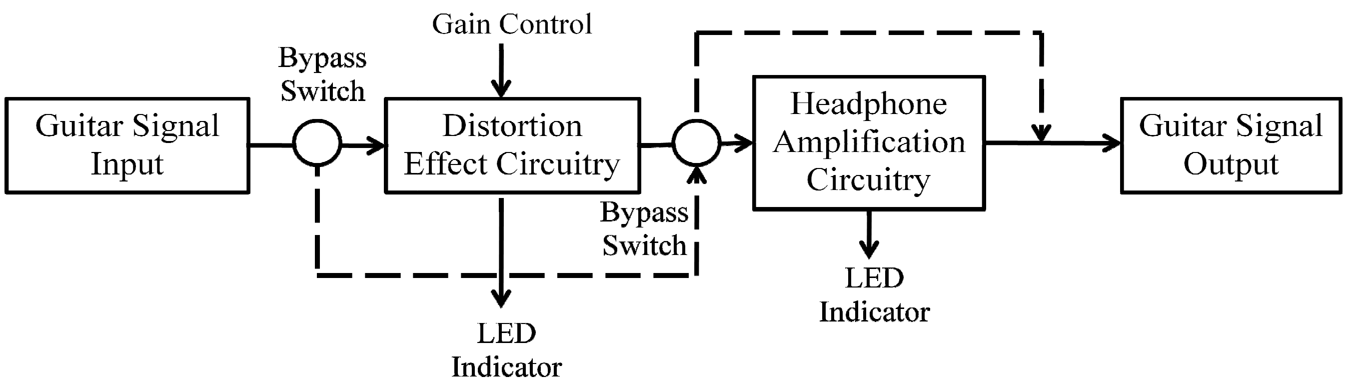

Figure 1: System Block Diagram

Modes of Operation

The system will maintain four separate modes of operation, allowing use with headphones as well as with an external guitar amplifier. This will allow the use of the new integrated distortion effect while listening through headphones or while plugged into a standalone amplifier. If no effects or amplification are desired, true bypass mode allows the clean signal to be output as if no electronics were installed. The modes of operation are as follows:

- Distortion Only
- Headphone Amplification Only
- Distortion and Headphone Amplification
- True Signal Bypass

IV. Design

The system design is divided into individual functional blocks, each with its own duty. The four main blocks of the system are:

- Distortion Effect Circuitry
- Headphone Amplification Circuitry
- Power Supply and LED Status Circuitry
- Switching Mechanism Hardware

Preliminary Design Review

A preliminary design was first performed to create an overview of how each functional block is implemented and how each interface with one another. System specifications are characterized and basic design principles are explained. Further design procedures are discussed in the Critical Design Review section.

Guitar Signal Characterization

Before the design process began, the electric guitar signal was characterized to determine the electrical properties of the waveform. An Ibanez GSA60 electric guitar was used for this process as seen in Figure 2.[5]

Figure 2: Ibanez GSA60 Electric Guitar

Using an Agilent 54622A 100Mhz Oscilloscope, the output waveform of the electric guitar was captured and analyzed as seen in Figure 3.

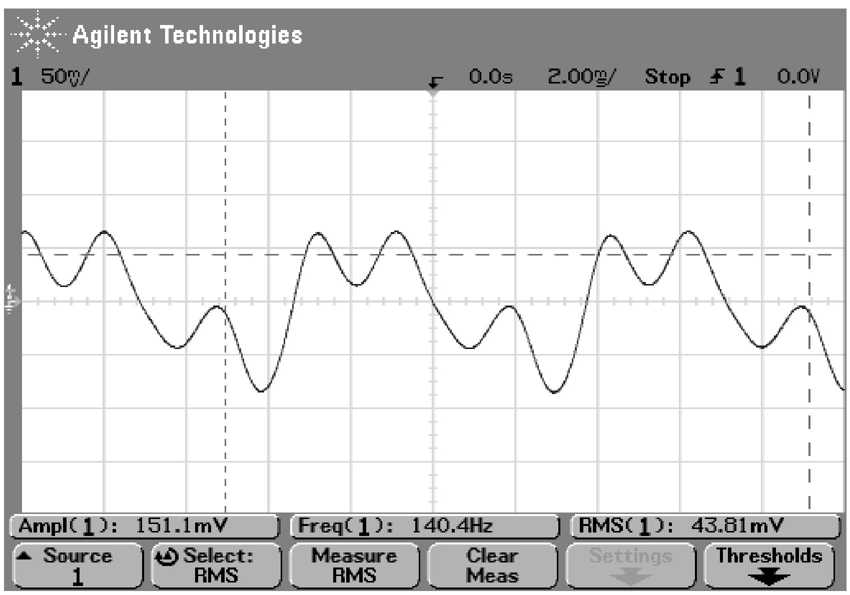

Figure 3: Electric Guitar Output Voltage Waveform

The signal comprised of a wide range of frequencies. While casually strumming, the waveform reached voltage levels near 50mV RMS, or 100-150mVpp. Strumming harder produced a signal with a slightly higher amplitude, while strumming softer reduced the amplitude of the signal.

Headphone Characterization

A pair of Koss UR-15C headphones were used to determine the signal requirements necessary to drive the speakers to audible sound volumes as seen in Figure 4.[6] The datasheet characteristics are shown in Table 1:

Figure 4: Koss UR-15C Headphones

Frequency Response	25-15,000 Hz
Impedance	32 ohms
Sensitivity	92 dB SPL/1mW
Distortion	< 0.3%
Cord	Straight, Dual Entry, 8ft

Table 1: Koss UR-15C Headphone Specifications

Using an Agilent 34401A Multimeter, the impedance of the two headphone speakers in parallel was measured to be 18Ω. Based on this data, the signal needed to drive the headphones to a comfortable loudness near 60 dB SPL was calculated based on the given sensitivity.[7]

$$P = \frac{V^2}{R} \qquad [8]$$

$$0.65mW = \frac{V^2}{18\Omega}$$

$$V = 0.11V\text{p} = 0.078\text{V RMS}$$

The headphones were then connected to a Line 6 Spider Jam 75W guitar amplifier to verify the required signal levels for driving the headphones. At comfortable listening volume, the output voltage was measured to be 0.056V RMS, in accordance with the calculated value. This voltage level is also similar to that measured from the direct output of the guitar. It was verified that the guitar produces a large enough voltage output signal, but due to its high output impedance is unable to drive a pair of low impedance headphones due to the inherent impedance mismatch and power loss, therefore requiring active electronics and maximum power transfer to achieve this performance.

Distortion Effect Circuitry Design

Preliminary design of the distortion circuitry began with the principle of using clipping diodes to add imperfections to the signal. By trimming the peaks and troughs of the audio voltage waveform, odd order harmonics are introduced into the response, creating a distorted, or crunchy tone.[9] While this behavior is often undesired in fields such as power electronics, its effect produces a desired sound for this application.

To reach the turn-on voltage of most silicon diodes, near 0.7V, an operational amplifier was used in a non-inverting configuration to provide voltage amplification to the guitar signal. Through the resistor pair R1 and R2, the voltage gain can be calculated through:

$$Vout = Vin(1 + \frac{R2}{R1}) \quad [10]$$

By using a potentiometer for R2, the gain can be adjusted as desired to reach up to and far beyond the forward voltage required by the diode. This change in amplification adjusts at which point the signal will begin to clip, altering the resultant sound.

The Texas Instruments TL071 JFET-Input Operational Amplifier was chosen for this application due to its high input impedance, low noise, and low voltage source requirements. With a high slew rate of 13 V/us, the output signal is well capable of maintaining performance within the audible frequency range. Two locations in the circuit for the diode arrangements were investigated:

Hard Clipping Configuration

By placing shunt diodes to ground at the output of an op-amp such as those in Figure 5, "hard clipping" of the voltage waveform occurs.[11]

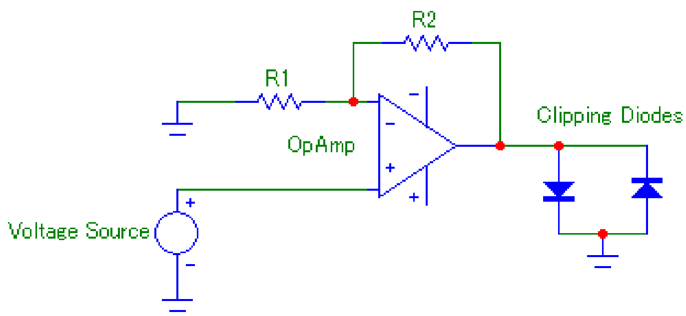

Figure 5: Hard Clipping Diode Configuration

When the voltage peak level exceeds the forward voltage specification of the diodes, the remaining peak signal shorts to ground, forcing an abrupt clip of the signal as can be seen in Figure 6. Adjusting this clipping level can be achieved by implementing diodes with various forward voltage characteristics and voltage drops or by placing more than one diode in series, resulting in varying output tones.

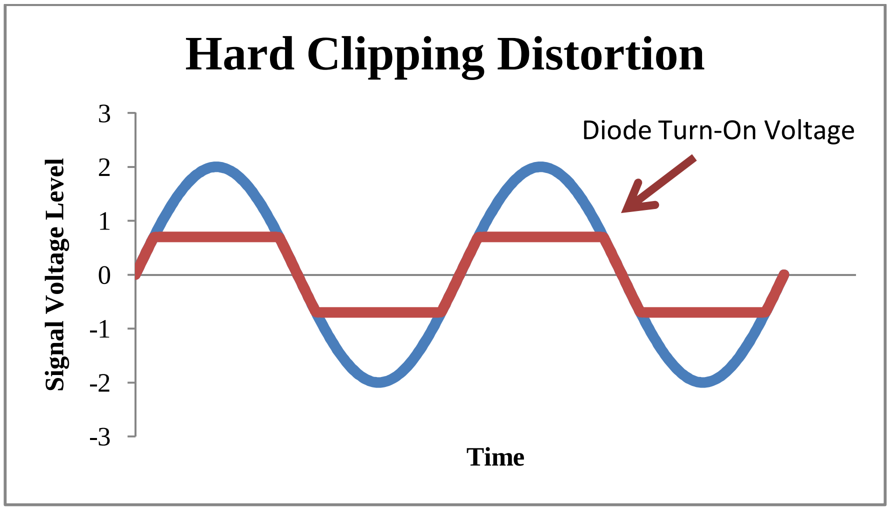

Figure 6: Hard Clipping Distortion Waveform

Soft Clipping Configuration

Distortion can also be produced by placing diodes in the op-amp negative feedback loop as seen in Figure 7. This arrangement creates a tone similar to that of a tube amplification system and is therefore often referred to as overdrive.[12]

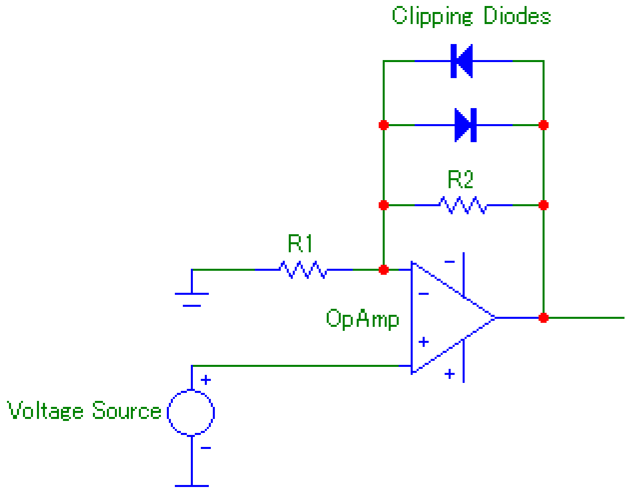

Figure 7: Soft Clipping Diode Configuration

This layout results in a voltage waveform with softer edges as can be seen in Figure 8. The rounding of the voltage waveform occurs when the amplified feedback signal exceeds the diode forward turn on voltage and bypasses resistor R2, resulting in gain limiting.

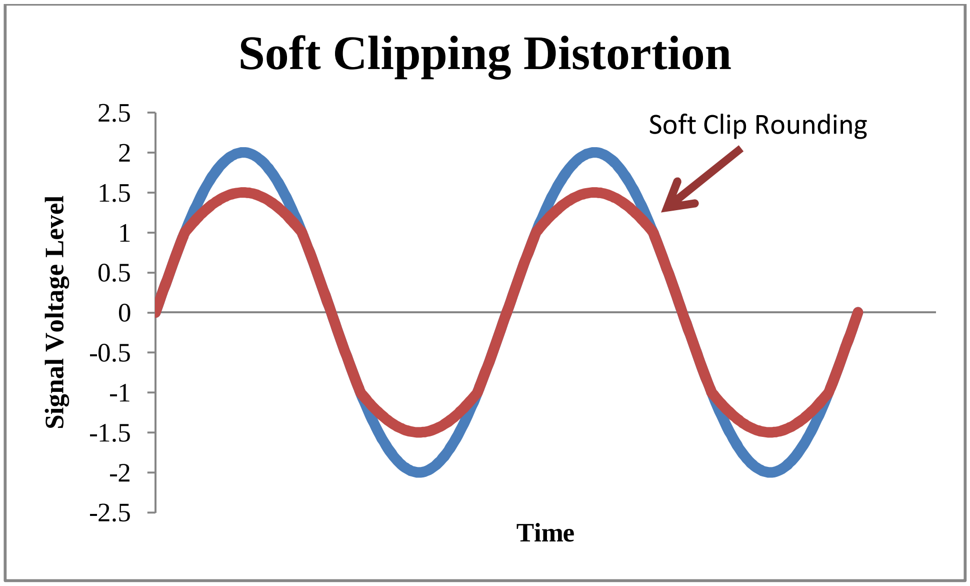

Figure 8: Soft Clipping Distortion Waveform

Due to the high gain required by the circuit to created distorted tones, RF interference and noise in the system is likely to be amplified as well. To prevent undesired inaudible frequencies in the range of 20Hz-25,000Hz from being amplified, I chose to implement low pass and high pass RC filters.

Headphone Amplification Circuitry Design

The output voltage of the electric guitar during casual playing was measured to be nearly 0.050V RMS, while the voltage required to drive the headphones at a comfortable listening level was measured to be similarly 0.056V RMS. For maximum power transfer of the signal from the guitar with a high output impedance, a high input impedance operational amplifier is needed with minimal gain requirements.

A National Semiconductor LM386 Low Voltage Audio Power Amplifier was chosen for this application as it is capable of providing enough power to drive a low impedance speaker. The LM386 provides a voltage gain of 20 in standard configuration without external components and has low source voltage requirements making it well suited for battery powered applications.

The headphone amplifier stage must work in modes of operation with or without the distortion stage preceding it, so filters must be included in this stage as well to reduce inaudible frequency levels and limit high frequency RF noise.

Power Supply and LED Status Circuitry Design

A single 9V alkaline battery is used as the voltage source to power the entire system. The TL071 op-amp has positive and negative voltage source rails, requiring polar sources. I employed input biasing techniques to offset the input voltage so that the guitar signal is maintained between the 0V and 9V rails without clipping. An LED indicator and current limiting resistor are tied to the same power rail as the TL071 positive source rail so that each is powered when enabled.

The LM386 amplifier has a single voltage source rail as well as a ground connection. This rail is connected to the +9V battery. By design, the output of the amplifier is DC offset by half of the supply voltage, requiring AC coupling techniques for use with a speaker configuration. An LED indicator and current limiting resistor are tied to the voltage source rail.

Switching Mechanism Hardware Design

The system maintains four separate modes of operation, allowing use with headphones as well as with an external guitar amplifier. To implement these different modes, I devised a switching mechanism utilizing two three-pole double-throw (3PDT) switches as seen in Figure 9.

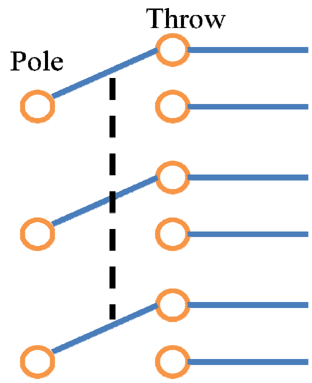

Figure 9: 3PDT Switch Architecture

When a stage is enabled, the battery connects to the corresponding circuit and LED indicator. When a stage is disabled, the battery is disconnected from the corresponding stage to conserve power consumption, prolonging battery life.

Critical Design Review

The critical design was performed once initial aspects of the system were analyzed and broken into functional blocks. I found that an iterative approach was necessary due to the nature of the audio application and the importance of feedback.

Initial Distortion Effect Circuitry Design

Critical design of the distortion effect began with a basic design and simulation to determine if the proposed distortion producing method would produce similar results to the desired sound. I utilized a non-inverting voltage amplifier configuration with a gain of approximately 20 and hard clipping diodes as can be seen in Figure 10. OrCad Capture 16.0 was then used to simulate the frequency response of the basic circuit. I applied a 100mV voltage signal to generate the input and a 1kΩ load to measure voltage at the output.

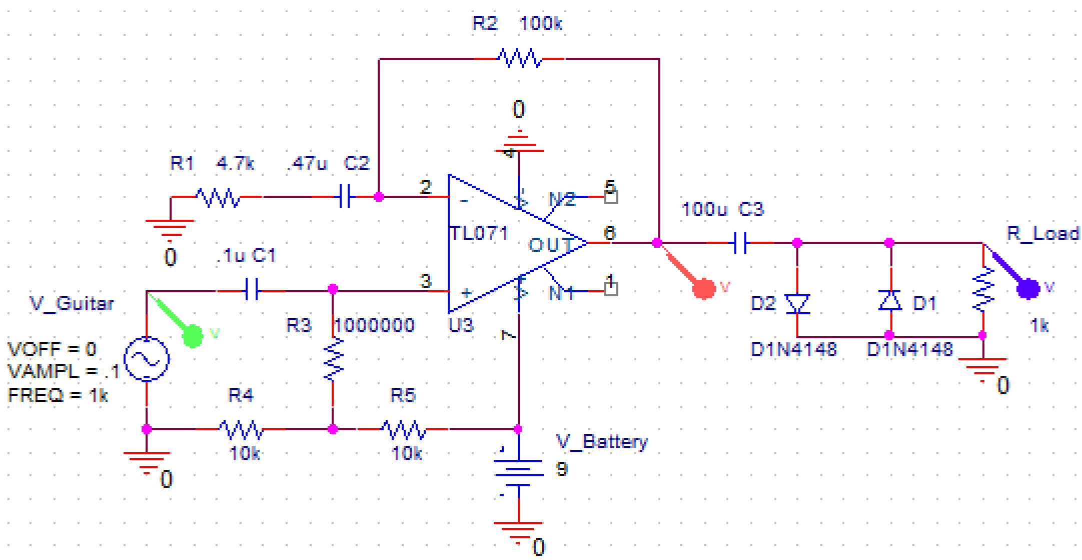

Figure 10: Initial Distortion Effect Circuit in Hard Clipping Configuration

Voltage waveforms can be seen at the input of the circuit (Green), output of the amplifier (Red), and output of the clipping diodes (Purple) in Figure 11. The effect of diode hard clipping is prevalent.

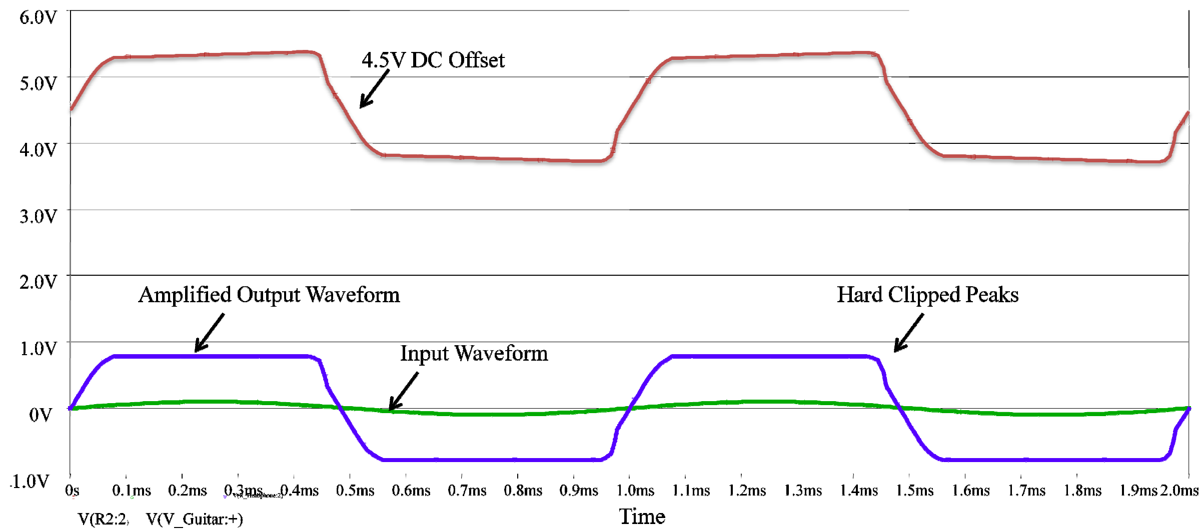

Figure 11: Simulated Hard Clipping Distortion Circuit Voltage Waveforms

The results of the simulation were as desired, so a basic prototype was constructed on a breadboard to determine if the design would function properly. I used the guitar for the input and placed a 10kΩ voltage divider potentiometer at the output to decrease the waveform to appropriate 100mV levels. The output was connected to a standalone guitar amplifier and casually played. A distorted and crunchy sound similar to what was desired was heard, confirming the basic design would be feasible, so further design continued to refine the sound.

The soft clipping technique was then simulated in a similar circuit as can be seen in Figure 12.

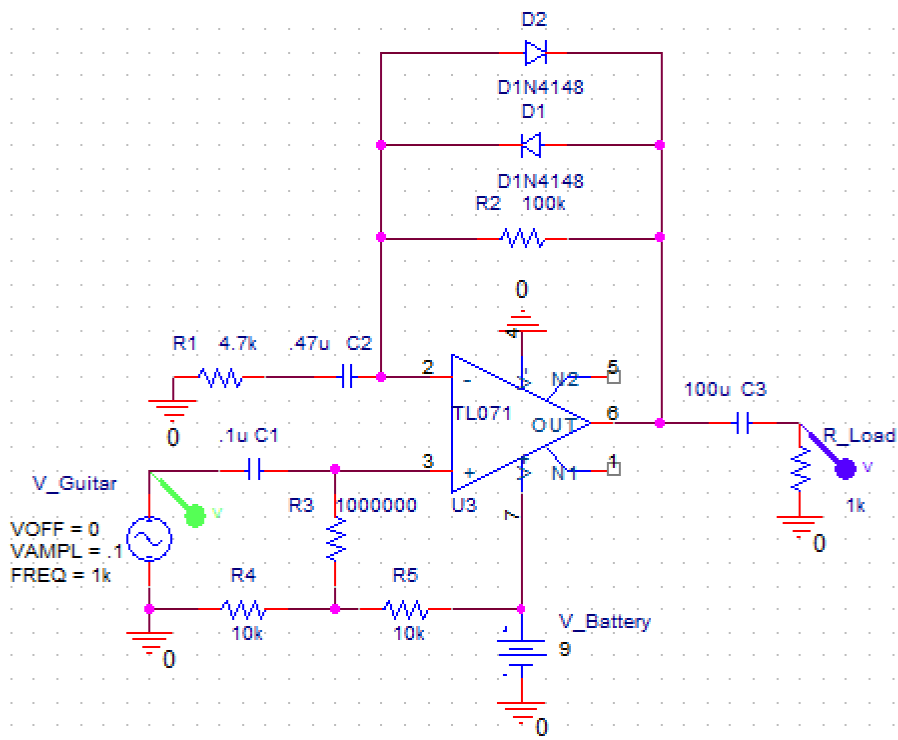

Figure 12: Initial Distortion Effect Circuit in Soft Clipping Configuration

The input voltage waveform (Green) and amplified output voltage waveform (Purple) are displayed in Figure 13. Noticeable rounding of the output voltage peaks is present, exemplifying the soft clipping, or overdrive technique.

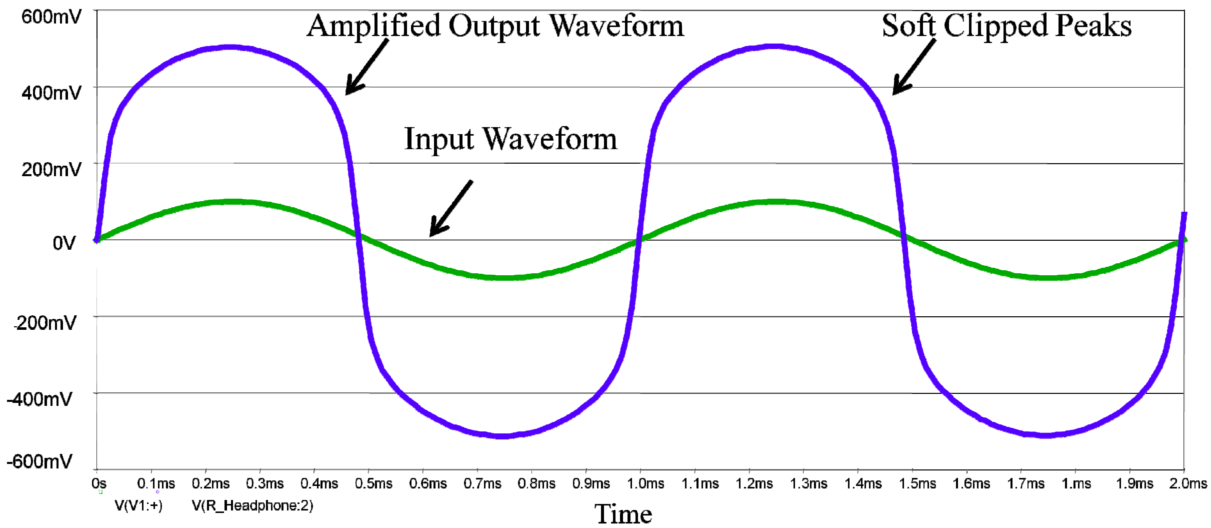

Figure 13: Simulated Soft Clipping Distortion Circuit Voltage Waveforms

This circuit was also assembled on a breadboard for audible testing. I placed a 10kΩ potentiometer at the output to decrease the waveform to appropriate 100mV levels. The circuit produced a similar crunchy distortion, yet provided a smoother texture compared to the harsh tone of the hard clipping diode configuration.

I continued to follow an iterative design approach to ensure that the desired integrity of the audio was maintained, while shaping the sound to a preferred tone. Noise was present while testing the initial design so high pass and low pass RC filters were implemented to reduce noise in the system. Components were added to the circuit and simulated before testing on a prototype breadboard.

Final Distortion Effect Circuitry Design

While listening to each implementation of the circuit design, both the soft and hard clipping techniques offered unique and desired effects to the tone of the signal. Each configuration was kept in the design with the option of disconnecting the diodes from the circuit. The final design is displayed in Figure 14.

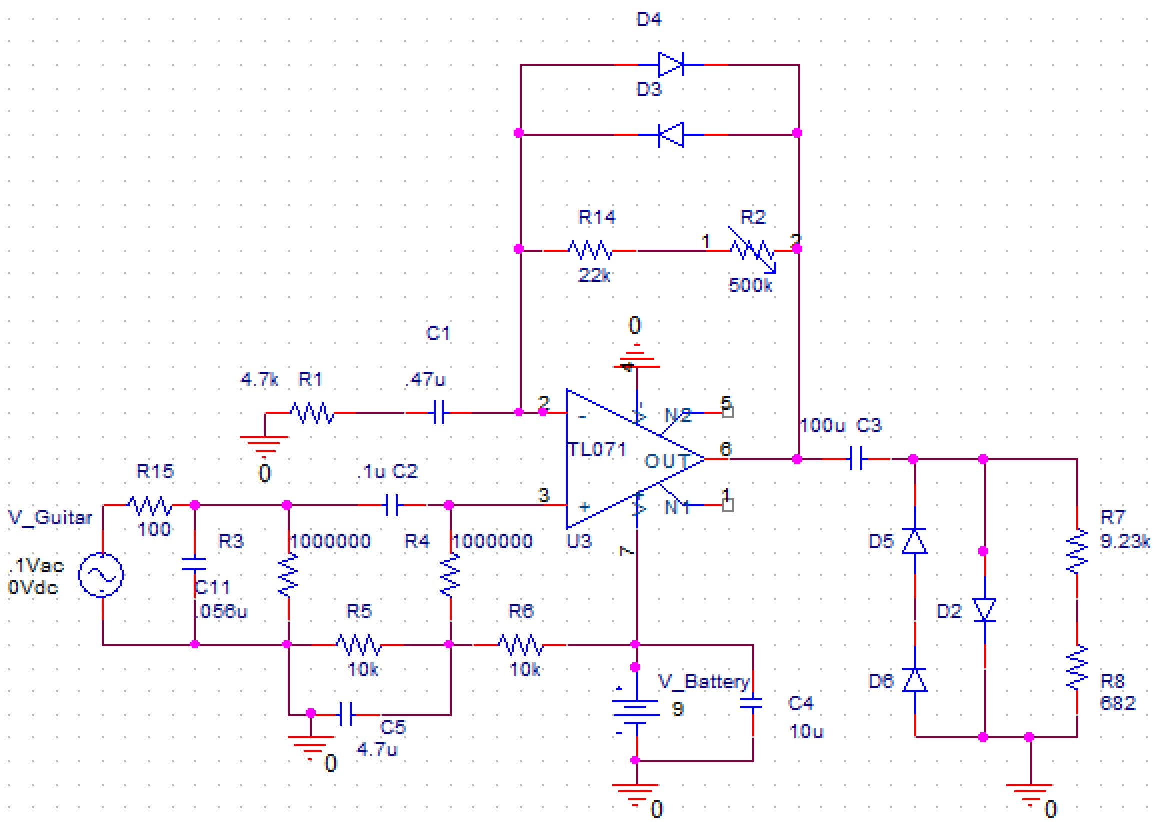

Figure 14: Final Distortion Effect Circuit

Distortion Circuitry Component Description

- From the input, R15 = 4.7kΩ and C11 = 0.056uF form a first order low pass RC filter which reduces amplitude by 20dB/decade with a cutoff frequency of 28.4kHz determined by:

$$fc = \frac{1}{(2\pi RC)} \quad [13]$$

  An active filter configuration was not implemented with a capacitor parallel to gain resistor R2 as it would result in a gain dependent cutoff frequency.

- C1 = 0.47uF and R1 = 4.7kΩ form a first order high pass active RC filter to reduce lower inaudible frequencies. The high pass cutoff frequency is calculated as above at 72Hz.
- Amplifier gain is adjusted through the resistor pair R2 = 500kΩ and R1 = 4.7kΩ through:

$$Vout = Vin(1 + \frac{R2}{R1})$$

  A linear potentiometer R2 = 500kΩ allowed a wide range of tones from little distortion to fuzzy tones. R14 = 22kΩ maintains constant clipping levels, allowing a minimum voltage gain of 5.7 and maximum gain of 112.

- A 10kΩ trim potentiometer visualized by R7 and R8 placed at the output reduces the amplified waveform to the desired 100mV.
- 1N4148 silicon diodes D3 and D4 create the soft clipping distortion effect by rounding voltage peaks in the feedback path. A toggle switch controls if the soft clipping or hard clipping diodes are connected to the circuit.

- 1N4148 Diodes D2, D5, and D6 create the hard clipping distortion effect by clipping the output voltage signal when amplitude exceeds the diode turn-on voltages of D2(0.7V) and D5-D6 in series(1.4V). A toggle switch controls if the soft clipping or hard clipping diodes are connected to the circuit.

Components used for bypass, op-amp powering, and DC offset biasing techniques are discussed in the section Power Supply and LED Status Circuitry section.

The magnitude response was simulated to verify the correct range of frequencies were being amplified while attenuating undesired frequencies as seen in Figure 15.

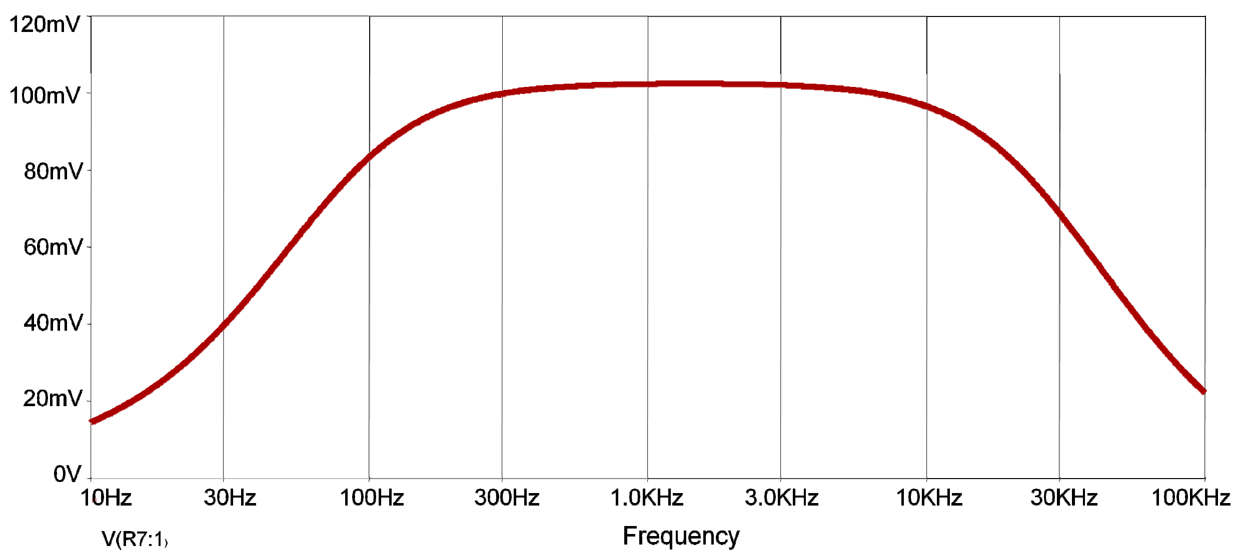

Figure 15: Simulated Magnitude Response of Final Distortion Circuit

The desired -3dB cutoff frequencies of 72Hz and 28.2kHz are present according to the simulation. Amplitude within the pass band was at the appropriate 100mV levels.

Initial Headphone Amplification Circuitry Design

Design for the headphone amplification circuitry again followed the iterative approach. A basic design first constructed using minimal components and was simulated as seen in Figure 16.

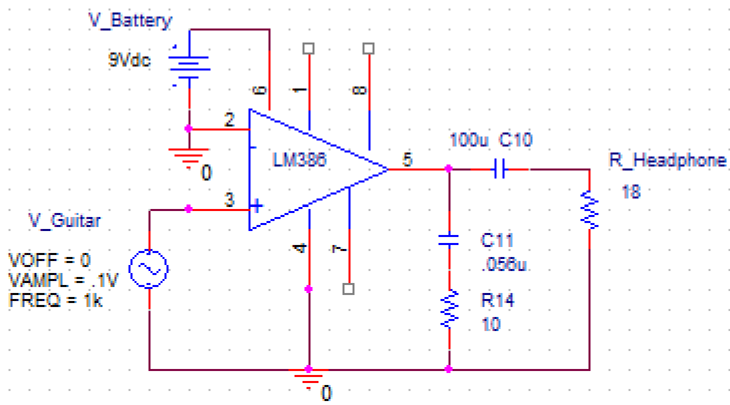

Figure 16: Initial Headphone Amplifier Circuit

The input voltage waveform (Green) and output voltage waveform (Red) can be seen in Figure 17. A voltage gain of 20 is present as expected due to the internal default gain of 20 of the LM386.

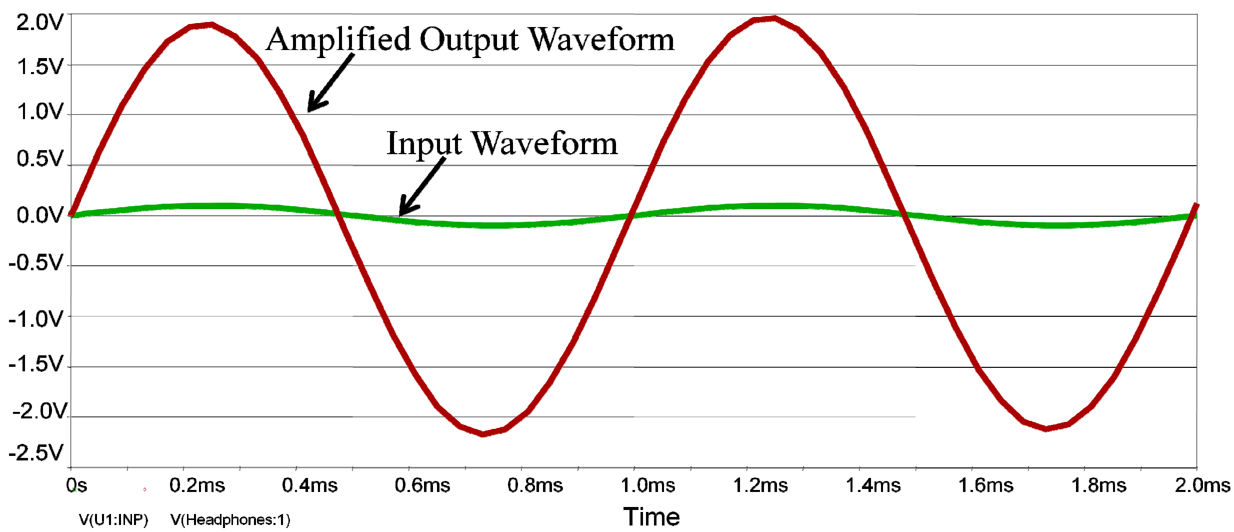

Figure 17: Simulated Headphone Amplifier Voltage Waveforms

This circuit was assembled on a breadboard for audible testing. I placed a 10kΩ trim potentiometer at the input to decrease the waveform to appropriate 5mV input levels to produce an output of 100mV. The guitar was connected to the input of the circuit and the headphones were connected to the output. At moderate playing levels, a clean guitar signal could be heard, but noise was present in the system. As the circuit was refined with filters to reduce noise levels, it was continually tested to ensure that audio functionality was maintained.

Final Headphone Amplifier Circuitry Design

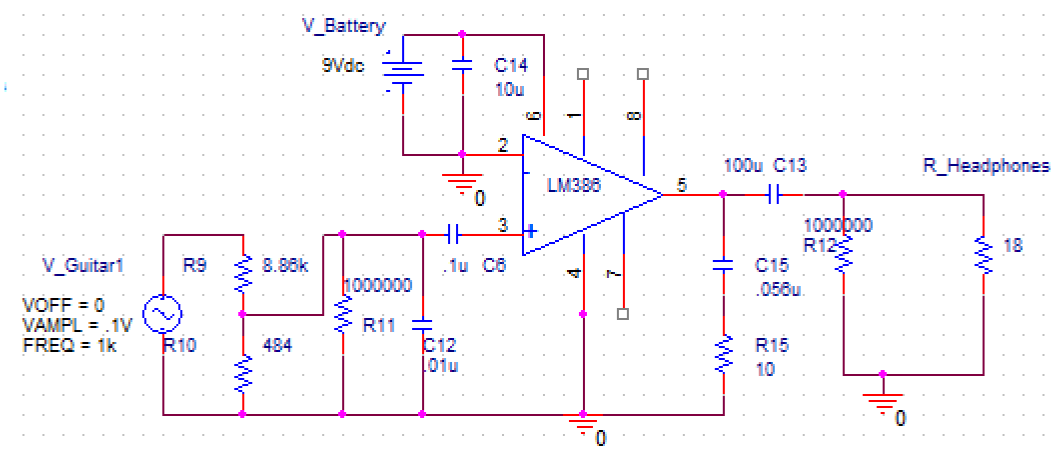

Figure 18: Final Headphone Amplifier Circuit

Component Description

- From the input R9 = 9.5Ω and R10 = 500Ω represent a 10kΩ trim potentiometer used to limit the incoming 100mV signal from the guitar or distortion circuit to 5mV levels before being amplified with a gain of 20 by the LM386 to return a 100mV output signal.

- A low pass first order RC filter is implemented through and R10 = 500Ω and C12 = 0.01uF with cutoff frequency 32kHz calculated by:

  This reduces high frequency RF noise amplified by the system and reduces audible noise from being heard.

- C15 and R15 provide feedback stability to the system as stated in the LM386 datasheet.

Components used for bypass, op-amp powering, and DC offset biasing techniques are discussed in section Power Supply and LED Status Circuitry section.

The magnitude response of the headphone amplification circuit was simulated to verify the correct range of frequencies were being amplified while attenuating undesired frequencies as seen in Figure 19.

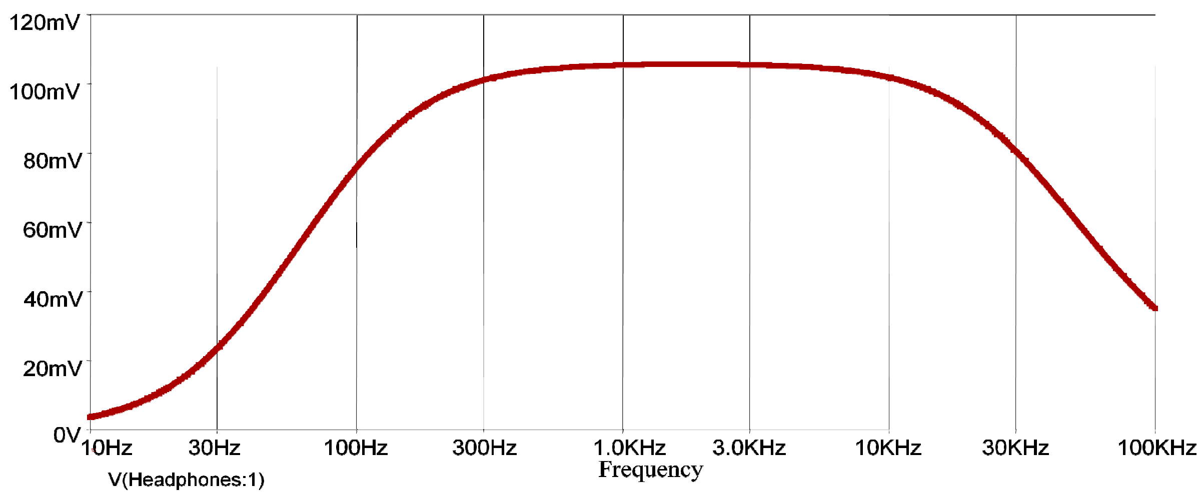

Figure 19: Simulated Magnitude Response of Final Headphone Amplifier Circuit

The high frequency cutoff was found to be near the desired 32kHz. Amplitude within the pass band was at the appropriate 100mV levels.

Power Supply and LED Status Circuitry

By powering the entire circuit with a single 9V battery, voltage biasing techniques were employed to provide necessary voltage source levels to each stage of the system. For the TL071 distortion stage op-amp, the positive voltage source rail is connected to the +9V polarity of the battery and the negative rail is tied to the 0V ground plane. To allow the signal to be amplified between the 0V and 9V rails, a matched pair of 10kΩ resistors was used to apply a 4.5V DC offset to the positive input of the op-amp. The clipping diodes prevent peak voltage levels from railing at 0V and 9V.

This powering technique however applies a positive DC offset voltage at the output of the amplifier which is undesired when driving a speaker load. To remove this DC voltage offset, a large 100uF AC coupling capacitor was placed in series with the output. This is achieved through the capacitor's frequency dependent impedance behavior acting as an open circuit at DC.

$$Zcap = \frac{1}{j\omega C} \quad [14]$$

A red LED indicator and biasing resistor for distortion indication are tied to the +9V rail of the TL071 and are powered concurrently with the op-amp. I calculated a current limiting resistor value for the 2.3V red LED to achieve 20mA current. At 325Ω the brightness of the LED was extremely high, so the resistor was increased to 10kΩ for a lower, more reasonable brightness.

$$R = \frac{Vs - Vled}{I\ led} \quad [15]$$

Distortion Powering Circuitry Component Description

- Matched resistors R5 = 10kΩ and R6 = 10kΩ provide a 4.5V input bias to the positive input of the TL071 from the voltage source. This offsets the output to 4.5V DC but prevents the signal from clipping the 0V and 9V rails.
- C5 = 4.7uF in parallel with R5 stabilizes the input bias voltage
- R4 = 1M provides a pull-up function to allow the 4.5V DC bias to reach the positive input of the TL071
- C2 = 0.1uF prevents DC voltages from entering the guitar and loading the pickups
- C4 = 10uF stabilizes the voltage source to prevent signal oscillations from entering the op-amp source rails resulting in an unstable response
- C3 = 100uF removes the 4.5V DC offset of the output by blocking the DC component of the signal, allowing only the AC guitar signal to pass to the output.

The LM386 headphone power amplifier is powered by connecting the positive voltage source rail to the +9V polarity of the battery. In standard configuration, the amplifier offsets the output voltage by half of the voltage source. Again an AC coupling capacitor is used to eliminate the DC offset voltage from reaching the headphone speaker. A blue LED and biasing resistor for headphone amplifier indication are tied to the +9V rail of the LM386 to be powered concurrently with the op-amp. I calculated a current limiting resistor value for the 3.5V blue LED to achieve 20mA current. A 2.2kΩ resistor was used to allow enough current to drive the LED at a reasonable brightness.

Headphone Amplifier Powering Component Description

- C6 = 0.1uF prevents DC voltages from entering the guitar and loading the pickups
- C7 = 100uF removes the 4.5V DC offset of the output by blocking the DC component of the signal, allowing only the AC guitar signal to pass to the output.
- C9 = 10uF stabilizes the voltage source to prevent signal oscillations from entering the op-amp source rails resulting in an unstable response

Switching Mechanism Hardware

The switching mechanism implemented required the use of two 3PDT switches. The distortion and headphone amplification circuitry can be independently enabled and disabled, allowing for four modes of operation. When a stage is enabled, the switch allows the battery to connect to the circuit, providing power and illuminating the proper LED. The wiring diagram is displayed in Figure 20.

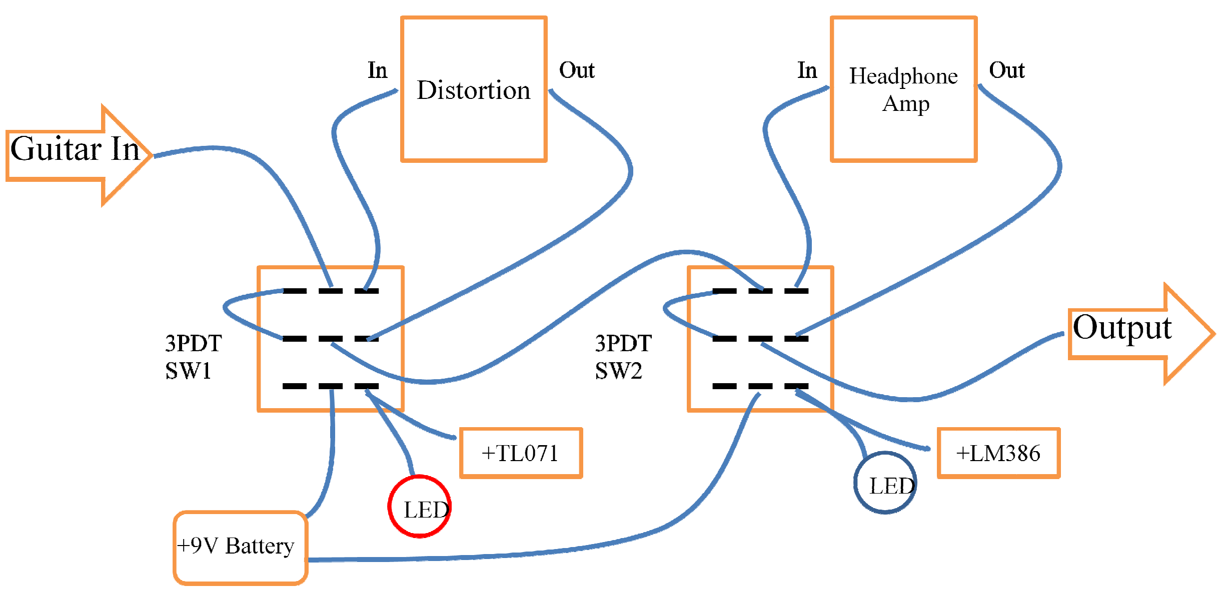

Figure 20: Switching Mechanism Wiring Diagram

When toggling the individual stages on and off, I discovered a popping noise. This was due to the output AC coupling capacitor of the headphone amplifier circuit abruptly charging and then discharging through the load. To allow the capacitors to discharge while disconnected, I added R12 = 1MΩ as a pull-down to ground.

V. Development and Construction

Printed Circuit Board Design

I designed a printed circuit board layout after the circuits were finalized utilizing Pad2Pad 1.9 PCB software. Using through-hole component templates, all necessary components were organized in a fashion to reduce board usage. Since the final circuit must fit in the body of the guitar, size was the main constraint for this task. Components were placed close to one another, yet with enough room to allow all copper traces to fit on one side of the board. Nets were created between components on the board to determine which pins of each component were to connect with surrounding components. This step was followed by laying out the traces themselves. The final dimensions of the board are 2.5” x 1.6” as seen in Figure 21.

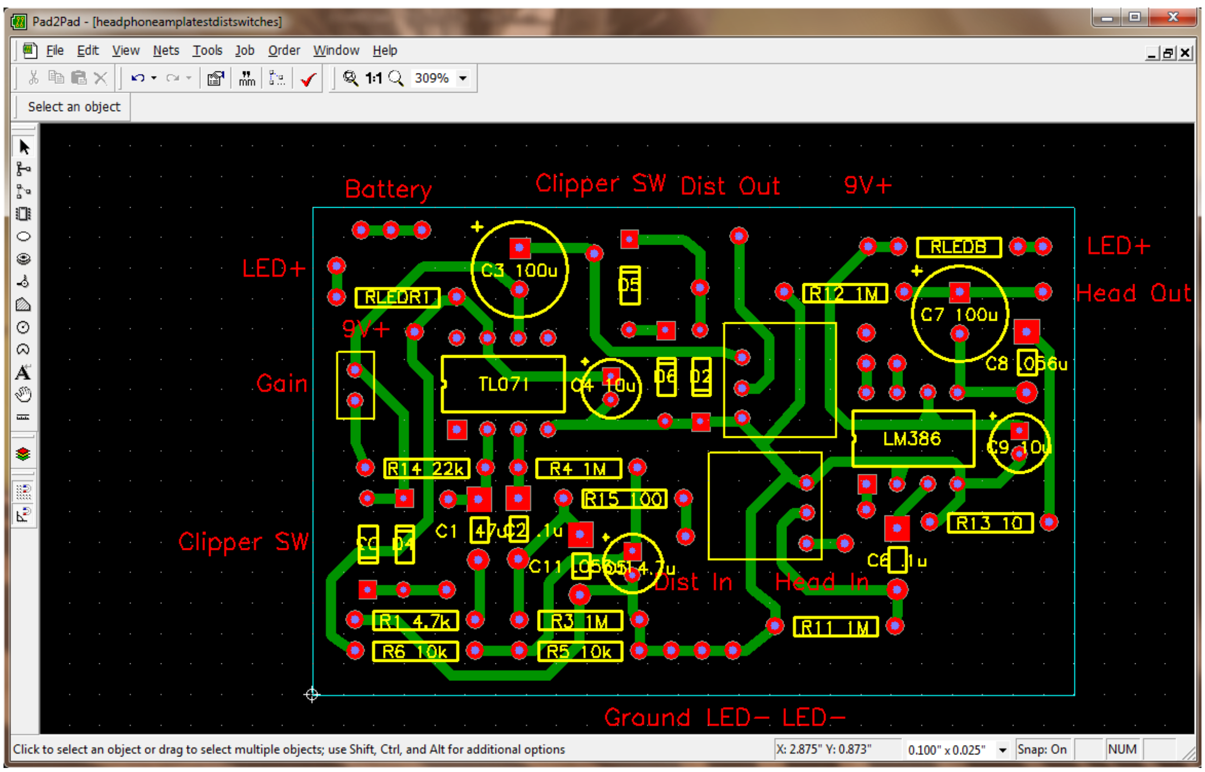

Figure 21: PCB Layout Design

The .pcb file for the board layout was sent to a small PCB manufacturing company named Futurlec. Ten boards were ordered with copper routing and holes for component pins. Once shipped, the boards were inspected and found to be of satisfactory quality as seen in Figure 22. Components were soldered to the PC board and verified for correct connectivity using a multi-meter.

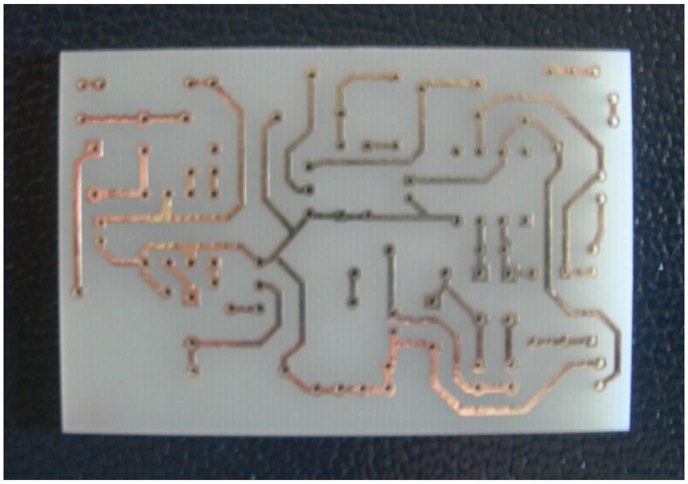

Figure 22: System PCB

VI. Integration and Test Results

System Verification

Measurements were performed on the finalized circuitry to verify functionality and performance. An Agilent 20MHz Function Waveform Generator was used as an input voltage source. Each mode of operation was characterized to verify satisfactory performance.

True Bypass Verification

With Switch 1 and Switch 2 toggled to bypass, a 5kHz, 100mVpp signal was applied to the input and the output voltage was measured as seen in Figure 23.

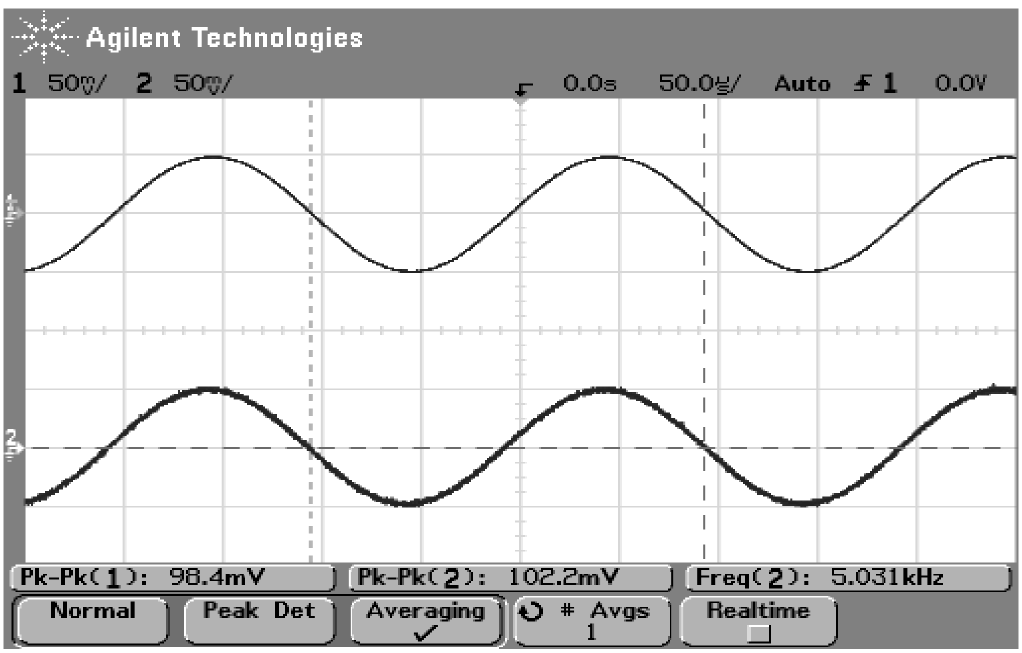

Figure 23: True Bypass Voltage Waveforms

As was expected, the output voltage (Top) maintained its amplitude in bypass mode. This performance allows operation with a standalone guitar amplifier.

Hard Clipping Distortion Verification

With the distortion switch enabled and the hard clipping diodes connected, the voltage at the diodes was measured as can be seen in Figure 24 with the gain potentiometer R2 set to 100.

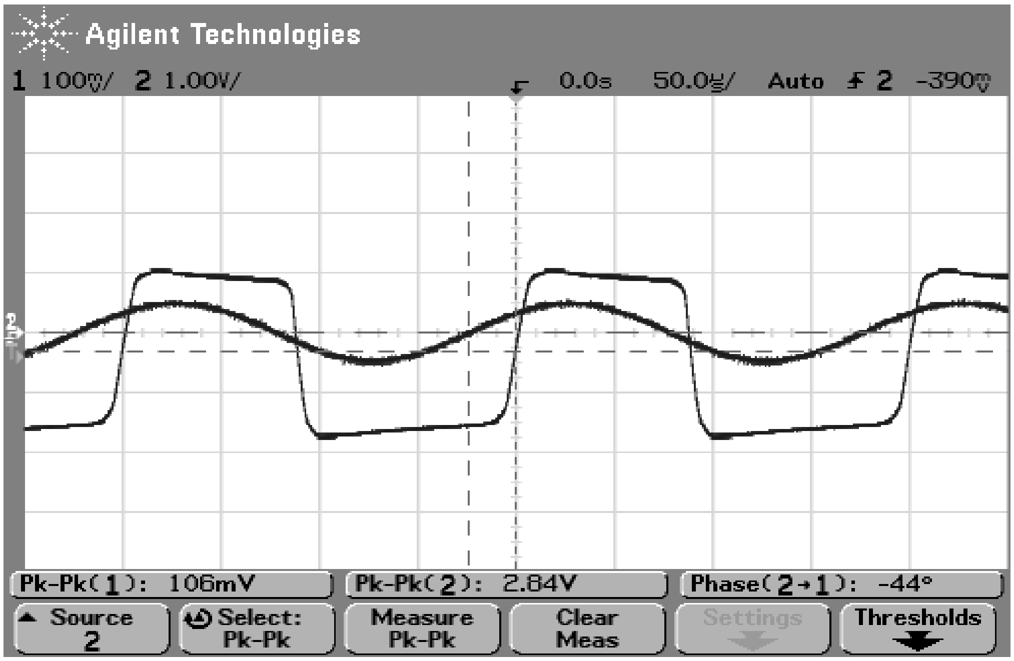

Figure 24: Hard Clipping Voltage Waveforms

The signal is noticeably clipped during the positive swing near 1V and during the negative swing near 1.8V due to the two diodes in series to ground. This signal is attenuated using a 10kΩ trim pot at the output to bring it down to 100mV levels.

Soft Clipping Distortion Verification

The hard clipping diodes were disconnected and the soft clipping diodes were placed in the feedback loop. The voltage at the output of the amplifier with a gain of 100 was measured as displayed in Figure 25.

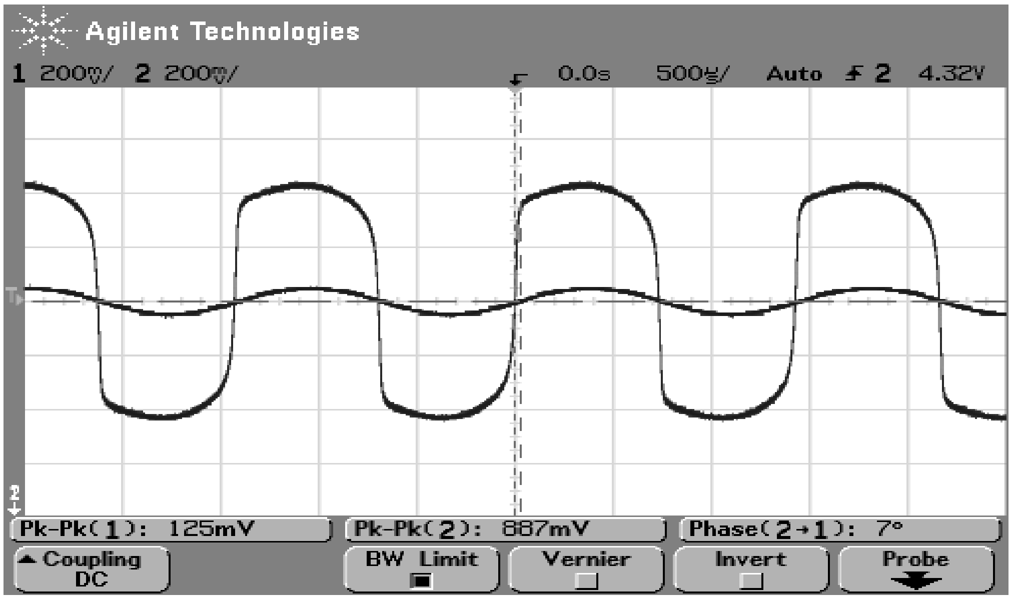

Figure 25: Soft Clipping Voltage Waveforms

Noticeable rounding of the peaks can be seen in the amplified output voltage waveform, verifying simulation results.

Headphone Amplifier Verification

I applied a1kHz 100mV sine signal to the input of the headphone amplifier as seen in Figure 26. The output voltage (Top) was measured after attenuating the signal with the input potentiometer.

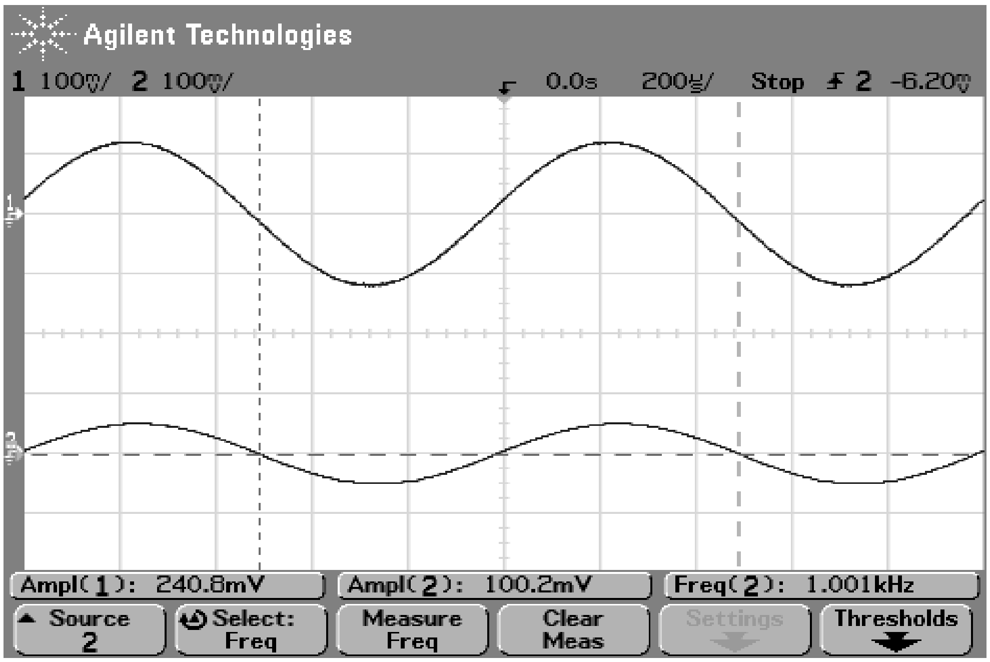

Figure 26: Headphone Amplifier Voltage Waveforms

The output signal contained minimal noise. I attached headphones to the output to ensure functionality and signal integrity were both maintained.

Frequency Response

The magnitude frequency response was measured with the soft-clipping diodes connected to determine if the desired frequency range was being amplified. A 1kHz 100mV sine signal was applied to the input of the distortion circuit, and the output voltage was measured. Data points were recorded and graphed as displayed in Figure 27.

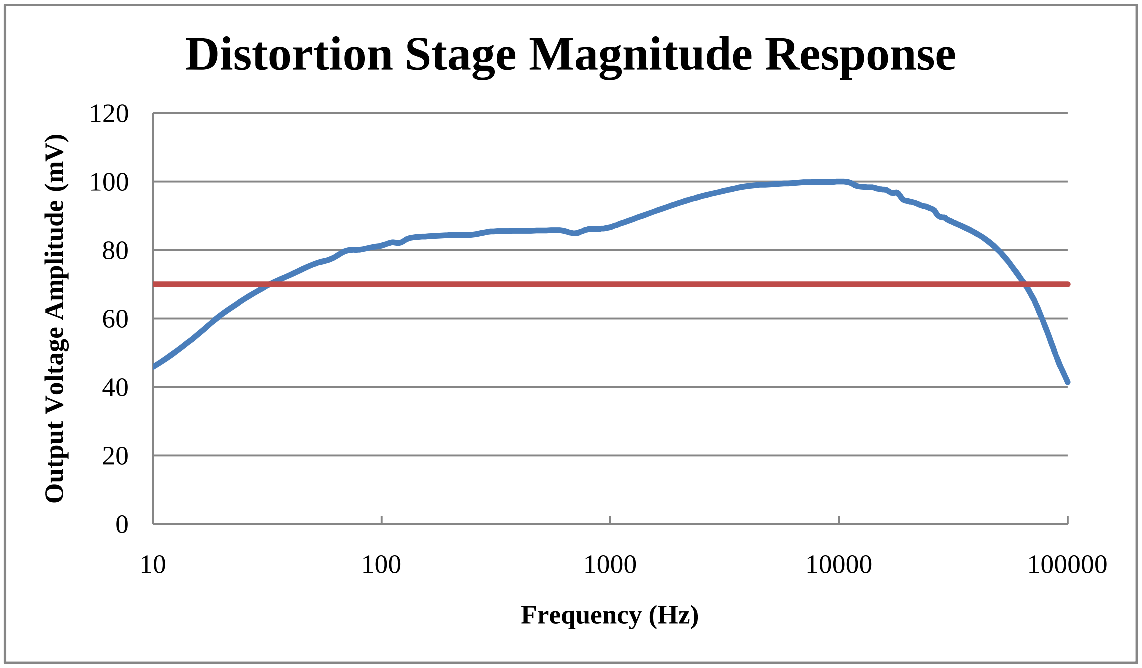

Figure 27: Distortion Magnitude Response

The red line marks the -3dB cutoff frequencies. There is a sharp roll-off higher than the audible frequency limit of 20kHz which reduces unwanted noise and radio interference.

The magnitude frequency response of the headphone amplifier was also measured. I applied a 1kHz 100mV sine signal to the input of the amplifier circuit, and the output voltage was measured. Data points were recorded and graphed as displayed in Figure 28.

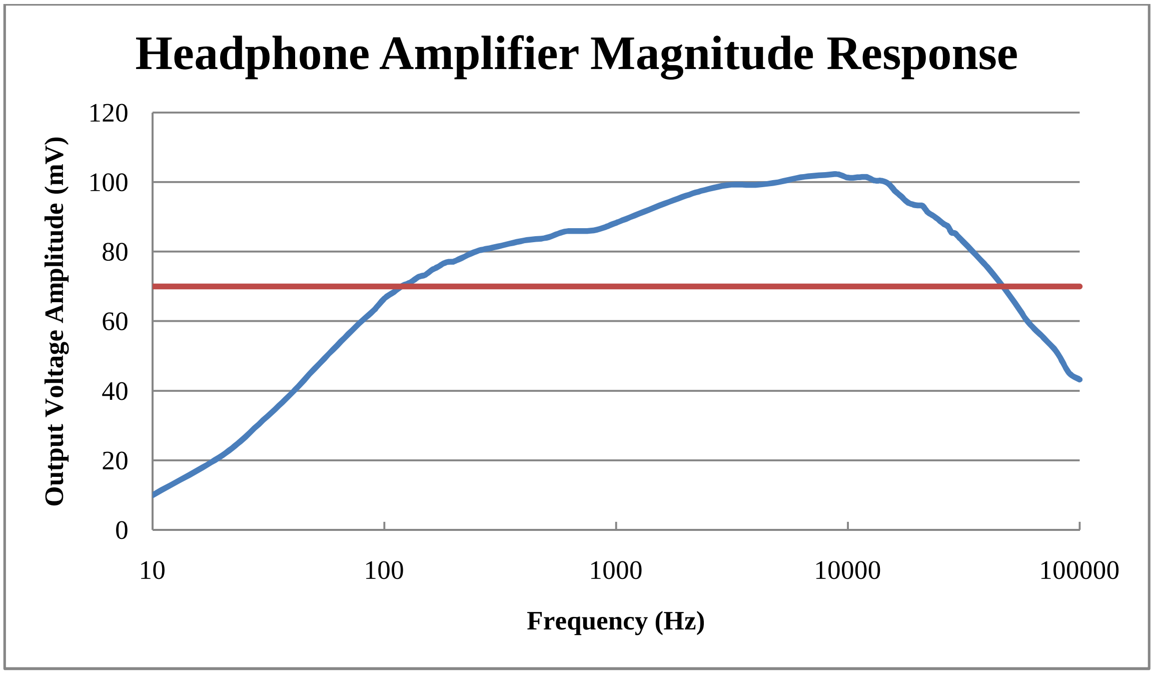

Figure 28: Headphone Amplifier Magnitude Response

Again, the audible frequency range maintains its magnitude while the undesired frequencies above 20kHz begin to attenuate, reducing noise in the system.

System Power Consumption

I measured total system power usage to determine approximate battery life. The voltage of the 9V alkaline battery was measured at 8.8V using a multimeter. Maximum battery life was estimated with a common 9V, 580mAh alkaline battery rating.[16]

Mode of Operation	Source Voltage (V)	Source Current (mA)	Power Usage (mW)	Estimated Battery Life (Hours)
Distortion w/ LED	8.8	15.5	136.4	37
Headphone Amp w/ LED	8.8	6.3	56.2	91
Both On w/ LEDS	8.8	24.8	218.2	23

Table 2: System Power Consumption

The distortion circuit was found to consume more power than the headphone amplifier due to its large voltage gains as well as use of more passive components. The headphone amplifier circuit consumes less power, providing a long battery life respectively.

System Integration

Using a Dremel 4000 rotary tool, I carved a compartment from the rear of the guitar to allow room for the PCB, wiring, LED's, and switching hardware as displayed in Figure 29.

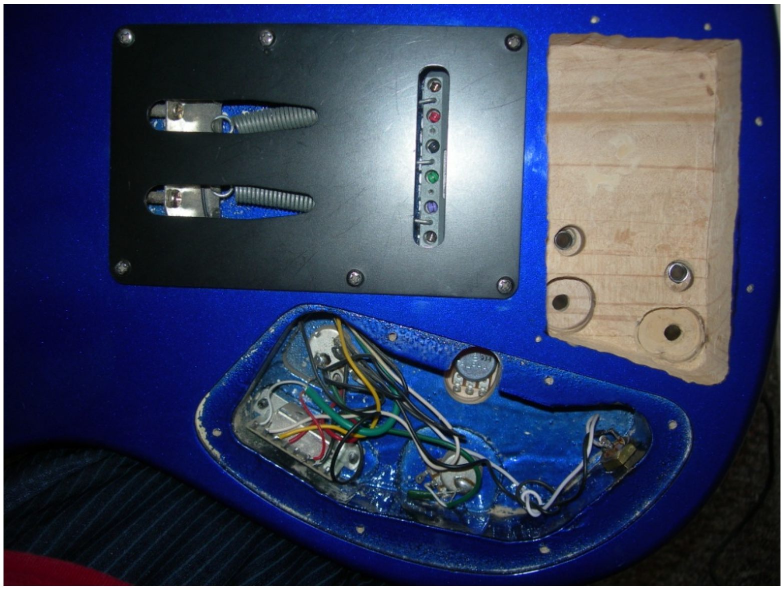

Figure 29: Compartment Created in Electric Guitar

I secured the circuitry into place and wired the switches properly as seen in Figure 30. The output of the guitar was wired to the input of the circuitry through the switches, and the output was fed to the ¼" output jack of the guitar. I then installed the battery and verified the switches for functionality.

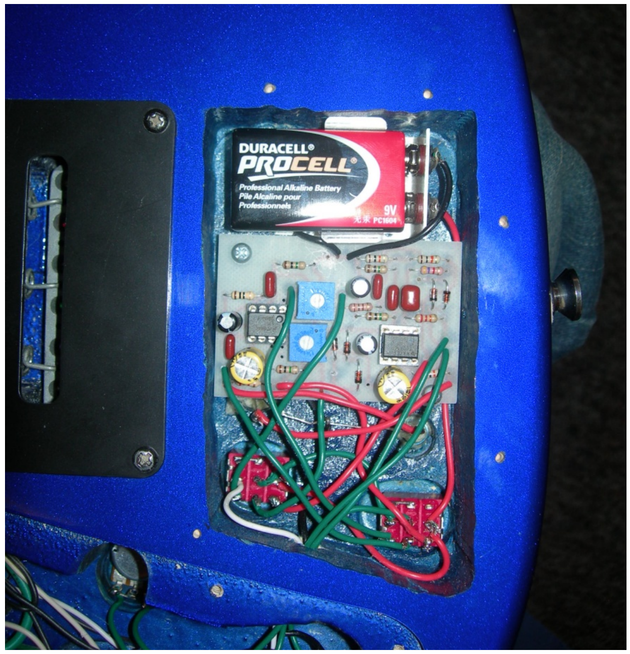

Figure 30: System Integrated into Electric Guitar

Headphones were plugged into the output of the guitar through a mono to stereo adapter so that each speaker would be driven. All modes of operation were again tested and found to be fully functional. The native volume control appropriately attenuated the signal and the LED’s properly lit to indicate each mode of operation as displayed in Figure 31.

Figure 31: Front View of Integrated System Hardware

VII. Conclusion

The design, construction, and implementation of the electric guitar distortion effect and headphone amplification system were successfully completed. After design and prototype revisions, the final system design met the given requirements and produced the desired functionality and sound containing minimal audible noise. The installation of the system into the body of the electric guitar has enabled an easy to use device with improved functionality allowing one to play without an external amplifier yet maintaining the ability to implement effects processing capabilities. By designing the system with a low component count and a minimal PCB footprint, units could be produced in bulk at a low price. Implementing trim potentiometers for signal level attenuators also allows the device to operate with a wide variety of electric guitars. If desired, the system could be installed in a standalone enclosure for use with a wide array of audio applications.

Endnotes

[1] Rusty Cutchin et.al., eds. The Definitive Guitar Handbook. (London: Flame Tree Publishing, 2008) 162.

[2] Donald Brosnac. Guitar Electronics for Musicians. (London: Wise Publications, 1983) 14.

[3] Rusty Cutchin et.al., eds. The Definitive Guitar Handbook. (London: Flame Tree Publishing, 2008) 162.

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[5] Ibanez Guitars. <http://www.ibanez.com/ElectricGuitars/model-GSA60>. (17 May 2010).

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[7] Sergio Franco. Design with Operational Amplifiers and Analog Integrated Circuits. (New York: McGraw-Hill, 2002) 122.

[8] Charles Alexander and Matthew Sadiku. Fundamentals of Electric Circuits. (New York: McGraw-Hill, 2007) 31.

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"Koss Stereophones". Koss Corporation. 10 Feb. 2010 <http://www.koss.com/koss/kossweb.nsf/p?openform&pc^fs^UR15C>.

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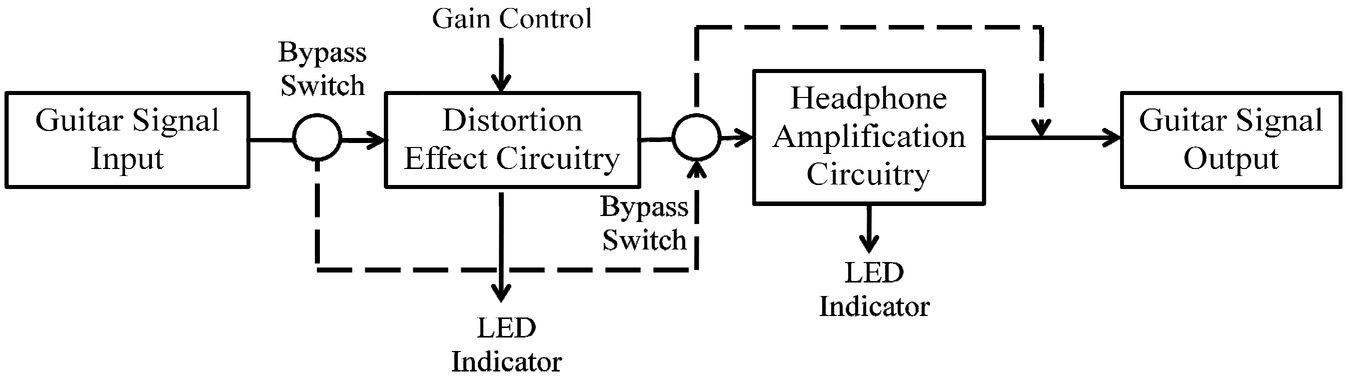
Appendix A

Specifications



System Block Diagram

Modes of Operation

- Distortion Only
- Headphone Amplification Only
- Distortion and Headphone Amplification
- True Signal Bypass

Summarized Feature List

- Distortion Audio Effect
- Headphone Amplification
- Bypass Functionality (Allowing use with headphones or guitar amplifier)
- Gain Control
- LED Status Indication
- Single 9V Battery Powered
- Small Form Factor for Electric Guitar

Appendix B

Part List

Distortion Circuitry

Part	Ideal	Actual
R1	4.7kΩ	4.70kΩ
R2	500kΩ Lin POT	498kΩ Lin POT
R3	1MΩ	1.01MΩ
R4	1MΩ	1.01MΩ
R5	10kΩ	10.02kΩ
R6	10kΩ	10.05kΩ
R7,R8	10kΩ T POT	9.98kΩ T POT
R14	22kΩ	22.1kΩ
R15	100Ω	99.8Ω
R LED Red	10kΩ	10.05kΩ

C1	.47uF	.471uF
C2	.1uF	.10uF
C3	100uF	99uF
C4	10uF	10.01uF
C5	4.7uF	4.69uF
C11	0.056uF	.0559uF

D1	1N4148
D2	1N4148
D3	1N4148
D4	1N4148
D5	1N4148

LED Red	2.3V Red

IC	TL071

Misc.

Part	Type
SW1	3PDT
SW2	3PDT
PCB	FR4
9V Batt	Duracell Alk.
Wire	24 Gauge

Headphone Amplifier Circuitry

Part	Ideal	Actual
R7,R8	10kΩ T POT	9.95kΩ T POT
R11	1MΩ	1.01MΩ
R12	1MΩ	1.02MΩ
R15	10Ω	10.1Ω
R LED Blue	2.2kΩ	2.21Ω

C6	.1uF	.10uF
C12	.01uF	.011uF
C13	100uF	99uF
C14	10uF	10.01uF
C15	.056uF	.056uF

LED Blue	3.5V Blue

IC	LM386

Appendix C

Schedule

Quarter 1

- Initial research of audio signal processing techniques (Weeks 2-3)
- Design of custom audio processing and amplification circuitry (Weeks 4-6)
- Part procurement (Week 7)
- Implementation of temporary circuitry for operational verification (Weeks 7-8)
- Circuit and functionality improvements (Weeks 9-10)

Quarter 2

- Custom PC board fabrication (Weeks 1-3)
- Preparation of electric guitar body (Week 4)
- Implementation of PC board circuitry inside electric guitar (Weeks 4-5)
- Test and Verification (Week 6)
- Report refinement and completion (Weeks 7-9)
- Demonstration (Week 10)

Appendix D

PC Board Layout