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# Theoretical Analysis and Design of Analog Distortion Circuitry

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THEORETICAL ANALYSIS AND DESIGN OF ANALOG DISTORTION CIRCUITRY

by

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GRADUATE PAPER

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I dedicate this work to my father Dr. Eli Saber, my mother Debra Saber, and my brothers Paul and Joseph Saber.

# Declaration

I hereby declare that except where specific reference is made to the work of others, that all content of this Graduate Paper are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This Graduate Project is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

Daniel Saber

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I would like to take this opportunity to thank my family. Thank you Paul, Joe, Mom, and Dad for your continual support throughout my college career. I would also like to thank my friends for their support as well; the friendships I have made with some of my colleagues have been invaluable to my success. Lastly, I would like to thank Professor Mark Indovina for offering me advice, guidance, and setting me up to be successful in my research.

# Abstract

The music industry is one that demands the use of modern engineering technologies, such as effects pedals, in order to achieve a customizable tone for a unique style. Using effects pedals such as distortion, delay, reverb, and many more, a musician can create a specific tone with distinct characteristics and adjust certain parameters of the sound to their own preference. This paper will focus on distortion pedals and the theory revolving around the design of a custom distortion pedal. Different kinds of distortion require different circuitry and different components. Certain types of guitar distortion pedals create distortion using simple transistor circuits and/or diode clipping. Others employ the use of operational amplifiers paired with diodes to create a "distorted" sound. Different musicians may demand various kinds of distortion, and certain types of distortion are used for different styles. For example, fuzz is a type of distortion which is very 'messy' in quality, but widely used for funk, blues, and rock music. There are two main classifications of distortion: overdrive (soft clipping), and regular distortion (hard clipping). Within these two categories, many different types of distortion can be produced. Using specific circuitry is imperative to attaining a specific tonality. By investigating and experimenting with different designs, this research paper attempts to explain and justify the theory behind the creation of distortion in a guitar pedal.

# Contents

# List of Figures

# Chapter 1

# Introduction

Guitar pedal technology has been extremely prevalent in the rock and roll scene since its inception in 1948. Different guitar virtuosos have achieved their signature tone through the use of very specific rigs, using specific pedals, which create a one-of-a-kind sound. Guitarists such Jimi Hendrix, Kirk Hammett, and Zakk Wylde are widely known for using wah pedals in their playing to create their signature tones. Randy Rhoads is known for using chorus pedals on his shred solos, and his high distorted tone is sought after by many. Using guitar pedals, musicians can invent and create different sounds for different styles, and build a brand based on said style.

There are many different kinds of effects that a musician can employ into their rig to create a unique sound. Such effects include delay, reverb, distortion, phasors, and many more. There are many ways to design different types of effects using various analog or digital techniques. For example, some delay pedals are designed digitally to create a more precise, more "robotic" delay. Conversely, analog delay pedals typically are known more a more ambient, warm sound. Due to the advancement in analog and digital technology in the electronics industry, many viable solutions are available to musicians so that they can achieve their custom tone through any means necessary.

This paper specifically focuses on the design and theory revolving around analog distortion circuitry. Analog circuitry offers many different advantages over digital technology. Analog pedals are generally considered to sound more natural to most musicians, which is a preferable trait for many musicians. Typically, even in amplifiers, analog circuitry is sought after due to its natural, classic sound – which is why tube amplifiers have been, and will continue to dominate the music industry. Similarly, analog distortion pedals aim to achieve a similar natural yet classic tone made famous by vintage amplifiers during the 70's and 80's.

### 1.0.1 Research Goals

During this research project, the main goal is to better understand the theory and design involved in creating a custom distortion pedal. Doing this project will help provide the necessary experience needed to be successful not only at RIT, but also as an practicing engineer. Ultimately, the research and design process used throughout this project will build a foundation of knowledge essential to being a professional audio-electrical engineer. Listed below are several main points the scope of this project aims to cover.

- To understand how various distortion types of distortion circuits function (operational amplifier circuits, transistor circuits, etc)
- To understand how different diodes can perform different types of clipping, and why certain diodes perform differently than others
- To design an effective but simple distortion pedal that provides the user with versatility, and reliability, with a satisfying distorted sound

### 1.0.2 Contributions

The significant contributions to the projected are as follows:

1. An input buffer circuit with high input resistance, and low output resistance
2. A distortion circuit with specifically sculpted tonal characteristics to create a "custom" distortion
3. An analysis of different diode characteristics and performance
4. Tone control circuit
5. Volume control circuit
6. Mathematical and logical justification using appropriate analog design theory and PSPICE analysis

### 1.0.3 Organization

The structure of the paper is as follows:

- Chapter 2: This chapter discusses background information and literature sources related to electric guitar, music, and basic concepts related to electrical applications in the music industry.
- Chapter 3: This chapter aims to discuss the general implementation of a guitar distortion pedal circuit. The overall design is divided into smaller subsections and discussed in detail.
- Chapter 4: This chapter delves into the specifics of the theoretical designs, the expected performance, and relevant theoretical simulations in PSPICE.

- Chapter 5: This chapter mainly focuses on the hardware application of the theoretical design, and the testing of the hardware implementation.
- Chapter 6: This chapter presents a summary of results and final conclusions.
- Appendix: This section includes relevant snapshots of some common guitar pedals

# Chapter 2

# Related Work

## 2.1 Introduction

This chapter aims to discuss background information about the history of electric guitars, and related work that has contributed to the development of musical engineering technologies and innovations. The following sections will present some important concepts in understanding the electric guitar, and its role in the music industry. Additionally, an explanation on how musical technologies have impacted the electric guitar, and the music industry will be touched on. It is important to understand the electric guitar's role in music, and its associated technologies because these technologies interact with each other in a very specific manner. Therefore, knowing the mathematics and theory behind these technologies will be useful when designing any type of guitar pedal.

## 2.2 A Brief History of the Electric Guitar

Before the invention of the electric guitar, musicians had already been playing acoustic guitar professionally for hundreds of years. Typically, the instrument was used in smaller ensembles, or performed solo, and it was generally for smaller scale performances. However, because of its quiet nature, it was not suitable for larger ensembles or bands. In larger ensembles, the guitar was typically unable to achieve volume levels easily achieved by other woodwind and brass instruments. Until the conception of the electric guitar and powered speakers, there was no way to combat this issue.

The electric guitar is an instrument that brought something to the music industry that the world had never seen before. Not only did it provide a means for a guitarist to attain higher volumes, but it would provide a whole new flavor of tonal options that the acoustic guitar was unable to offer. Because of this, the electric guitar was an invention that would revolutionize the music industry in the coming decades like no other instrument had ever before.

In the 1950's, rock and blues music began to take over the music industry, and it was becoming a sensation that was sweeping the United States, and the rest of the modern world. As technologies continued to advance, new sounds continued to emerge. Suddenly, guitar virtuoso players such as Jimi Hendrix, Eddie Van Halen, and Jimmy Page were blasting distorted rock guitar riffs and solos, made possible by tube amplifiers and guitar pedal effects. With the help of classic tube amplifiers and an abundance of emerging guitar pedal technologies, the electric guitar was able to evolve into an instrument that filled a niche in the music industry that no other instrument could imitate. As a result, we now remember the 70's and 80's as the decades of classic rock.

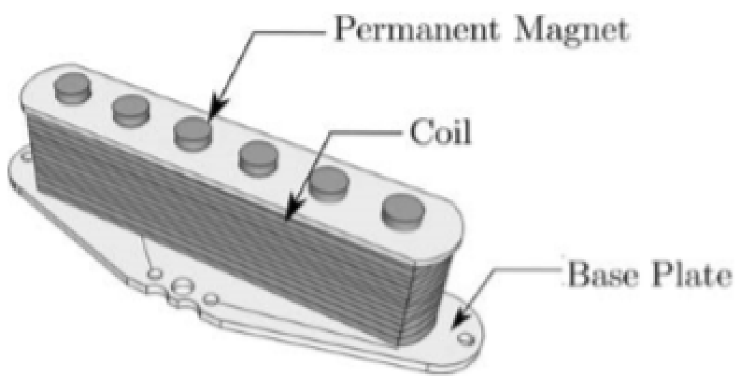


Figure 2.1: Single Coil Guitar Pickup [1]

## 2.3 The Electric Guitar: Elementary Concepts

### 2.3.1 Magnetic Guitar Pickups

The electric guitar is an instrument that uses magnetic pickups to sense vibrations made by the strings on the guitar. The theory and background of how a pickup works is discussed in detail in [1, 2, 7**?** ]. Essentially, a guitar pickup is made of several magnets, wound with copper wire. A guitar pickup has an inherent magnetic field associated with it created by the permanent magnets. When a guitar string vibrates, it creates a disturbance in the magnetic field of the pickup. This induces a voltage onto the pickups which mathematically represents the sound being produced by the string. This signal is what defines the sound of an electric guitar. In [8] the mechanics of how a guitar string vibrates are discussed, and mathematical modeling of real world analog sound is demonstrated. Shown in Fig. 2.1 [1], is a standard single coil guitar pick up 3D model.

We can describe the behavior of a guitar pickup using the Faraday-Lenz laws of physics [1]. The flux of a magnetic field can be described as the integral in Eqn. 2.1. B represents the magnetic field at a given point in time for a permanent magnet, and $dS$ is the surface represented by the magnetic single coil pickup.

$$\Phi = \iint B(t) \bullet dS \tag{2.1}$$

When a guitar string vibrates, it alters the magnetic field emitted by the pickup, which changes the flux across the coil. Faraday's law states that the negative change in flux will induce a voltage onto the coils of the guitar pickup. This voltage induced is the signal that gets input to a guitar amplifier, and output by the speakers.

$$u(t) = \frac{-d\Phi}{dt} \tag{2.2}$$

The sound of a guitar pickup is extremely sensitive to coil length, the type of magnets used, as well as the position of the pickups. Different pickups can produce slightly different sounds depending on how these specifications are designed. In [2], the magnetic field strength of a single magnet is modeled as a function of vertical and horizontal displacement. In Fig. 2.2, the measured magnetic field due to a single magnet as a function of vertical displacement is displayed. In Fig. 2.3, the relative change in the magnetic field of a single magnet due to vibrations of a wire placed above the magnet is displayed.

Understanding these laws are essential to engineering guitar pedal circuits because as engineers, we need to know how to represent analog sound as a mathematical waveforms. Typically, a guitar signal is a relatively small signal, ranging anywhere between 50-900 mV peak-to-peak voltage. In addition to knowing how much voltage a guitar can output, it is important to be aware of the output impedance of a guitar. It is very important in general audio applications for the input signal of a device to have a high impedance, and the output of an audio device to be low impedance. Under perfect ideal conditions, a guitar would have an output impedance of 0

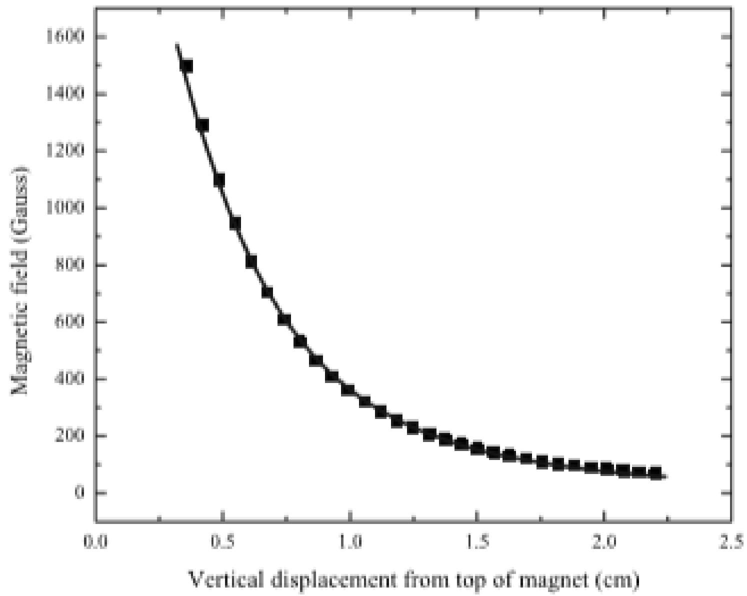


Figure 2.2: Magnetic Field as a Function of Vertical Displacement [2]

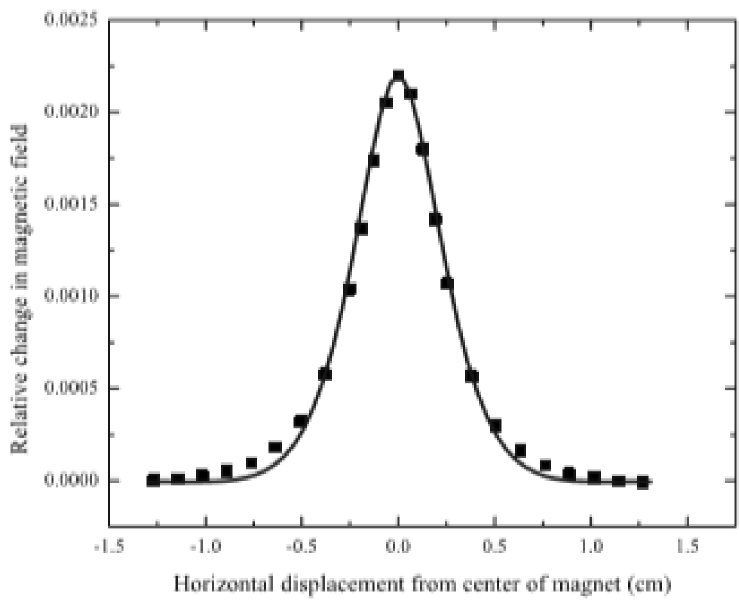


Figure 2.3: Changing Magnetic Field Due to Vibrating Wire [2]

ohms, which would enable an 100% efficient signal transfer. However, due to the impedance of the pickups and internal circuitry, a guitar typically has an output impedance of around 5k-15k ohms[9]. All of these factors and specifications must be taken into account when designing a guitar effects pedal.

### 2.3.2 Guitar Amplifiers: Valve vs Solid State

The guitar industry offers a wide range of different kinds of amplifiers for the practicing musician. There are two main types of amplifiers primarily used by guitarists: Valve amplifiers , and solid-state amplifiers. Valve amplifiers [3, 4, 10] are a type of amplifier that use vacuum tubes to amplify and distort a signal. Many guitarists prefer this type of amplifier for its “classic” sound, made popular by bands like AC/DC, Guns n’ Roses, Van Halen, and many more. However, due to their large size, and high power requirements, guitar pedals and solid-state amplifiers stray away from using tubes to create distortion, in favor of using transistor circuits to create gain [11–13]. These amplifiers tend to have very different tonal characteristics from tube amplifiers. Tube amplifiers are known for having a more natural, warm sound, while solid-state amplifiers are known for having pure cleans and more harsh distortions. In [14], a digital model of a the sound of a tube amplifier is modeled, and discusses the non-linearity associated with distortion.

Both types of amplifiers offer a different set of advantages and disadvantages. Solid state amplifiers tend to be cheaper, and much lighter, which makes them easier to take to performances. Solid state amplifiers also usually don’t require much maintenance, and typically have a very long life cycle. Because of the nature of how vacuum tubes function, they can often crack, break, or just burn out from long periods of use, and thus often need replacing. However, while being more fragile, they usually offer a more versatile distortion than a solid state amplifier. There are certain types of distortions you cannot produce with a solid state amplifier that a tube amplifier can offer.

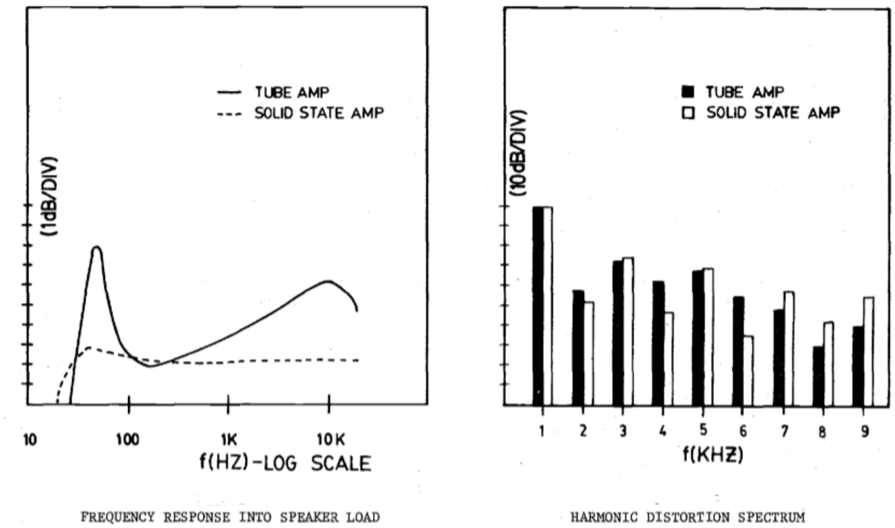


Figure 2.4: Valve vs Solid State Frequency Response [3]

Tonal differences between the two types of amplifiers are talked about in [3, 4]. Although these differences can be subtle to the untrained ear, they can make all the difference to a professional musician.

The reason why tube amps are generally preferred by many guitarists is the way a tube distorts a signal, as opposed to solid state transistor circuits. When a guitar signal is distorted, it produces a new range of harmonics not present in clean guitar signals. Transistor amplifier circuits tend to create a "harder" clipped distortion; the peak of the guitar signal is cut off more abruptly. In tube amplifiers, the clipping is more gradual, and thus allows for more full range of frequencies. Hard clipping a signal causes ultra high frequencies to contain much more energy than the softer clipping offered in valve amps, thus solid state amplifiers are known to have a much harsher distortion.

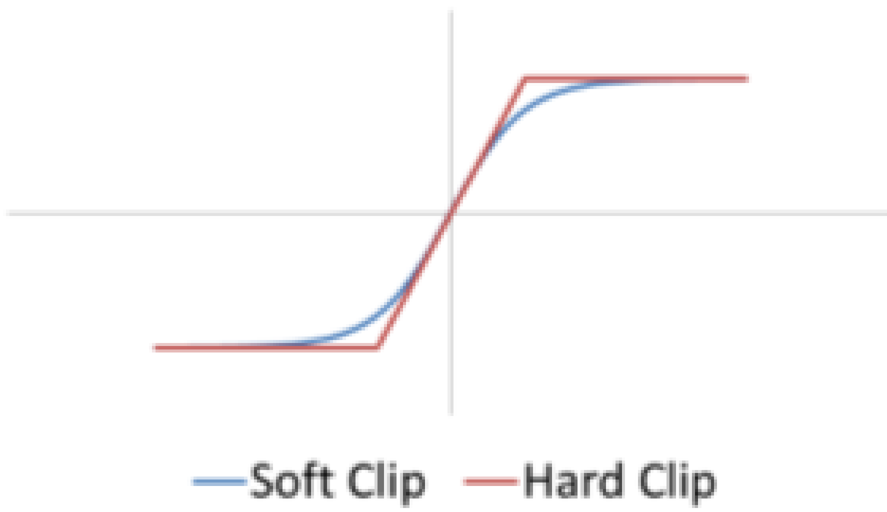


Figure 2.5: Different Types of Clipping by Guitar Amplifiers [4]

### 2.3.3 Guitar Effects Pedals: Analog and Digital Models

Guitar effects pedals are are an essential part to any professional guitarist's rig. There are all sorts of different kinds of ways a guitar signal can be manipulated. Guitar pedals provide simple, yet effective means of manipulating a guitar signal. A guitar pedal is similar to a function in C programming. If you provide an input to a function in C, it will take the input, process it, and return with an output. Similarly, if you provide an input signal to a pedal, it will process that signal, and apply an effect to it, then supply the amplifier with the output signal.

There are many different ways to make a guitar pedal effect. The guitar pedal industry offers a vast selection of different implementations of distortion, both in analog [12, 13], and in digital technologies. Models of digital implementations of guitar effects pedals are explored in [15–17]. While this paper will be focusing on analog distortion specifically, digital implementations still apply the same system level concepts to create distortion. Digital implementations typically approach pedal design by using analog to digital conversion of real-world signals, then manipulating the sampled signal using programming algorithms [17]. In analog design, the manipulation of the signal is done using a combination of transistor and operational amplifier circuits [12, 13].

In most situations, analog pedals rule the market, as the sound quality of such designs are often preferred by most musicians. Analog circuitry is simply just more suitable to deliver what humans perceive to be natural, while digital implementations offer more clean-cut, robotic sounds. For example, one of the more popular delay pedals used by many guitarists today is the MXR Carbon Copy delay. This delay provides a more ambient, muddy delay. Whereas, a digital implementation such as the BOSS DD-8 creates nearly an exact replica of a given input signal, and just offsets the delivery time using linear system theory of the sampling of a signal. However, both pedals have their place in the market, as they can both provide different sound models that can be appropriate for different situations. The modeling of certain nonlinear guitar effects pedals is talked about in [18, 19].

### 2.3.4 Creating Distortion and Overdrive

Overdrive and distortion is an essential effect to have for most professional blues or rock musicians. In the formative years of rock music and the electric guitar, overdrive and distortion was commonly created by over-driving vacuum tubes which would clip the signal, creating a distorted sound. This sound was made famous by bands like the Rolling Stones, Led Zeppelin, and Black Sabbath. Back then, analog circuitry dominated the industry when it came to creating distortion pedals, and amplifiers. Today, there are some other modern digital applications available, but analog circuitry still dominates the industry because of its signature tone. In [20], some numerical analysis and mathematical models are presented for distortion.

Analog circuitry creates distortion and overdrive primarily using some combination of transistors, operational amplifiers [12, 21], and diodes. Distortion is the result of a sound wave being clipped at the peaks of a given waveform. Thus, because of this clipping of the signal, distortion is a non-linear effect. Typically, in guitar pedal applications, the clipping is done by limiting diodes. Recall, that diodes are a type of component that can limit current flow in a specific direction. Hence, when placed at the output of a gain amplifier, they are able to clip the signal when that signal is greater than or equal to the forward voltage of the diode. The type of diode, and placement of the diode is critical in the formation of the sound and tone of the distortion. If the diodes are placed in the feedback path of a gain amplifier circuit, it can create a softer distortion, classified in the music industry as overdrive [22]. When the clipping diodes are placed at the output of a gain amplifier, it creates a hard clipping effect, known as distortion in the music industry. However, overdrive and distortion are used interchangeably in casual conversation.

Some very popular distortion pedals in the industry include the Ibanez tube screamer TS-9, and the BOSS DS-1. Real time modeling of these circuits is done in [23]. Both of these configurations use non-inverting operational amplifiers to apply gain to the input signal. Displayed in Fig. 2.6, is the block diagram the BOSS DS-1[5] uses to create distortion. This diagram, in general, is the same format in which many other companies design their distortion pedals. Usually, in any type of effect pedal in the industry, the input and output are buffered using a simple emitter follower circuit, or some variation of a unity gain operational amplifier circuit. Then, a gain block takes the input signal, scales it, and the diode clipping circuit clips the scaled version of the signal. Usually, some amount of filtering is done in the gain block to reduce harsh high end harmonics and/or muddy low end harmonics. Additionally, a tone control implementation following the clipping circuit is often placed to give the user further control of the harmonic content of the output. In Fig. 2.7, a simple diode clipping circuit is pictured . Some circuit analysis, and physical modeling of distortion is presented in [24]. This paper includes some explanation

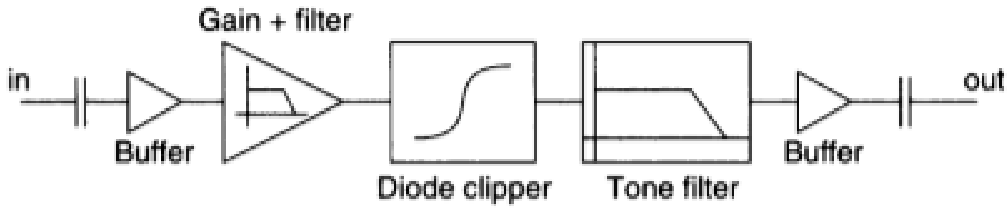


Figure 2.6: Boss DS-1 Block Diagram [5]

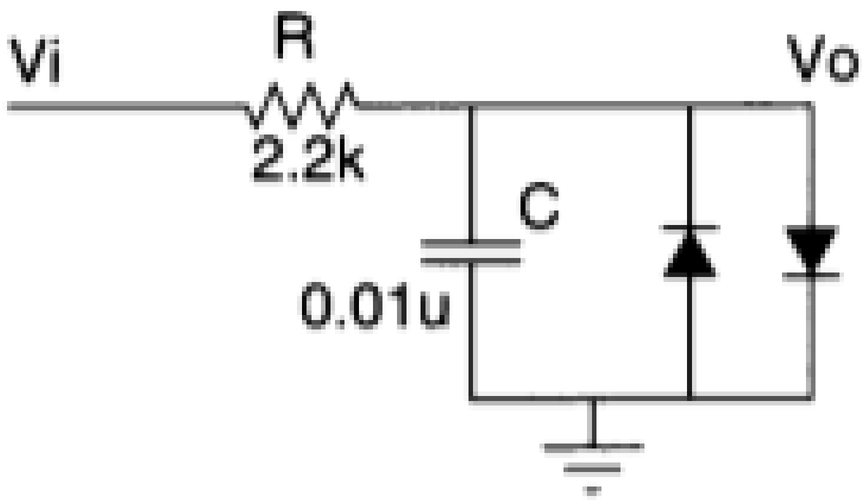


Figure 2.7: General Diode Clipping Circuit [5]

of the non-inverting amplifier configuration, as well as diode clipping characteristics and theory, and several other common simple circuits often associated with analog guitar pedal design.

# Chapter 3

# Architecture and Implementation of Design

## 3.1 Block Diagram Overview

This portion of the paper outlines the high-level block diagram design of the system. Each section of this chapter covers each of the low-level blocks which make up the overall design. The block diagram begins with a buffer circuit block, followed by a gain block, a hard clipping stage, a tone control block, and finally an output buffer circuit. This basic block diagram is a very common configuration that many analog distortion pedals use in the industry today [5, 23].

### 3.1.1 Top Level Block Diagram

Shown below in Fig. 3.1 is the top level block diagram of the system. This section is meant to give a brief summary of each block in the system. Each block performs one specific task which is required for the overall system to function. The power block provides the integrated circuits in the system with a 9 V power source, as well as providing a 4.5 V virtual ground reference. The input buffer circuit allows for accurate and complete transferal of the input signal to the gain stage, and prevents any loss of signal. The gain stage takes the given input signal from the

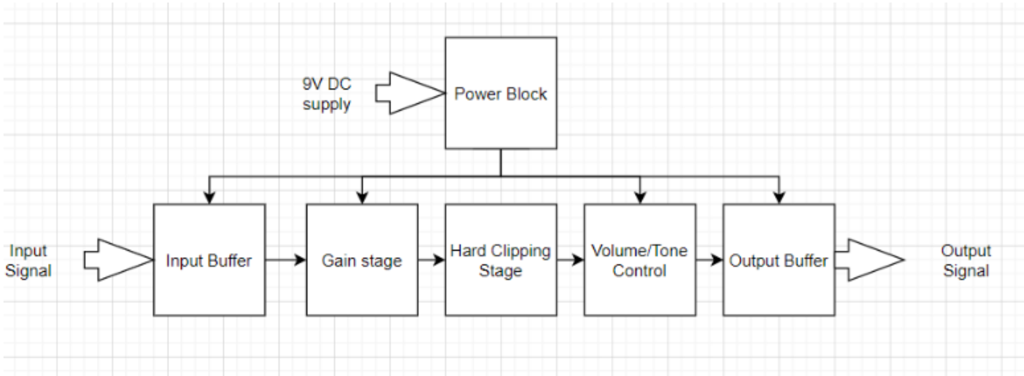


Figure 3.1: Top Level Block Diagram

guitar, and applies a gain to it [25]. Additionally, diodes may be placed in the feedback path of this circuit to provide a soft clipping effect. The hard clipping stage uses diodes to clip the final output of the signal to achieve a true distorted sound. Following this, the volume and tone control interfaces are represented to allow the user to shape the sound of the pedal to their specific preference. Finally, an output buffer is implemented to accurately transfer the signal to the guitar amplifier input. The implementation and details regarding these blocks will be discussed in the following sections.

## 3.2 Power Block

The power section in this circuit is supplied by a 9 V DC source. This source provides the needed operating voltages for several of the operational amplifiers used in this application. The vast majority of guitar pedals in the industry operate using 9 V DC. This standard was upheld to provide a convenient experience for the user, while also providing a suitable amount of power to the circuit. Additionally, a voltage divider was used to create a 4.5 V DC voltage source point. Through the use of a unity gain op. amp configuration, this 4.5 V DC was used to create a virtual ground for the op. amp circuitry, so that the input signal voltage was at an appropriate DC

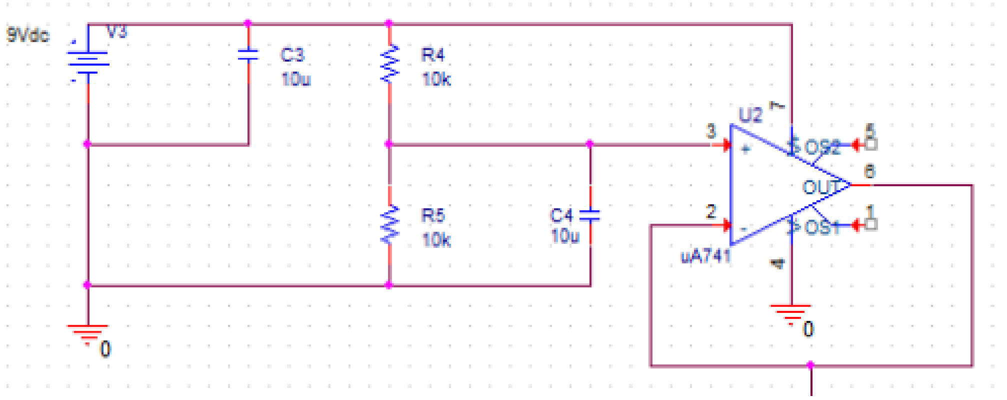


Figure 3.2: Power Block

voltage. By establishing a virtual 4.5 VDC ground at the op. amp input terminals, it ensures that the signal will be within the swing voltage range of the amplifier. An operation amplifier was used to transfer this virtual ground to the other circuits for purposes of isolation. By buffering the voltage point with an op. amp, it denies the opportunity for interference from other components in the voltage division.

## 3.3 Buffer Stage

Nearly every distortion pedal made in the music industry modernly has a built-in input and output buffering circuit. This circuit is imperative in ensuring the integrity of a given input signal. Typically, an electric guitar can output a signal with an amplitude between 50 mV to 500 mV. To maintain the integrity of this signal, a unity gain buffer circuit must be enacted. For most guitar pedal applications, there are two common ways of doing this: an emitter follower circuit[24], or a unity gain operational amplifier circuit. Both of these circuits attempt to achieve a large input impedance, with a low output impedance. This is because of the simple concept of how a voltage divider functions. In a buffer circuit, the buffering device, whether transistor, or otherwise, will act as a voltage divider. As according to ohm's law, voltage will drop across high impedance

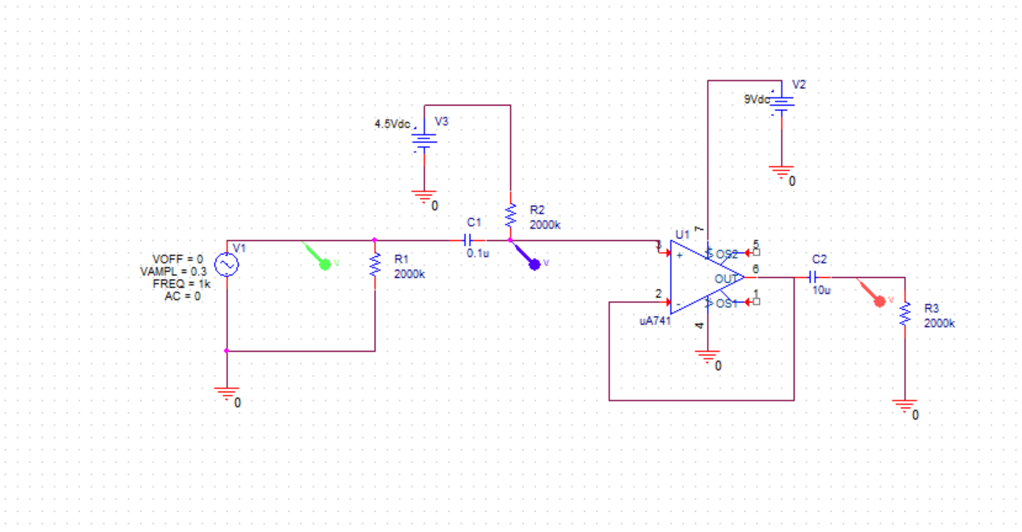


Figure 3.3: Buffer Circuit

components. Hence, to maintain as much of the signal as possible, the input resistance should ideally be infinite, and the output resistance should be zero. This would result in a complete transferal of signal. In real applications, this ideal condition is impossible, but using the buffer circuit, most of the signal is preserved. In this particular application, a unity gain operational amplifier is utilized to buffer the guitar signal from the distortion circuit. As previously mentioned, it is also possible to make a similar functioning circuit using an emitter follower transistor circuit. Older pedals such as the Ibanez TS-9 use this method to isolate the guitar signal from the gain stage of the pedal. However, given that modern operational amplifiers are simpler to design around, more universal, and overall more effective, a unity gain op. amp configuration was chosen for this particular design. Pictured in Fig. 3.3 is the circuit layout in PSPICE for the buffer circuit, as well as the DC voltages at each point.

## 3.4 Gain Stage

The gain stage of the circuit was designed using a non-inverting op. amp configuration. This configuration is a very common method to apply gain to a given signal [12, 13, 24], and is used in many different guitar pedals on the market presently. Essentially, this stage takes the signal delivered by the input buffer circuit, and applies a gain which depends on the values of the feedback loop resistor R4, and resistors R3 and R2, which are shown in the Fig. 3.4. This stage of the circuit is critical to the functionality of the overall design. By applying gain to the signal, it is ensuring that the peak voltage is reaching a high enough level so that it can be clipped by the chosen diodes found in the hard clipping stage. Typically, silicon diodes have a forward voltage of 0.7 V, while germanium diodes typically have a forward voltage around 0.3 V. Because a guitar signal is often lower in amplitude than these two voltages, a gain must be applied so that the signal reaches a suitable level. For example, if a given guitar signal is only 100 mV in amplitude, and the clipping diodes at the output are silicon 0.7 V diodes, then the signal won't clip, meaning the sound will not be distorted. However, if the gain stage amplifies the signal by a factor of 10, then the signal will clip once it reaches 0.7 V. Note that potentiometer R3 in Fig. 3.4 gives the user the ability to adjust the amount of gain to their preference. This feature allows for the customization of sound by the user. If a highly distorted sound is desired, the user can dial the potentiometer to its maximum setting. If a moderate amount of distortion is desired, the user can adjust the potentiometer to be at a neutral setting. Or, if little to no distortion is desired, the user can dial the potentiometer to a minimum.

## 3.5 Hard Clipping Stage

This stage of the circuit is critical to the signature sound of a distortion pedal [20]. There is an endless amount of possibilities when choosing a type of diode to create a signature distortion.

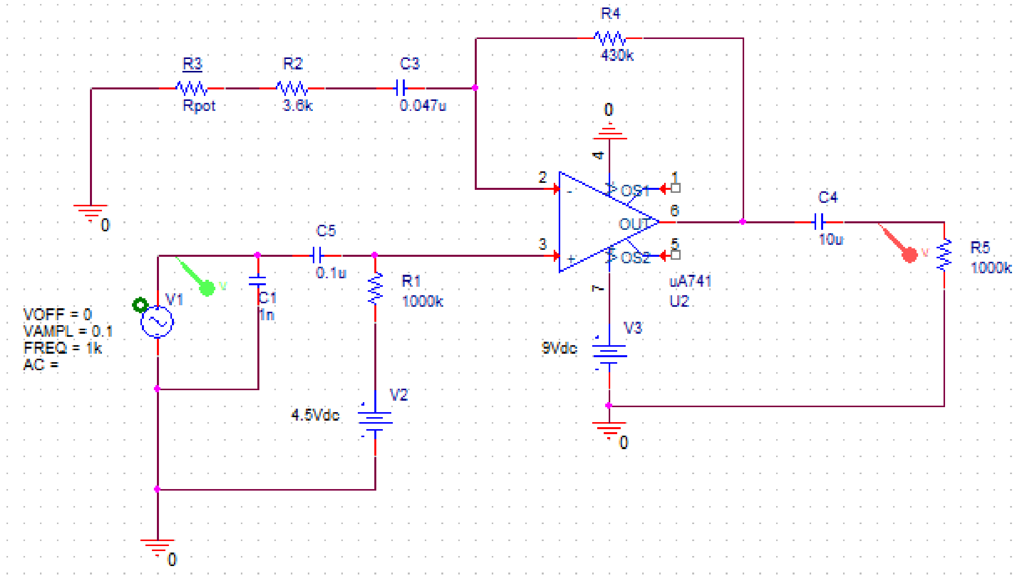


Figure 3.4: Non-inverting Amplifier: Gain Stage

Recall that a diode is a component that only allows current to flow in one direction. This fundamental concept allows the incoming guitar signal to be clipped at the output, creating a distorted guitar sound. In the music industry, many different pedals use different kinds of diodes to get a different signature sound. The type of diodes used depend on the preference of the designer, or user of the pedal. In this paper, several different diodes are explored and tested to determine the effects different diodes can have on the sound and frequency response of the circuit. In terms of function, the clipping stage does not depend on the type of diode used, except that the forward voltage can vary between different types of diodes. In terms of sound definition and tone, the type of diode is key in defining the characteristics of the sound. Some diodes can produce a more muddy sound, while others may deliver a more precise sound. In this paper, several different types of diodes are examined and modeled to show the difference in sound quality that certain diodes can offer compared to others. Often times, these differences can be subtle, but any small difference can mean a lot to the attuned ear of a practicing musician. In the world of music, a small tonal difference can make or break a song, or even an entire album. Hence, knowing which

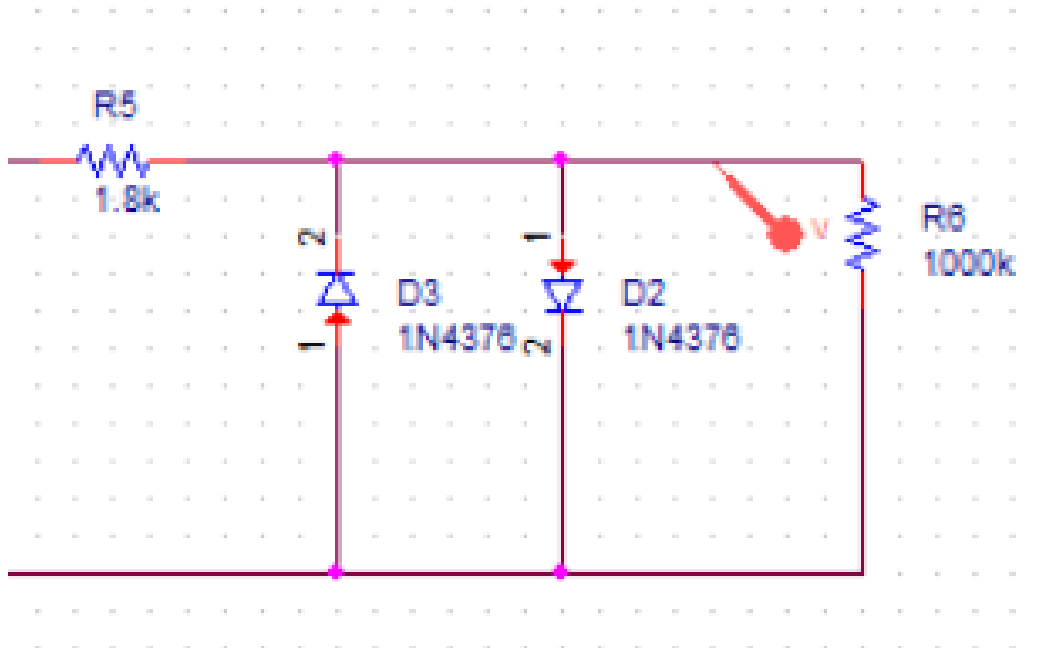


Figure 3.5: Hard Clipping Stage

types of diodes provide certain types of characteristics is not only interesting, but also practically invaluable to any serious musician or audio engineer.

Note that, during testing of this simple clipping circuit in Fig. 3.5, the load resistor R6 was placed at the output. This resistor will be replaced with a potentiometer to allow for adjustable volume. A volume knob is standard on any guitar distortion or overdrive pedal, and is usually placed at the output of the clipping stage, so that the load resistance can vary the amplitude of the final signal. Typically, either a linear or logarithmic potentiometer can be used here, but generally logarithmic potentiometers are known to provide a more "smooth" sound due to how the human ear perceives sound.

## 3.6 Tone Control Stage

In addition to the hard clipping stage, the tone control stage is yet another way a distortion pedal can create its own signature sounds. This stage provides a lot of creative freedom to the designer, as it allows for sculpting of the frequency response of the signal. Many pedals in the industry have 3 separate equalization dials: treble, mid, and bass. Others have just one master tone control for simplicity and ease. These circuits, while very powerful and useful, are also actually no more than simple RC filtering circuits. Using RC filter circuits such as low-pass, high-pass, band-pass, and band-reject filters, a design engineer can mathematically place desired cutoff frequencies along the frequency range to achieve a desired tonal signature. In this application, an operational amplifier low pass filter circuit is used as a master tone control to allow for versatile but simple tonal control. This low-pass filter is comprised of resistors R2 and R4, as well the capacitor C6. The low-pass filter was placed at the output of the op. amp for isolation purposes. The way this circuit functions is actually quite simple; the potentiometer allows the cut off frequency to be adjusted as preferred by the user. The higher the value of the potentiometer, the lower the cutoff frequency. So if the user were to prefer to have a lot of treble and presence, then they could adjust the potentiometer to a lower setting. If the user preferred less prominent high frequencies in their tone, they could adjust the potentiometer to a higher position. Pictured below in Fig. 3.6 is the tone control op. amp circuit design.

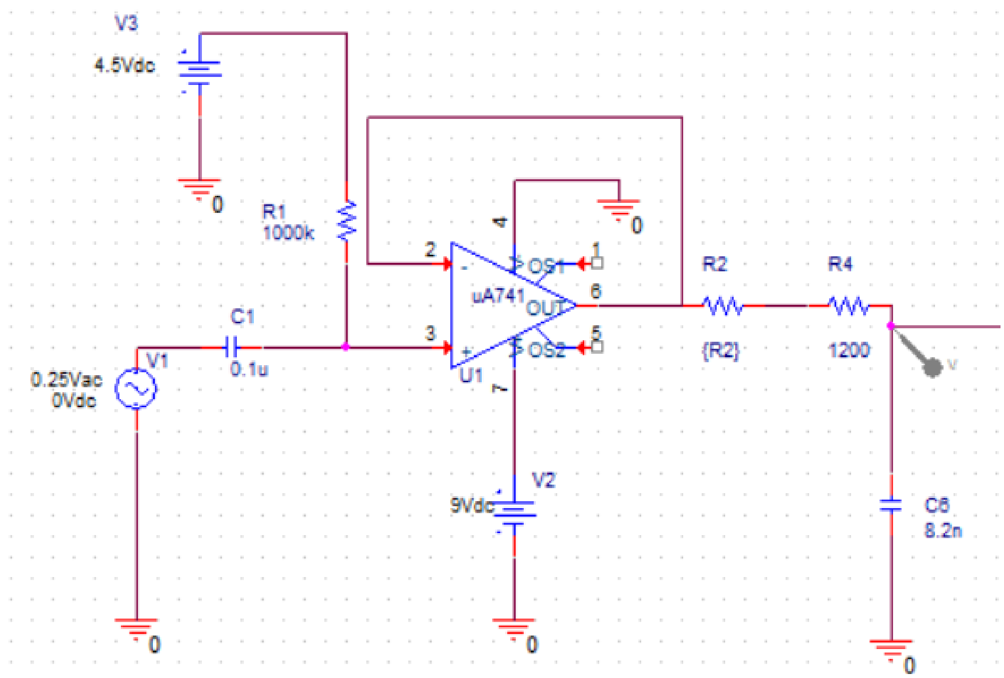


Figure 3.6: Tone Control Stage

# Chapter 4

# Theoretical Analysis and Design

In this section of the paper, the aim is to go over in detail all of the mathematics and theory involved in the design process of an analog distortion pedal. Additionally, the material presented in this section will offer explanation and justification for specific design decisions made for the analog circuitry. Lastly, a proof of concept will be established in the theoretical simulations provided, which will provide a logical expectation for the performance of the design, and its characteristics.

## 4.1 Fundamental Theoretical Concepts

### 4.1.1 Operational Amplifiers

Modernly, most analog distortion pedals are created using cascaded operational amplifiers coupled with supporting passive circuitry. Operational amplifiers are an active linear component that can be used to create gain in a circuit, which is essential in the case of creating distortion. The operational amplifier is a very universal in nature; it can be used for a wide range of applications including but not limited to signal conditioning, active filters, and mathematical operations. Because of its nearly ideal operating conditions, it has become an industry staple for analog guitar pedal design. In Fig. 4.1, an ideal operational amplifier is shown [6]. An operational amplifier, commonly known as an op-amp, is a device with a positive terminal, a negative terminal, and a single output. An op-amp has two input terminal conditions that should be taken note of when designing analog circuitry. Firstly, the voltage at both the positive and negative terminal will always be equal. Secondly, no current will flow into either one of the inputs. Additionally, an op-amp should ideally have an input infinite input impedance and zero output impedance. It is impossible to achieve this ideal condition of course, but generally op-amps are considered to be near ideal in performance for most applications. Because of this characteristic, it makes the op-amp perfect for signal conditioning applications and buffering. By understanding all of the previously mentioned characteristics of op-amps, we can utilize them to design analog circuitry.

In addition to the previously mentioned op-amp characteristics, some other parameters to take into account are the bandwidth and slew rate of an operational amplifier. The bandwidth of an amplifiers is the frequency range in which an amplifier can apply a gain within 3 dB of the maximum gain [21] . Most modern operational amplifiers offer a wide bandwidth suitable for almost any distortion application, as humans can only detect frequencies of up to 20 KHz. As for the slew rate, this parameter indicates how fast the output of the amplifier can adjust relative to the input signal. Generally, with a slew rate of 0.5 V/us or better, no audible difference will be detectable. Because guitar signals are smaller signals, a 0.5 V/us slew rate would allow for the op-amp to adjust 5 volts in 10 micro-seconds. Hence, 0.5 V/us is fast enough to have no significant impact on performance of the circuit for this specific audio application. Later in this chapter, this concept is proven using the LM741 op-amp, which has a slew rate of 0.5 V/us.

Operational amplifiers [21, 24] have several different common configurations that can be used to amplify a signal. However, in this paper we will primarily focus on the non-inverting

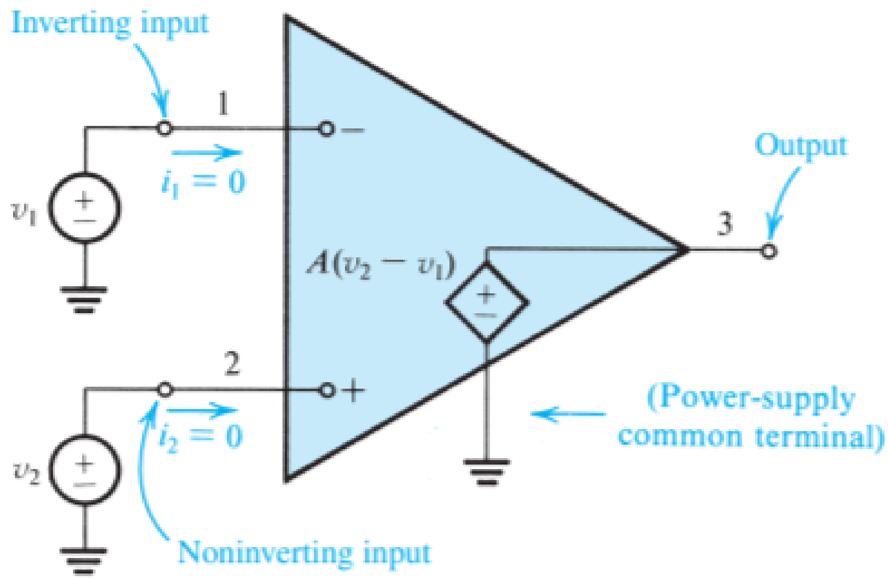


Figure 4.1: Ideal Operational Amplifier [6]

configuration commonly used in analog distortion pedals. The non-inverting amplifier configuration, pictured in Fig. 4.2 , is capable of producing voltage gain depending on the feedback loop resistors associated with the negative terminal of the amplifier [6]. Take note of the equation in the Fig. 4.2 denoted as #6; this equation is the fundamental gain equation for a non-inverting op-amp. Using the feedback loop resistors, an engineer has the opportunity to set the gain to a constant value, or a controlled variable value by implementing a variable resistor. Additionally, note that if unity gain is desired, simply connecting the inverting input directly to the output will produce a one-to-one input to output voltage ratio.

### 4.1.2 Diodes and Clipping Circuits

The diode is a simple nonlinear device that allows current to flow in the forward direction, and blocks current from flowing in the reverse direction. A diode has two terminals, the positive terminal known as the anode, and the negative terminal, which is the cathode. When a diode

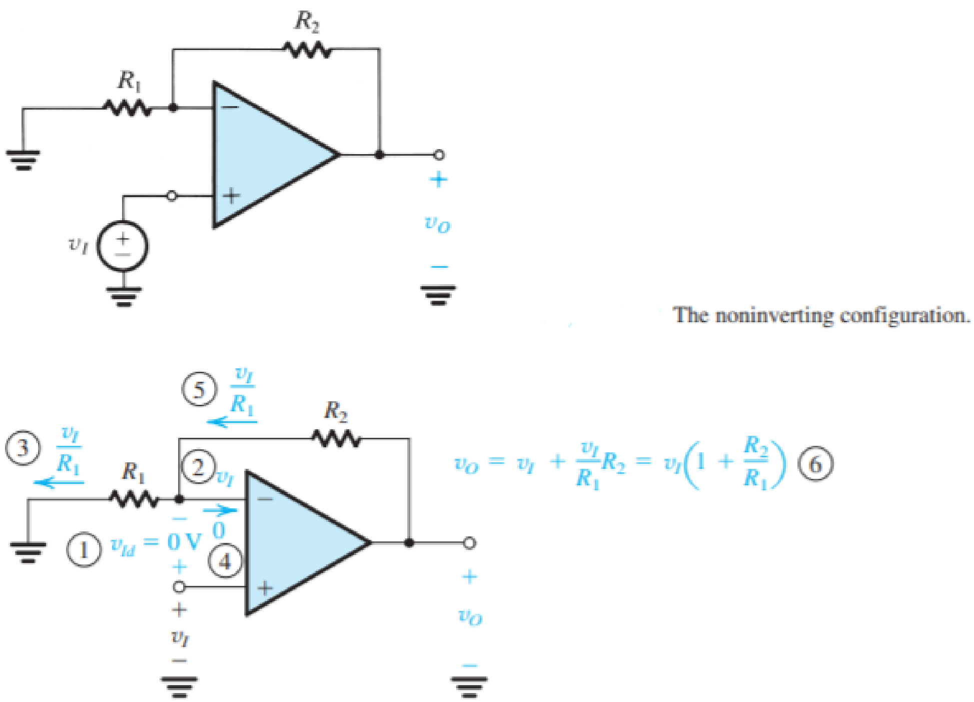


Figure 4.2: Non-inverting Configuration [6]

is connected to a circuit in the forward biased position, current will flow from the anode to the cathode. However, if the diodes position is reversed biased, the current will not flow through the cathode to the anode. See Fig. 4.3 for an IV curve of a diode [6]. Unlike a typical resistor, its IV curve is nonlinear in nature. It behaves similarly to an on-off switch. When the forward voltage is reached, it will allow the complete flow of current. Before the forward voltage is reached, some current will flow through, but only a fraction of the current available will pass through.

The characteristic equation that describes semiconductor diodes is given as the equation shown below [12]. The current flowing through the diode is $I_D$,the saturation current is given as $I_s$. The voltage drop across the diode is $V_D$, and $V_t$is the thermal voltage. For different types of diodes, the saturation current and thermal voltage can vary depending on the P-N junction

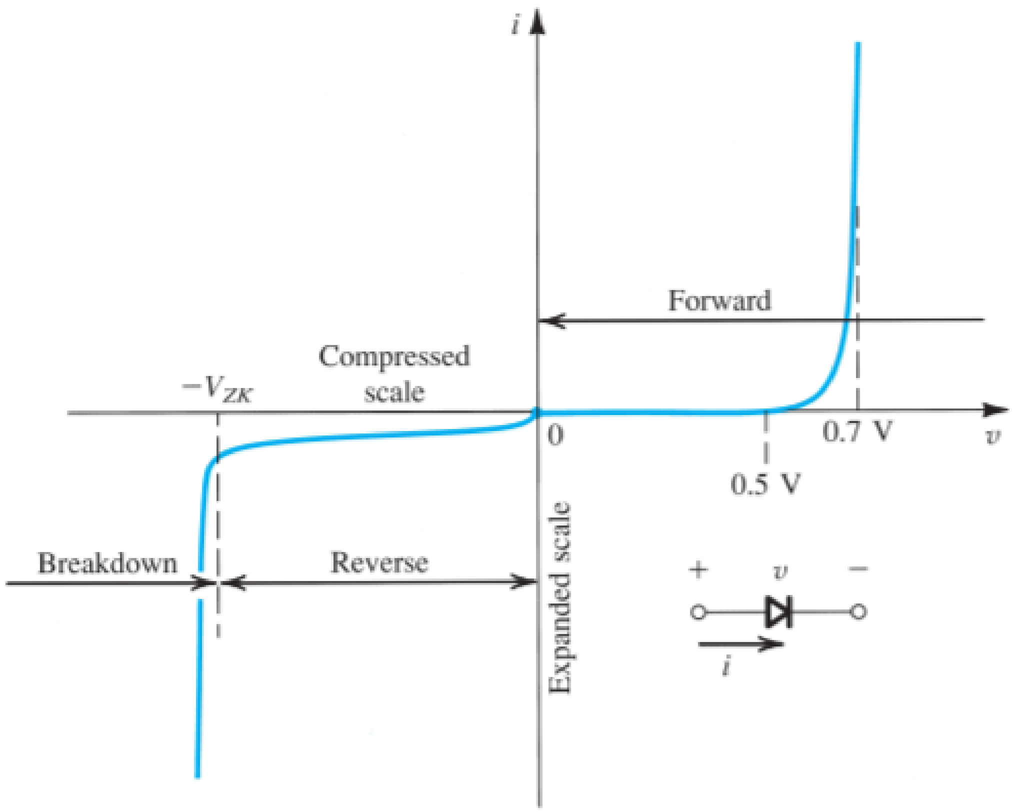


Figure 4.3: Diode IV Curve [6]

properties. For silicon diodes the diode characteristic equation is shown in Eqn. 4.1.

$$I_D = I_s(e^{V_d/V_t} - 1) \tag{4.1}$$

When a diode is forward biased, is will have a small voltage drop across it. This voltage drop can vary depending on the type of diode being used in the circuit. For silicon diodes, a 0.7 V voltage drop is usually standard. Germanium diodes on the other hand typically have a forward voltage of only 0.3. Other diodes like LED's can have even larger voltage drops than silicon and germanium diodes. The forward voltage of a diode is a critical detail in designing clipping circuits for guitar distortion pedals. Besides clipping circuits, diodes have many other applications in electronics including (but not limited to) circuit protection, rectifier circuits, and lighting. However, this paper will specifically focus on how diode clipping circuits can be used in guitar distortion pedals [12, 13, 24].

In analog guitar circuits, diodes are responsible for creating the sound our brains perceive as distortion. Inserting two opposing diodes into the feedback path of a gain amplifier circuit will cause soft clipping (overdrive) to occur in the signal if the voltage is equal to or exceeds the diode forward voltage. Inserting two opposing diodes at the output of a gain amplifier circuit will cause hard clipping (distortion) to occur in the signal if the voltage is equal to or exceeds the diode forward voltage. Both of these types of clipping can have different frequency response characteristics that defines the sound [25].

Diodes are one of the primary aspects of a distortion circuit that can help form the signature tone of a guitar pedal. Of course, there are other aspects in a analog distortion circuit that can affect the frequency response, such as filters, type of op-amp used, and guitar cables [26], but diodes are the primary component in determining the characteristics of the distortion itself. Certain diodes may provide a more square clipping, which would result in a fuzzier sound. Some diodes may have a higher forward voltage, and thus clip less of the signal than lower rated diodes.

Fig. 4.4 is a general diode clipping configuration used in analog guitar circuits [12, 13, 20, 24]. Using the previously discussed theory about diodes, we can dissect the general operation of this circuit. When a guitar signal enters the circuit, and its amplitudes do not exceed the forward voltage of the diode, then theoretically, little to no current will flow to ground, and the signal will pass through to the next stage of the circuit effectively unaltered. However, if the amplitude of a guitar signal should exceed the forward voltages of the diodes, then at the positive peaks of the wave, the forward biased diode will leak all current to ground. Similarly, the reversed biased diode will cut off the negative peaks of the sound wave when they exceed the forward voltage.

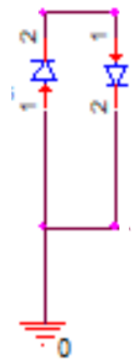


Figure 4.4: General Diode Clipping Circuit

By using gain supplied by an op-amp circuit, the user can adjust the amplitude of the waveforms entering the clipping circuit, allowing the user to control the degree to which the diodes clip the signal. This is the single most significant concept an engineer must understand to design an analog distortion pedal.

## 4.2 Theoretical Design and Simulation

This section of the chapter aims to go over specific design decisions made in the making of the analog distortion circuitry, and verification of chosen designs using PSPICE simulations. The op-amp used for the theoretical PSPICE simulations was the LM741. This general purpose op-amp is suitable for modeling purposes, but eventually will be replaced in the PCB design in favor of a faster, lower noise amplifier.

### 4.2.1 Buffer Circuit Design

The buffer circuit was a necessary design decision for the circuit, as it provides isolation between the guitar and the distortion circuitry. Many pedals in the industry use a buffer circuit at the input and output to ensure proper transferal of a guitar signal [12, 13, 20, 24].

For the buffer circuit in Fig. 4.5 shows the chosen design for this application. While it is common to use emitter follower circuits when designing buffers, a unity gain op-amp configuration was favored over the emitter follower due to its ease of design, and more modern approach.

First and foremost, the operational amplifier supply voltage was chosen to be 9 V, as it is an industry standard for guitar pedals to have 9 V supplies, whether from wall adapter or battery. Also, this will provide plenty of DC power for the circuit to function properly considering a guitar signal is typically smaller in magnitude comparatively. The parallel resistors attached to the non-inverting input of the op-amp were chosen to be 2.2MΩ. The Thevenin equivalent circuit would result in the input impedance being approximately 1.1MΩ. These resistors help maintain a high input resistance to the op-amp, which is an important characteristic for a buffer amplifier circuit. Recall, guitar pickups typically have an output impedance of 5k-15kΩ [9]. By having an input resistance of 1.1MΩ, it minimizes loading the preceding stage of the guitar pedal [24].

This circuit at the core is a unity gain op-amp. The signal enters in via the positive terminal. The output, which is wired directly to the negative terminal, then delivers the unaltered signal to the distortion stage of the circuit. The capacitors C1 and C2 are meant to isolate DC power from entering or exiting the circuit. This is necessary so that a DC voltage does not enter the guitar, or exit into the amplifier, which could cause damage to internal circuitry. Additionally, it is important to note that capacitor C1 forms a high pass filter with the resistor R2. Due to this, a capacitor value of 0.1 $\mu F$ was chosen so that no frequencies would experience filtering at this stage. Similarly, the output capacitor forms a low-pass filter with resistors in the following stage of the circuit. To prevent any unwanted filtering, a large capacitor value was selected.

For this circuit, a virtual ground of 4.5 V was created using a standard voltage divider. This virtual ground supplies 4.5 V of DC voltage to the AC guitar signal, to ensure that the voltage level is within suitable range of the op-amp supply voltage. In the Fig. 4.6, the DC voltages at

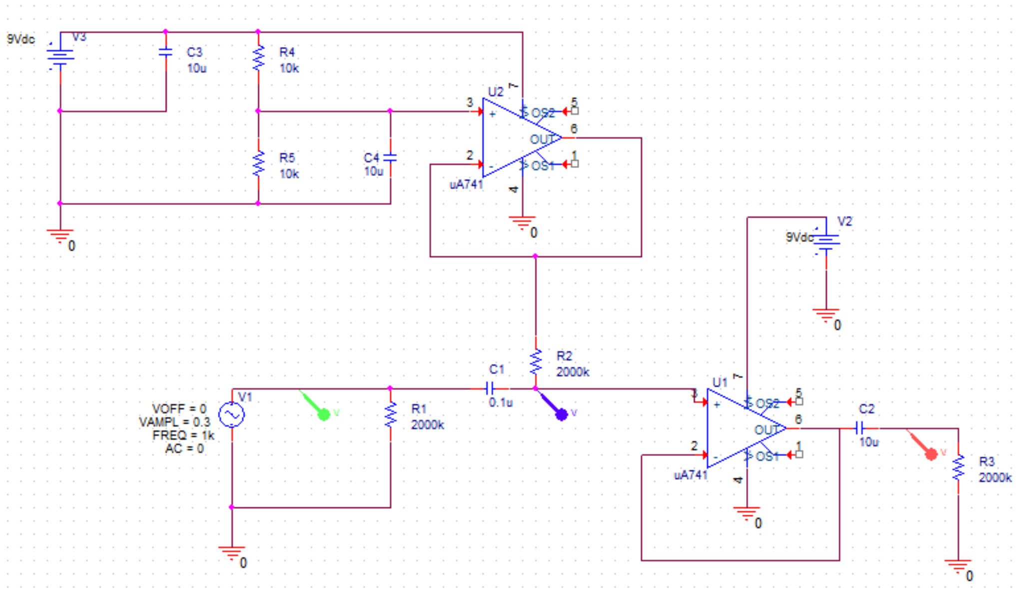


Figure 4.5: Buffer Circuit Theoretical Design

each point in the circuit are shown. The capacitors successfully isolate DC from the source as well as the intended output. The DC voltage is only supplied to the signal as it interacts with the op-amp, and is then filtered out after the unity gain operation has been completed.

From a theoretical standpoint, this circuit should deliver an identical signal to the output. To test this speculation, a PSPICE transient simulation was performed. In Fig. 4.7 the buffer simulation result can be observed. Notice that the original signal (green) and the final resulting signal (red) are identical, which indicates that the unity gain circuit design is valid. The intermediate signal (blue) is also identical to the input signal, except that it has a DC voltage of roughly 4.3 V. This further confirms the operation of the buffer circuitry.

### 4.2.2 Gain Stage

The gain stage of the analog circuit design is instrumental in the function of the distortion pedal. By providing gain to the input guitar signal, we can effectively adjust the degree to which the

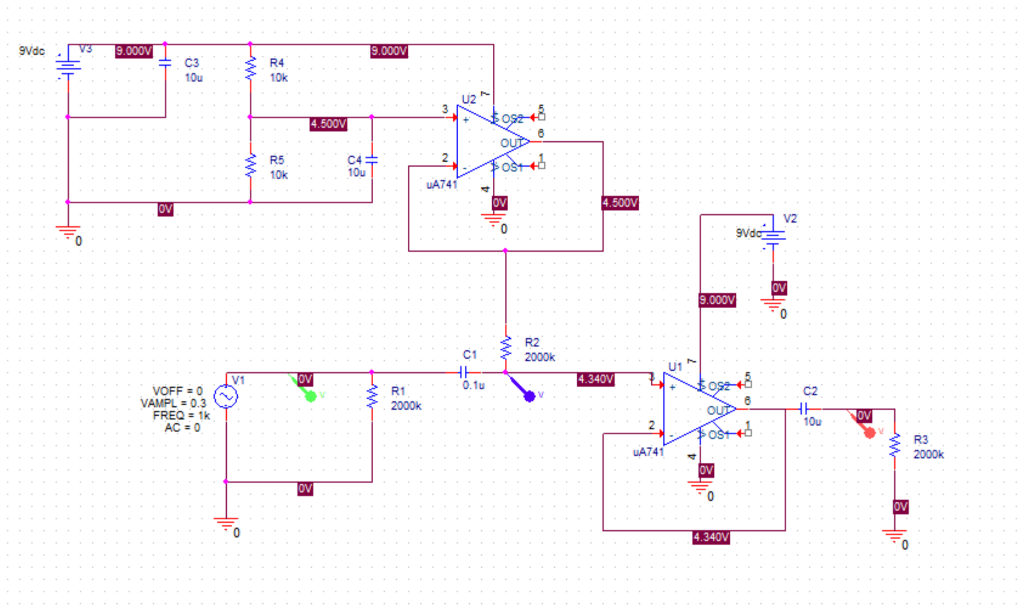


Figure 4.6: DC Voltages

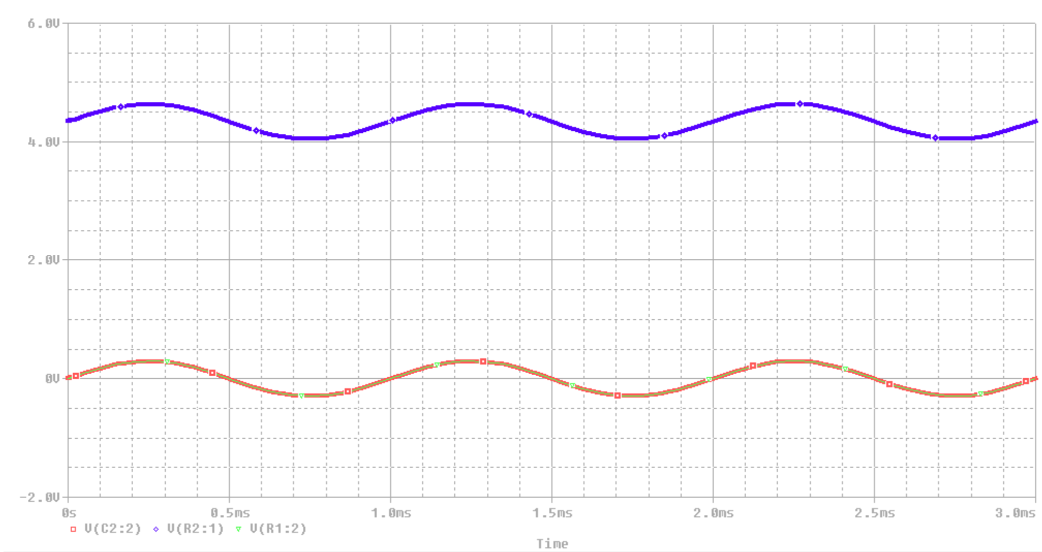


Figure 4.7: Buffer: Theoretical Simulation

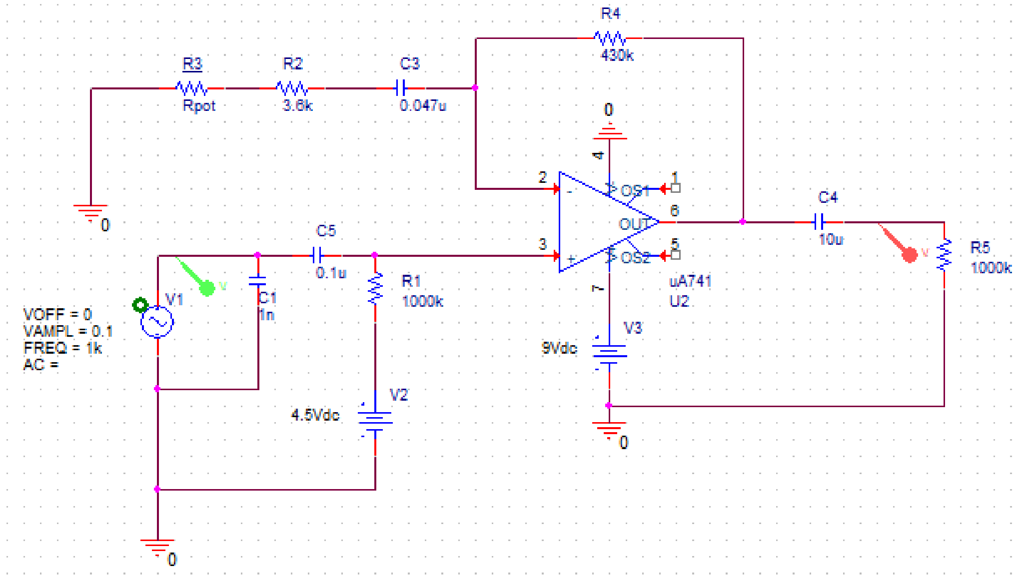


Figure 4.8: Theoretical Schematic: Gain Stage

diodes clip the signal. This stage takes advantage of the non-inverting configuration commonly used in many guitar distortion pedals in the industry [11, 13, 24]. In Fig. 4.8 the schematic design of the gain amplifier stage can be observed.

To understand the schematic design, first take note of the similarities to the buffer circuit. DC blocking capacitors were used once again to prevent DC voltages from infiltrating other circuitry. Additionally, this circuit also uses a 1MΩ resistor to maintain a high input impedance to the circuit. The main difference between this circuit and the previous buffer circuit is the gain factor. In the previous buffer circuit, the gain was set to be unity. In this configuration, the gain is calculated using resistors R2, R4, and variable resistor R3, which has a maximum value of $1M\Omega$. From these values, one can calculate the minimum and maximum gain the non-inverting amplifier circuit can apply to the signal [21].

The gain equation for the non-inverting op-amp configuration in Fig. 4.8 is given as:

$$\frac{v_o}{v_i} = 1 + \frac{R4}{R2 + R3} \tag{4.2}$$

The max gain setting of the circuit is achieved when potentiometer R3 is set to 0, which applies a gain 41.62 dB to the signal. When the resistor R3 is set to 1M$\Omega$, the gain is 3.10 dB, which is the minimal gain setting. To prevent the gain of DC voltage by the op-amp circuit, capacitor C3 was placed in front of the series resistors shunt to ground. This capacitor also provides another key role in this circuit design besides blocking DC, which is forming a high-pass filter with resistors R2 and R3.

Recall the equation for calculating the cut-off frequency of a passive filter:

$$f_c = \frac{1}{2\pi RC} \tag{4.3}$$

In this case, R is the sum of the series resistors shunt to ground from the feedback path. Because R3 is a 1M$\Omega$ variable resistor, the filtering will be adjusted as the gain is adjusted. At the minimum gain setting, the cut-off frequency of the high-pass filter is 3.4 Hz, which means the filter will have little to no effect on the frequency content of the signal. However, as gain is dialed up, the filtering also increases. At the maximum gain setting, the high-pass filter will have a cut-off frequency of 940 Hz, meaning frequencies below this point will be attenuated. This filter was designed to prevent the distortion from containing too many muddy low frequencies, but is ultimately a subjective design decision. This cut-off point can be changed to the designer's preference depending on the desired sound. By adjusting the value of the resistor R2, the filter cut-off frequency can be lowered or raised, but not without affecting the maximum gain setting of the circuit.

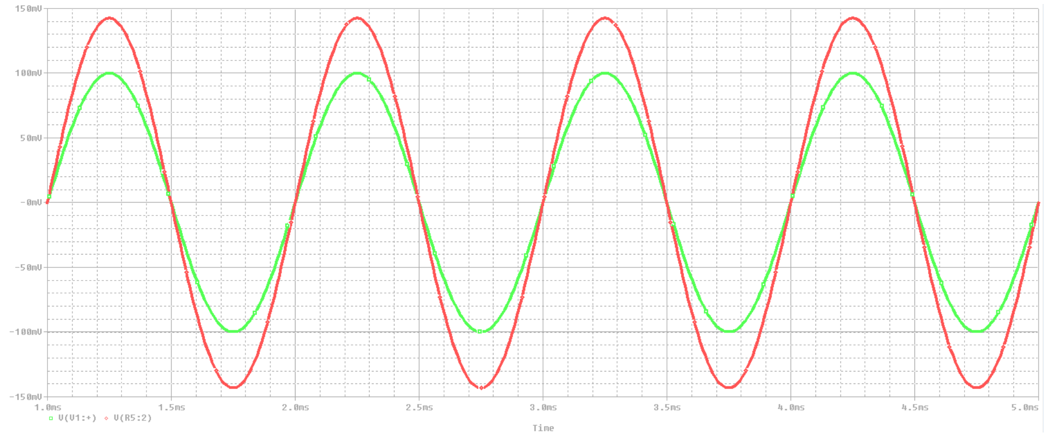

Figure 4.9: Minimum Gain Setting: Potentiometer = 1MΩ

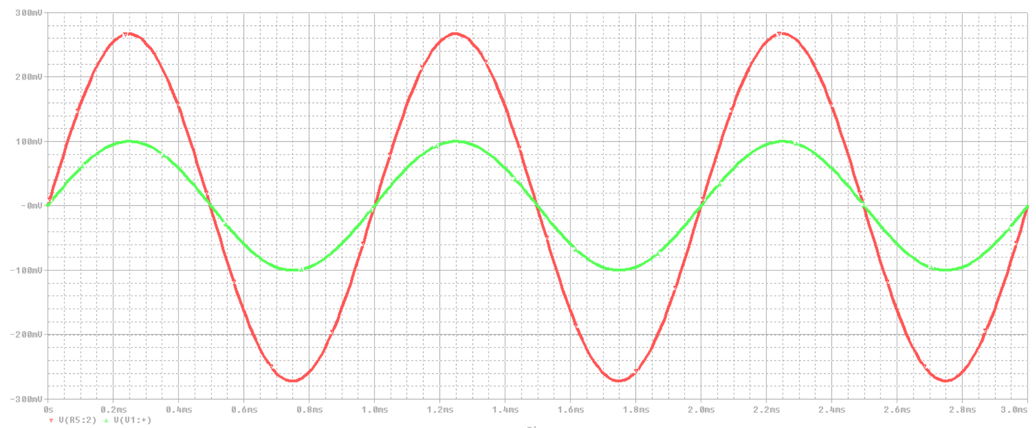

Figure 4.10: Potentiometer = 250kΩ

Figures 4.9, 4.10, 4.11, and 4.12 are from simulations of the gain stage at different potentiometer values. The clipping stage was not added for these simulations. These simulations functionally confirm that adjusting the potentiometer R3 increases the gain in the circuit as anticipated. At the max gain setting, take note of the signal peak being clipped. This is because the op-amp rail-to-rail voltage is clipping the signal at the DC virtual ground, thus demonstrating the purpose of the virtual ground. In the final circuit implementation, the op-amp will not clip the signal due to the diode forward voltage values being lower than 4.5 V, meaning the diodes will clip the signal at a lower value, effectively negating the effects of the op-amp rail-to-rail clipping.

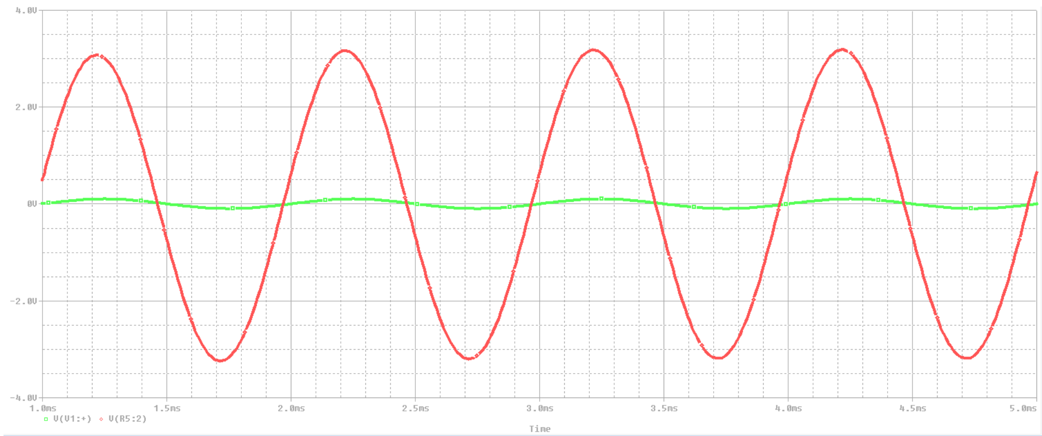


Figure 4.11: Potentiometer = 10kΩ

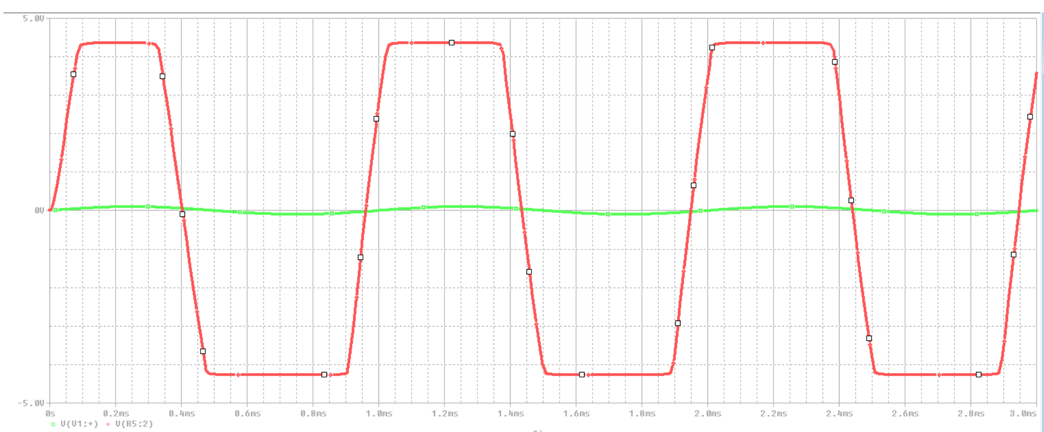


Figure 4.12: Maximum Gain Setting: Potentiometer = 100 Ω

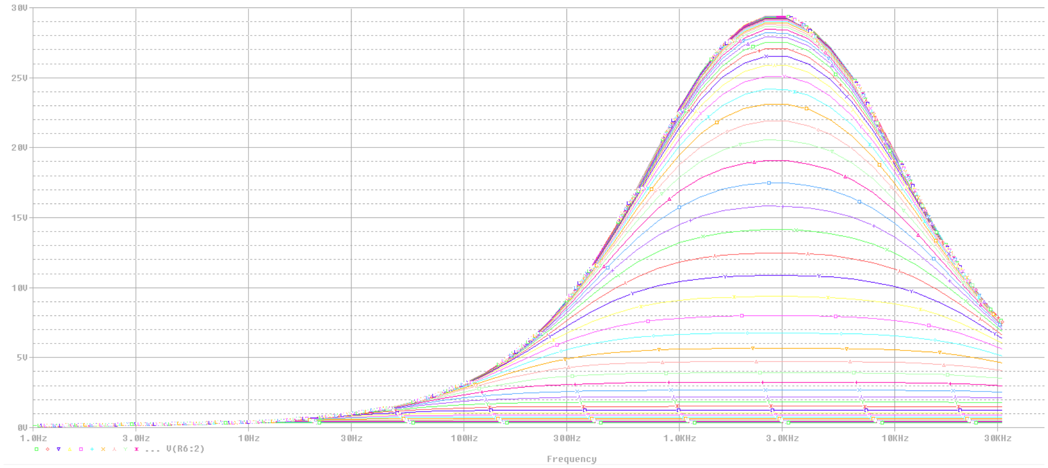


Figure 4.13: Gain Stage: Frequency Response

After establishing theoretical proof of concept of the gain amplifier, a frequency response sweep was performed to gauge the frequency content of the outgoing signal. While doing a frequency response sweep, the gain setting potentiometer was also swept to observe the effect of changing the gain on the response of the signal. From the Fig. 4.13 it can be observed that as the gain increases, the op-amp applies a high gain value to mid range frequencies centered at roughly 3KHz, and attenuates frequencies between 0-900 Hz. Based on this graph, the sound of the distortion would characteristically be rich in middle and high frequencies, and contain some (but much less) bass frequencies. The frequency response in musical applications is generally very subjective. Different sound profiles can appeal to different types of players. Adjusting the frequency response for this circuit would be as simple as adjusting the passive circuitry values in the feedback loop. Additionally, a tone control implementation would allow for further customization of the frequency response, which will be presented in a later section of this chapter. Selecting a different op-amp would also result in a slight change in the frequency response, but ultimately the filters embedded within the circuit make the biggest impact on the response.

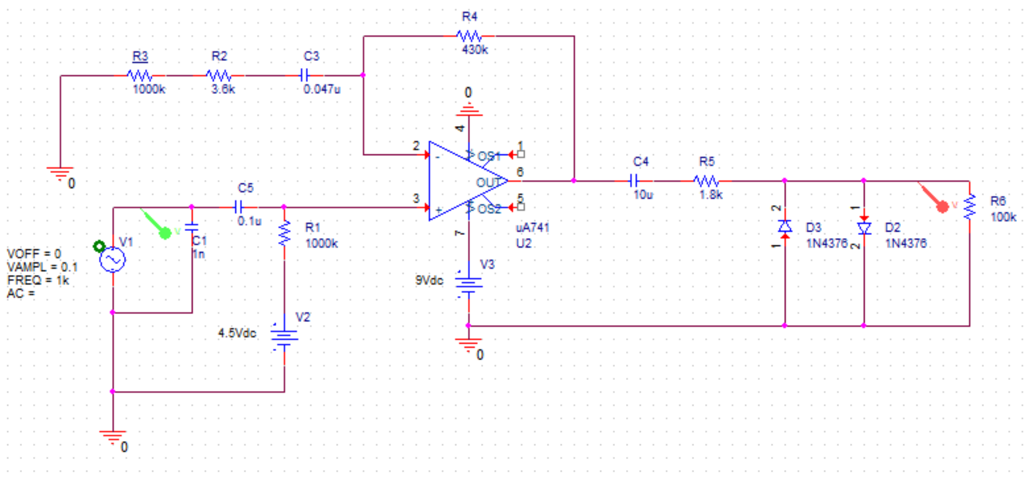


Figure 4.14: Gain Stage with Hard Clipping Stage

### 4.2.3 Hard Clipping Stage

The hard clipping stage and the gain stage preceding it go hand-in-hand. The gain stage makes it possible for the clipping diodes to clip the signal and create distortion. In Fig. 4.14 the gain stage is pictured, but this time with clipping diodes at the output, and a 100k potentiometer represented by R6. The potentiometer provides a means of volume control for the user, so that if a louder or quieter volume is desired, simply dialing the potentiometer up or down will adjust the amount of current leaked to ground. The hard clipping diodes used for the theoretical simulation were silicon diodes, with a forward voltage of approximately 0.7 V. Hence, in the simulations, we expect to see the circuit clip the output when it exceeds this voltage, rather than allow the op-amp to clip the signal.

Before testing the capabilities of the clipping circuit, the volume potentiometer was tested using transient simulations. In Fig. 4.15, the output signal bleeds to ground due to the low magnitude of the potentiometer. In Figures 4.16 and 4.17, more of the signal is present at the output due to the higher potentiometer values. This is a proof of concept, and shows that the volume of the circuit is being properly adjusted by the variable load resistor.

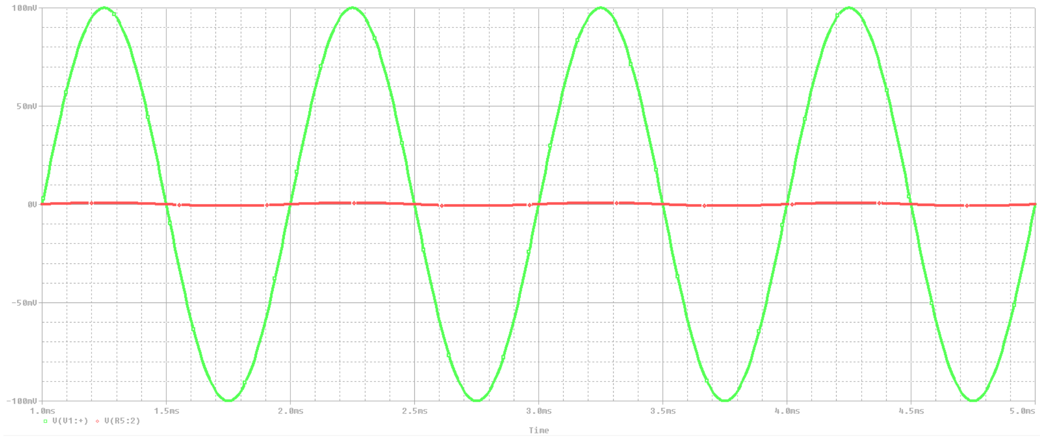


Figure 4.15: Volume Test: Load Resistor = 10Ω

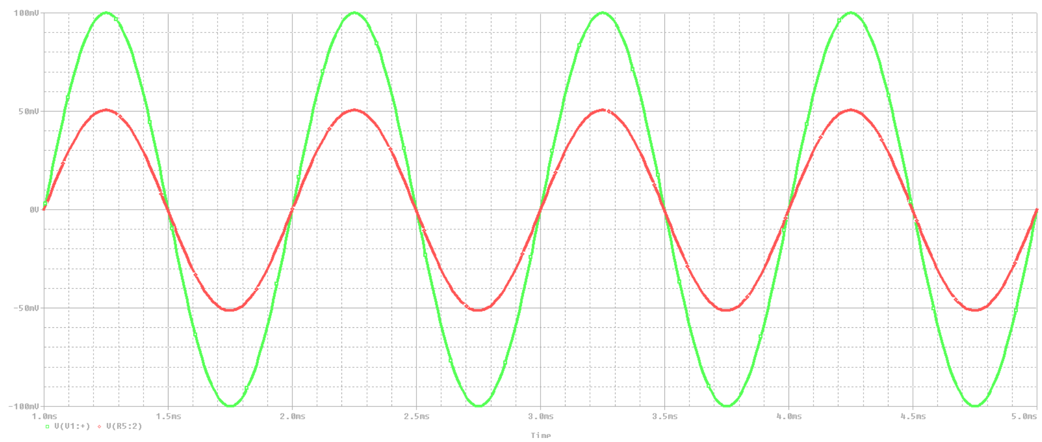


Figure 4.16: Volume Test: Load Resistor = 1kΩ

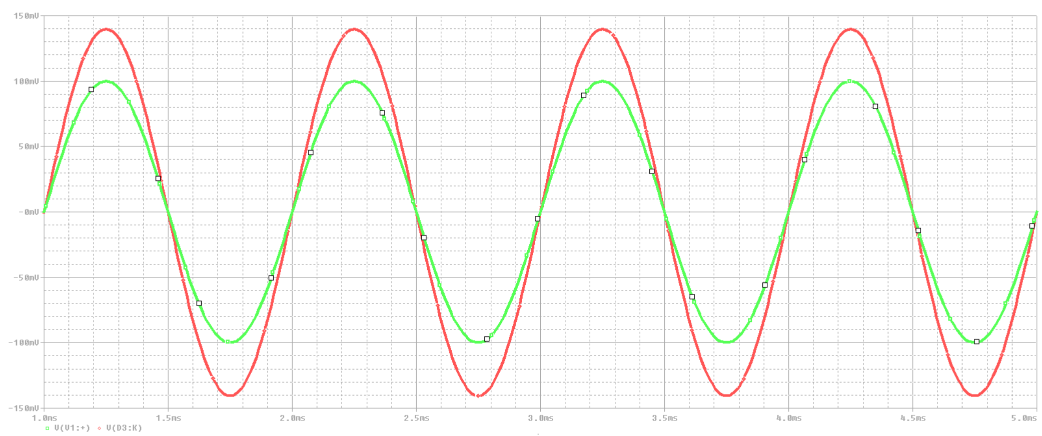


Figure 4.17: Volume Test: Load Resistor = 100kΩ

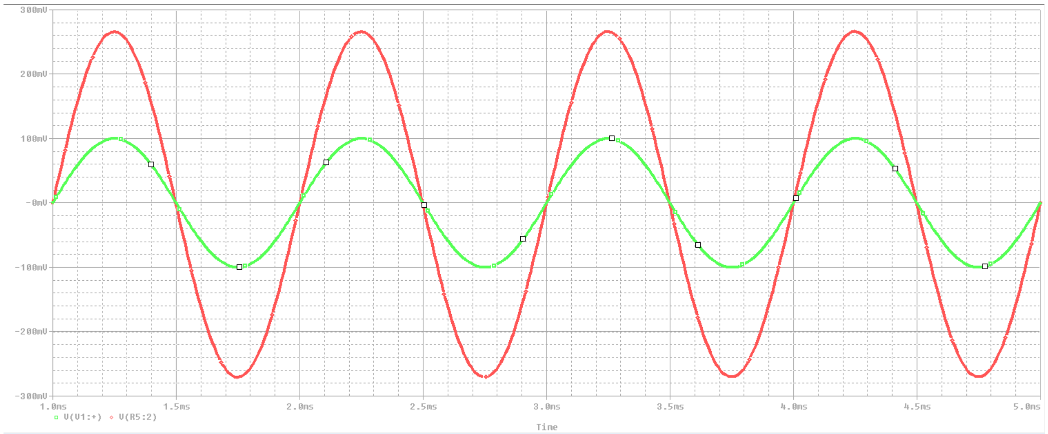


Figure 4.18: Clipping Test: Gain Resistor = 250kΩ

After confirming the functionality of the volume potentiometer, the hard clipping circuit was tested using transient simulations. Recall, in the previous section the voltage amplitude of the signal got up to approximately 4.3 V before being clipped by the rail-to-rail voltage of the op-amp. In the following simulations, we should theoretically see the diode clip the signal once it exceeds 0.7 V in amplitude. The term “clipping” refers to the flattening or rounding of the peaks of the analog guitar signal. This effect is what musicians perceive to be distortion.

In the following three figures, the gain potentiometer was set to three different values to demonstrate the output of the circuit at different gain levels. As shown in Fig. 4.18, the voltage does not exceed the diode forward voltage, and therefore the signal is not clipped. In the Fig. 4.19, the circuit is set to a higher gain setting, and as a result the signal clips at roughly 0.7 V as expected. The clipping diodes flatten out the peak of the signal, and it takes on a rounder shape overall compared to the first simulation. In the last simulation shown in Fig. 4.20, a maximum gain setting is shown. The peak of the signal is much more square for the final simulation because more of the signal is being clipped by the diodes due to the increased gain. These simulations provide justification for the hard clipping circuit design, and confirm that the theoretical design is valid.

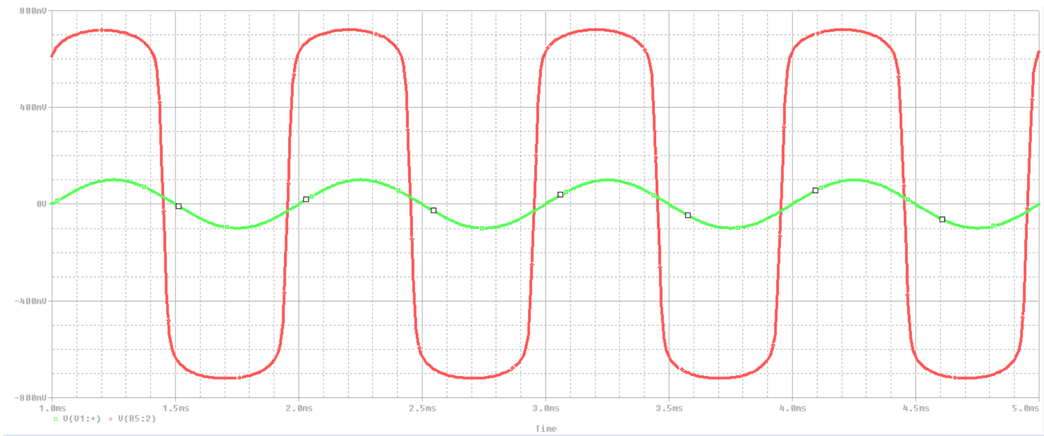


Figure 4.19: Clipping Test: Gain Resistor = 6.2kΩ

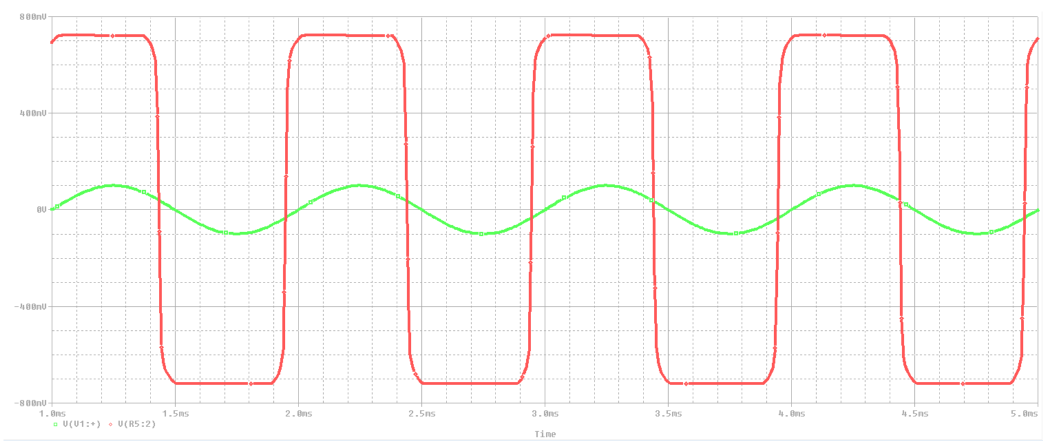


Figure 4.20: Clipping Test: Gain Resistor = 100 Ω

### 4.2.4 Tone Control Stage

This stage of the design is meant to offer the user a single dial tone control for a simple, yet versatile sound. The core of this circuit is the adjustable low-pass filter circuit, which can be seen in Fig. 4.21. Note, that the second op-amp is simply the unity gain buffer discussed in Section 4.2.1.

The tone control stage features supporting passive circuitry at the input and output of the circuit, whose purpose is also explained in Section 4.2.1. The main new addition this circuit provides to the overall analog design is a means for the user to control the frequency response of the circuit. Using resistor R4 (1.2kΩ) , and potentiometer R2 (1kΩ), a low-pass filter is formed with capacitor C6, which was chosen to be $8.2nF$. These values were chosen carefully and intentionally using the formula for calculating the cut-off frequency of a filter [27].

Using Eqn. 4.3, when the potentiometer is set to 1k, the cut-off frequency of the low-pass filter will be 8822 Hz. This will roll off some of the high frequencies present in the distortion created in the clipping stage. So, if the user prefers a guitar sound with less high-end in the tone, they can dial the potentiometer to a higher value. However, if the user desires a guitar tone with a lot of high-frequency content, the potentiometer can be dialed to a minimum setting, which would adjust the cut-off frequency to roughly 16.2k Hz.

This filter theoretical design was a first attempt at providing a meaningful single dial tone control to the user. The specific values of the resistors and capacitors in the low-pass filter are subject to some change. For example, widening the range of the cut-off frequency would be a viable way to allow more noticeable tone control to the circuit. This would simply mean adjusting the resistor and capacitor values, and going through the process of trial and error until a preferable tone control frequency response is attained. For the above circuit, a frequency

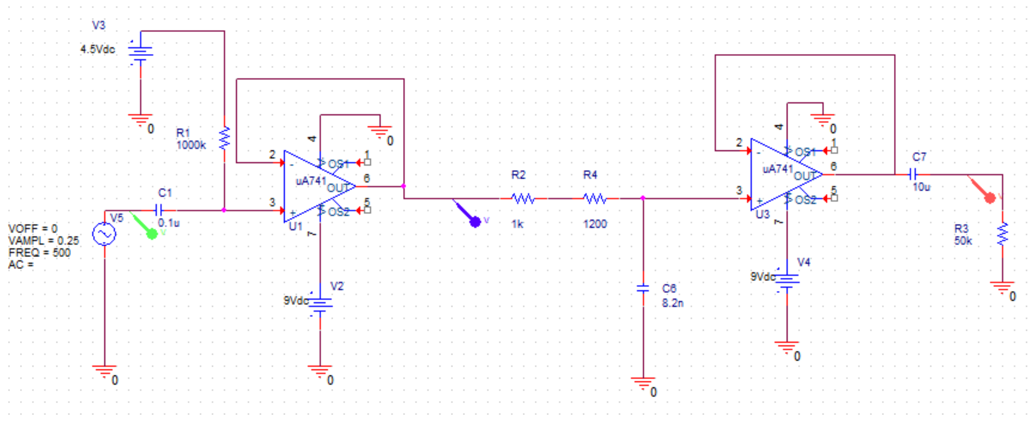


Figure 4.21: Tone Control Theoretical Schematic

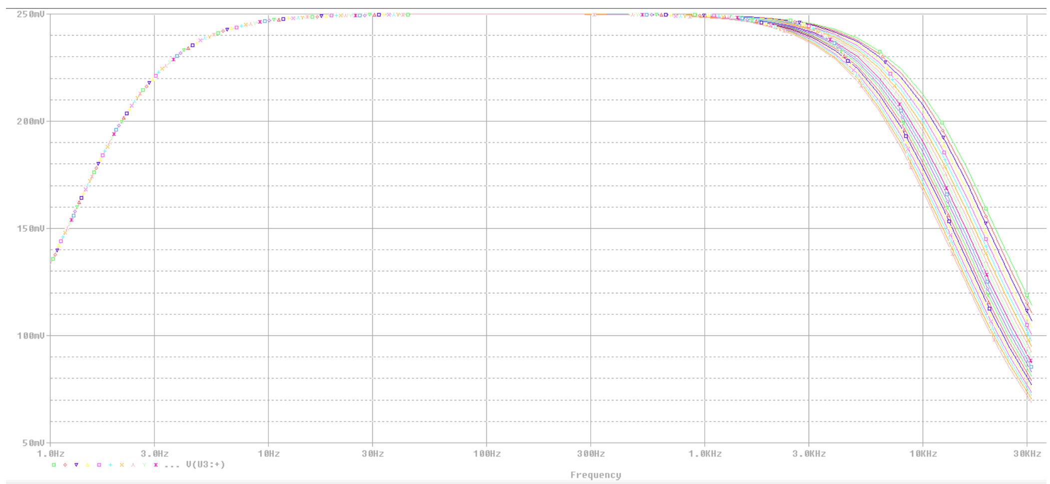


Figure 4.22: Tone Control Frequency Response

response simulation was done to demonstrate the effect of adjusting the potentiometer. This simulation can be seen in Fig. .

To establish proof of concept of the circuitry, the DC voltages at each point in the circuit are shown in Fig. 4.23.. As anticipated, the blocking capacitors prevent DC from exiting the circuit from either end of the circuit. In Fig. 4.24., a transient simulation was performed to ensure that unity gain was maintained in this circuit. These simulations along with the frequency response simulation conclude the demonstration of the proof of concept for the tone control circuitry.

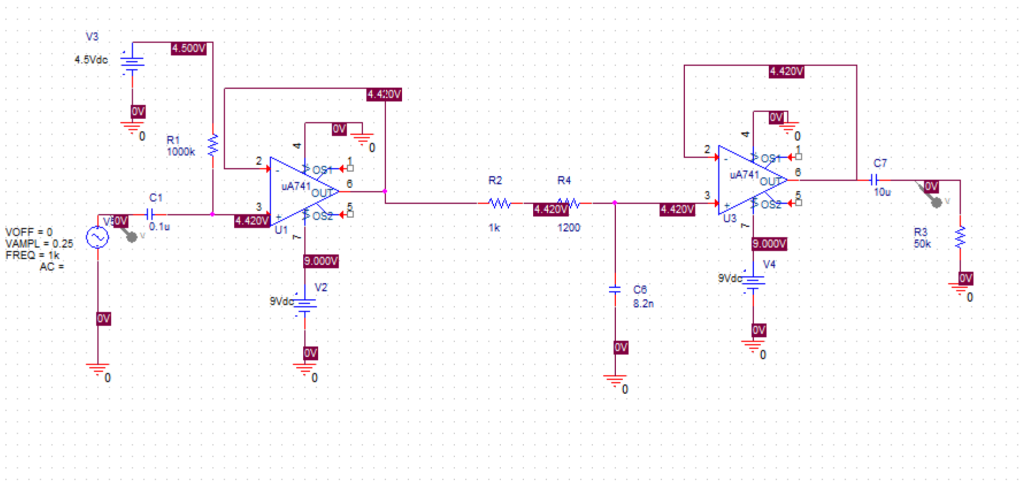


Figure 4.23: Tone Control: DC Voltages

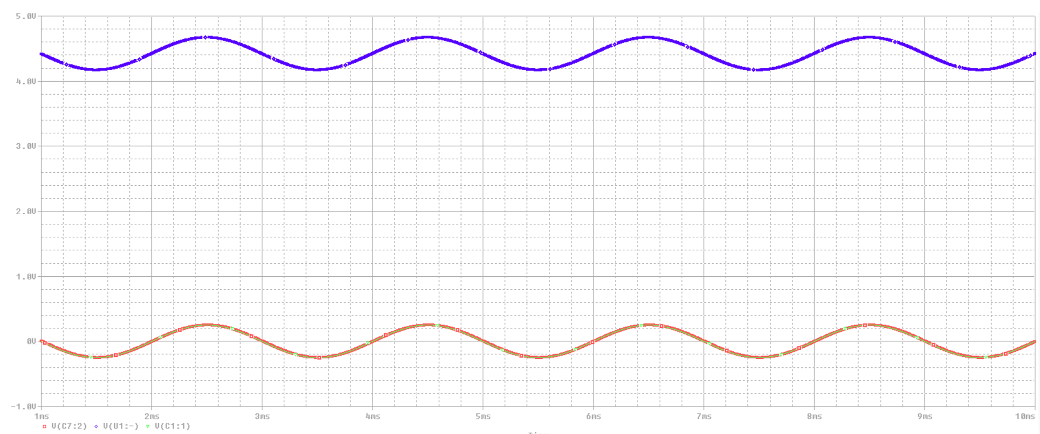

Figure 4.24: Tone Control: Transient Simulation

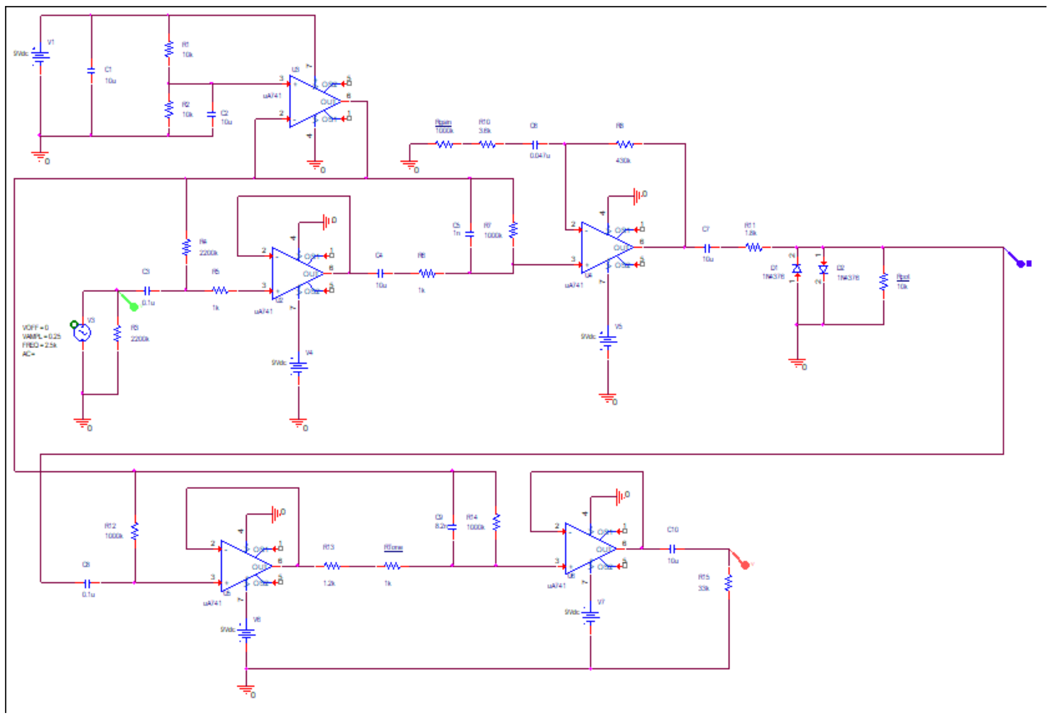

Figure 4.25: Complete Theoretical Schematic

# 4.3 Complete Analog Circuit: Final Theoretical Simulations

This section of the chapter combines all previously validated circuitry into the final theoretical schematic diagram. In Fig.4.25, the complete schematic can be viewed. In the following sections, simulations of the complete design were done to examine the behavior of the overall circuit.

## 4.3.1 Simulation and Validation

To confirm the function of the circuit, firstly, transient simulations were run on the completed circuit to examine to input waveform was properly represented at the final output. Note that for the following simulations, the volume potentiometer was set to 10kΩ (maximum setting), and the tone potentiometer was set to 1kΩ (maximum filtering). The gain potentiometer was changed for each simulation to demonstrate the effect of adjusting the gain. Additionally, note that the

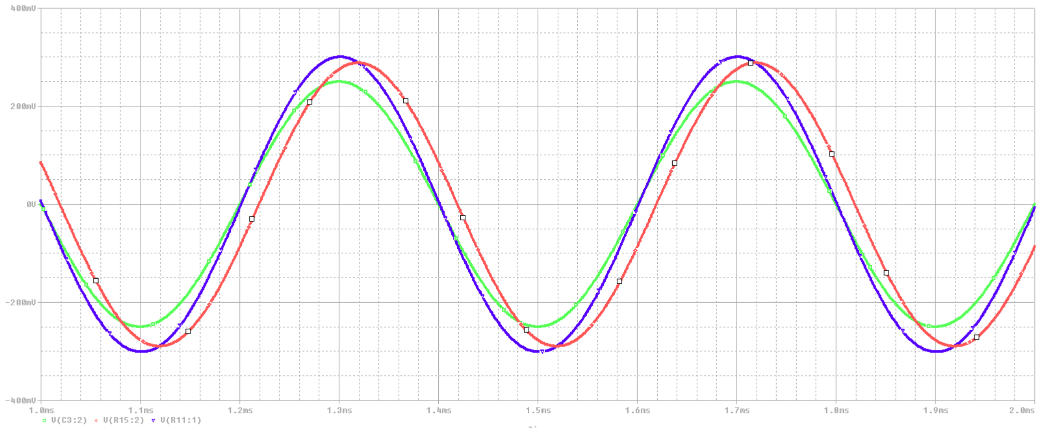


Figure 4.26: Transient 1: Gain potentiometer = 1MΩ

input waveform is represented in green, the output of the clipping circuit in blue, and the final output in red. The input waveform amplitude was set to 0.25 V, and the frequency was set to 2.5KHz.

In the following simulations, the time offset from the output to input was approximately 0.022 ms. In Fig. 4.26 the voltage of the output was 0.29 V in amplitude. These results are acceptable, as the small time offset is negligible for musical applications. Also, even at minimum gain setting, there will still be slight gain applied to the signal due to the resistor feedback loop configuration. In Fig. 4.27 and Fig. 4.28 the gain applied to the signal causes the diode clipping effect to engage, which confirms the functionality of the analog circuitry.

Finally, to conclude the theoretical design, a frequency response analysis was done with varying levels of gain, and varying levels of tone filtering (by the tone control circuit). In Fig. 4.29 , a minimum gain was applied to the circuit, which resulted in little to no filtering from the feedback loop high-pass filter. However, the high-end frequencies were still adjusted using the tone control circuit.

In Fig. 4.30, it demonstrates that increasing the gain in the circuit causes a slight alteration

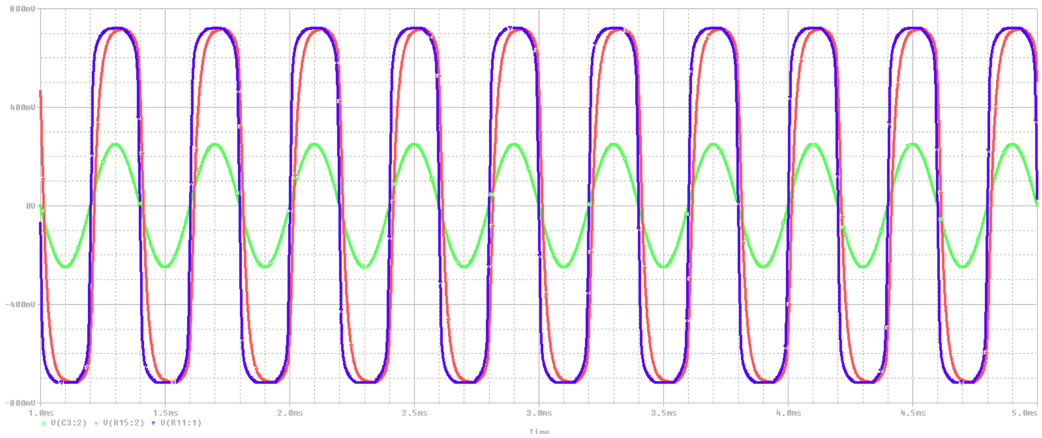


Figure 4.27: Transient 2: Gain potentiometer = 20kΩ

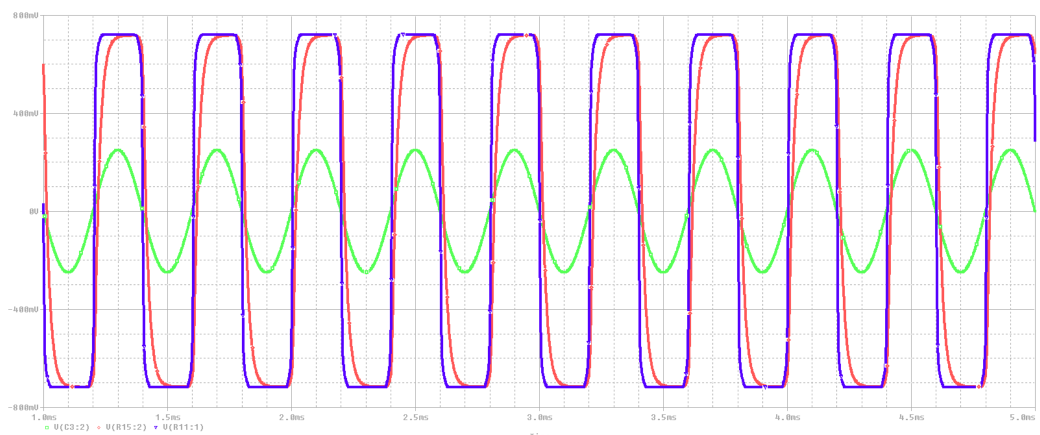


Figure 4.28: Transient 3: Gain potentiometer = 8kΩ

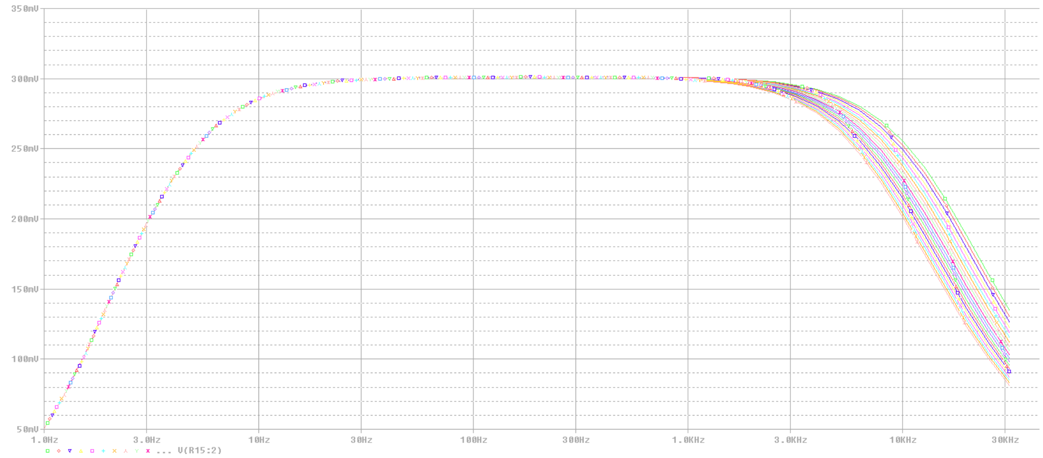


Figure 4.29: Frequency Response: Gain potentiometer = 1MΩ

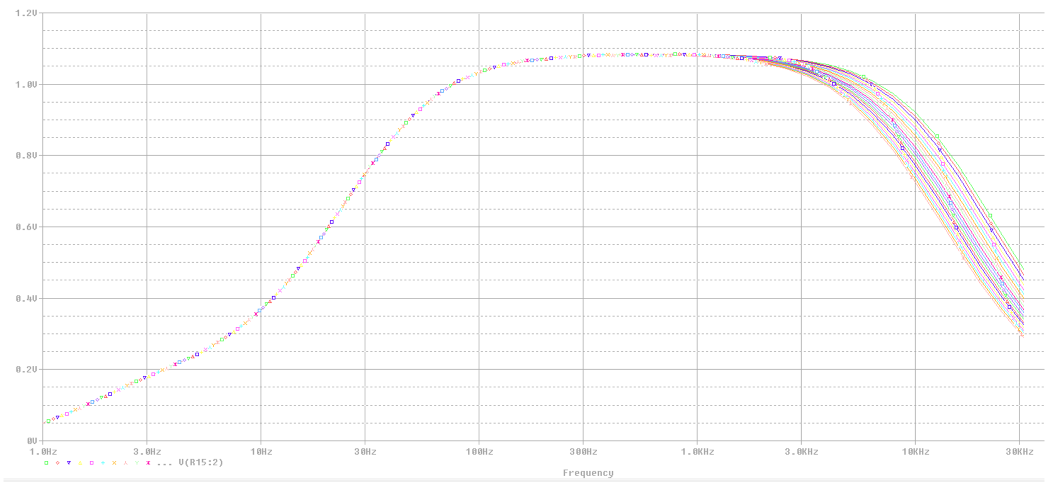


Figure 4.30: Frequency Response: Gain potentiometer = 100kΩ

of the frequency response, primarily focused on attenuating lower bass frequencies. This trend is continued as the gain increases in the circuit. This results in high gain distortions to sound “crunchy”, and very “bright”; terms which are used to describe a sound rich in middle and treble frequencies. The tone control circuit does implement some control over the ultra high harmonics in the 12-16kHz range, effectively filtering out harsher harmonics. However, because the bass frequencies are fairly attenuated at high gain levels, the sound will still maintain a rich middle frequency profile. This concludes the theoretical analysis of the overall analog design.

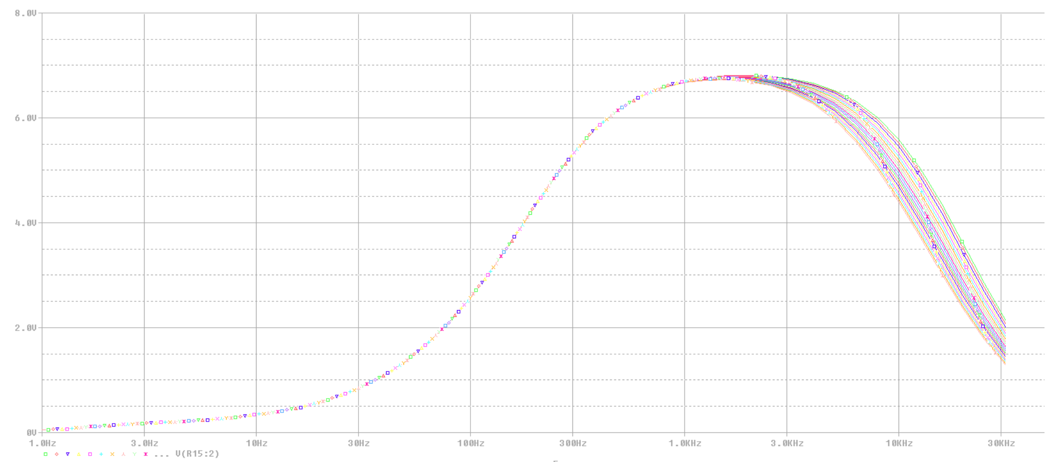


Figure 4.31: Frequency Response: Gain potentiometer = 10kΩ

# Chapter 5

# Hardware Analysis and Testing

In this chapter of the paper, the aim is to go over in detail the physical application of the designed analog distortion pedal. Using the schematic presented in the previous chapter, a bread-board version of the circuit was constructed and tested to validate the function of the design. In the following sections, observations about the sound, and results will be discussed in further detail.

## 5.1 Final Hardware Schematic and PCB Layout

In Fig. 5.1 the final schematic design was constructed. There are a few notable differences in this schematic design compared to the theoretical schematic, but the overall architecture remains the same. Most of these adjustments consist of slight changes in passive circuitry values, primarily for the gain stage and the tone stage. While these changes are subtle at first glance, the impact on the frequency response is significant.

The first key difference between this schematic and the theoretical schematic is the series DC-blocking capacitor connected to the feedback loop of the gain stage. In the theoretical schematic, this value was chosen to be 0.047 microfarads. In the Altium schematic, this value was adjusted to 0.062 micro-farads. The reason for this adjustment was to adjust the frequency filtering at high gain values. In the theoretical schematic, at the highest gain setting, the high-pass cut-off frequency was 940 Hz. By doing this, bass frequencies were highly attenuated at high gain settings, leaving the frequency response to contain mostly middle and high frequencies. This created a very bright, thin tone as a result. This isn't necessarily a good or bad characteristic; some guitarists may prefer this type of tone. Regardless, by replacing this capacitor with a 0.062 micro-farad capacitor, the high-pass cut-off frequency (at maximum gain) was adjusted to 713 Hz. This allowed for less filtering of bass frequencies, giving the sound a fuller feel while also maintaining a clear tone. Some experimentation was done with lower cut-off frequencies between 500-650 Hz, but the sound was found to be too muddy in quality. Designing a cut-off frequency of 713 Hz seemed to be a reasonable middle ground, with the best tonal quality.

Another slight adjustment made was to the theoretical tone control. Recall, that the low-pass cut-off frequency range was set to 8.8-15.9 kHz. As discussed previously, this filter was meant to give a subtle high-end adjustment to the frequency range of the circuit. By replacing the previous low-pass filter components with a 1 kΩ series resistor, and a 10 nF capacitor, the frequency range of the tone dial was fixed to 7.9 kHz-15.9 kHz. This change does not majorly affect the sound, but does prove that the circuit can be later modified to further adjust the tone control. It is reasonable to expect that this circuit could be modified in a future iteration to improve the effectiveness of the tone control.

One final key adjustment was the addition of an analog 3PDT switch. This switch essentially allows the user to bypass the effect completely when switch off, and enable the distortion effect when switched off. By stomping on the metal analog switch, the user can instantaneously add distortion to an otherwise clean signal. This can be extremely useful for songs which require both clean and dirty guitar sections. A small series resistor LED circuit was added to the switch as

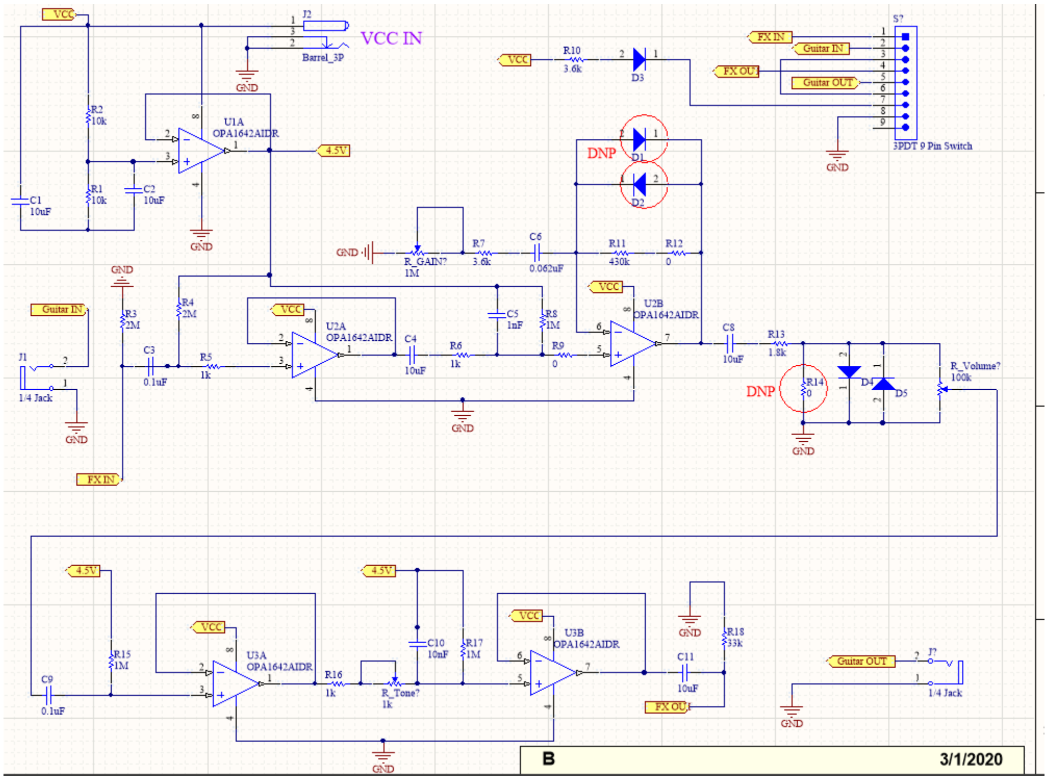


Figure 5.1: Final Altium Schematic

well, so that when the effect is toggled on, the LED illuminates. This simply is a visual indicator for the user, to determine whether the distortion circuit is enabled or bypassed.

Below in Fig. 5.2 is the final PCB layout of the above schematic.The layout features 4 separate electrical layers: two routing planes, a ground plane, and a 9V DC plane. Both soft and hard clipping diodes were included to accommodate for future modifications; a typical 1N4004 through hole footprint was used for these components. All passive circuitry was chosen to be surface mount, and the package size was selected to be 0805 or larger. This size is ideal as it leaves plenty of free space on the board for routing, while also being large enough to make soldering the boards manageable and convenient. It is customary for most foot-switch guitar pedals to place the stomp-switch on the bottom half of the pedal, so the footprint for the analog switch was placed appropriately at the bottom. The 9 V connector will be available from the top side of the pedal to allow for easy access from the voltage source.

In the bread board version of the hardware schematic, there was some occasional AM radio interference due to the magnetic coupling of the wiring. The PCB version of the circuit will most likely reduce a lot of this RF noise due to the smaller traces, and well established ground plane. Additionally, the PCB design features high quality, low noise op-amps (OPA1641). These op-amps are very high quality compared to the 741 amplifiers used during the hardware simulations, and may eliminate noise that otherwise would be present due to the 741's operating characteristics.

## 5.2 Hardware Testing and Validation

In this section the theoretical schematic design was reproduced on a bread board. To verify the function of the design, several simulations were performed on the circuit for comparison to the theoretical simulations. First, each section was tested individually to confirm the isolated function of each stage. After confirming the performance of each individual stage, the schematic design was simulated as a whole. Note that for the following simulations, the output waveform is represented by channel two (blue), while the input is represented by channel one (yellow).

### 5.2.1 Validation: Buffer Circuit

In Fig. 5.3, a hardware simulation of the isolated buffer circuit was performed. For this simulation and the simulations in the following sub-sections, the input source was set to 250 mV peak-to-peak, and the frequency was set to 1kHz. In the theoretical simulation of the buffer circuit, it was shown that unity gain was achieved from the input to the output [21]. This simulation

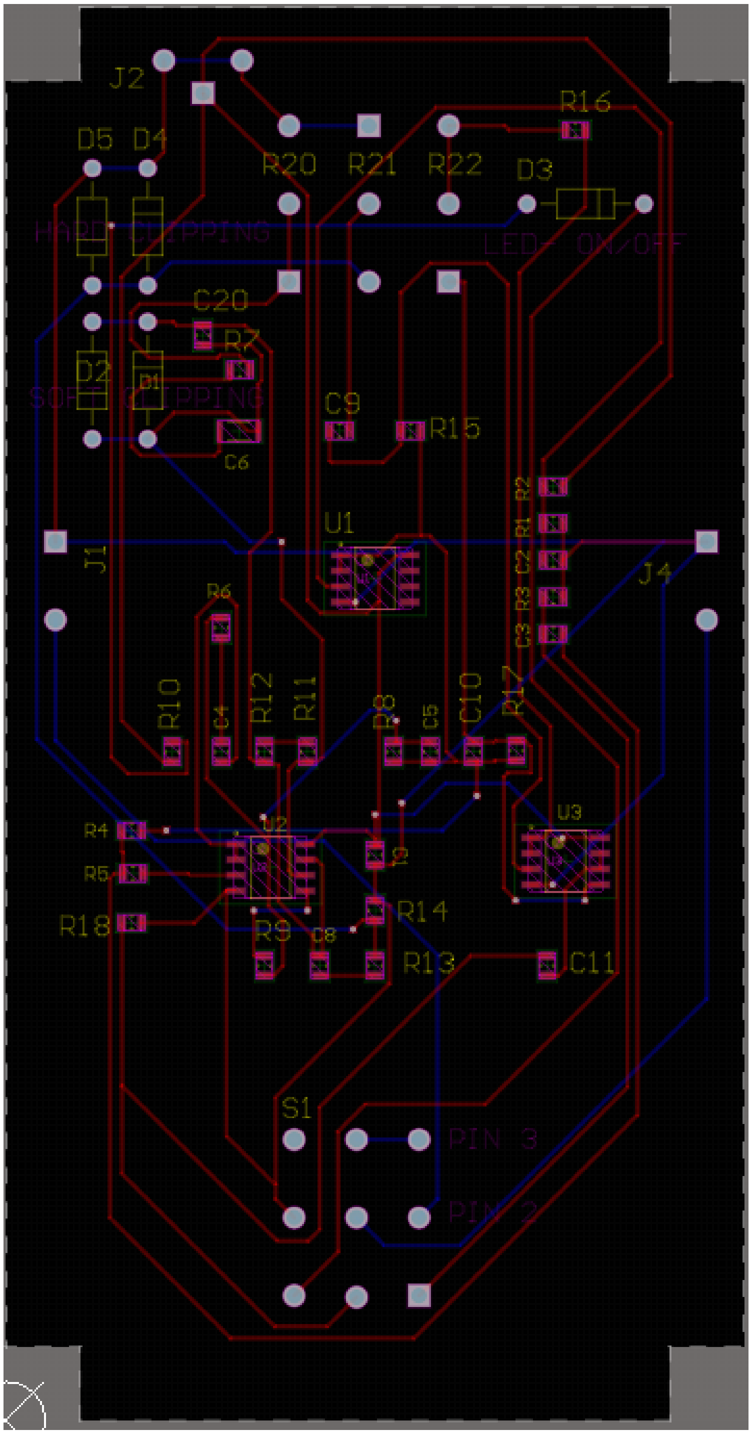


Figure 5.2: Final PCB Layout

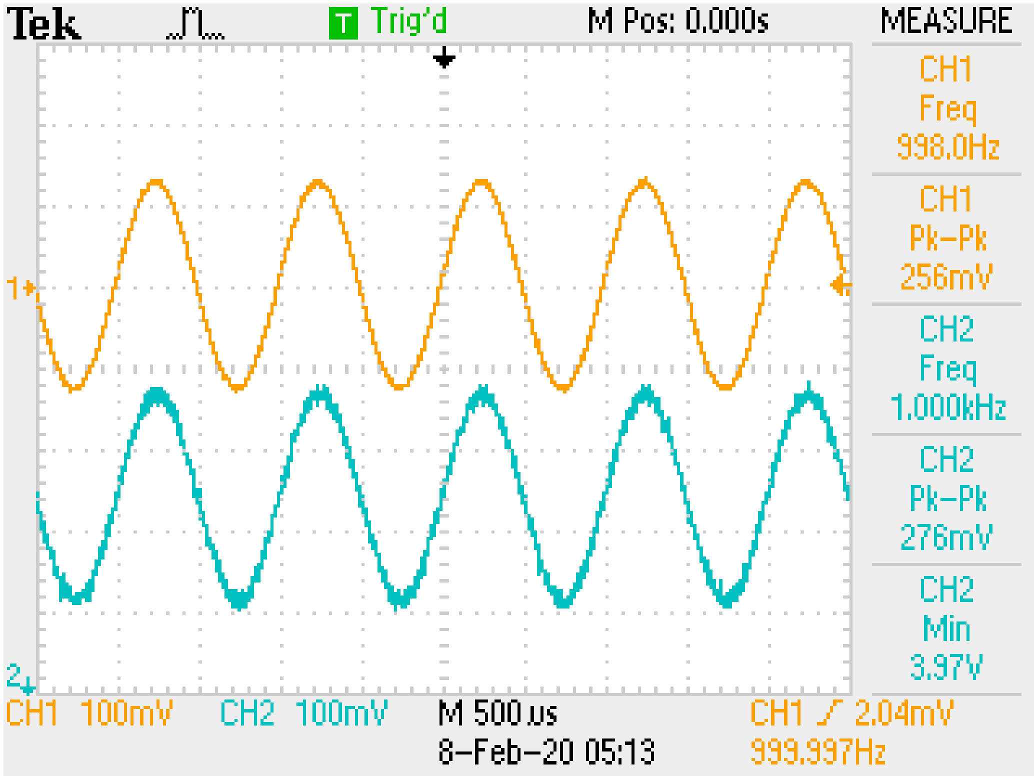


Figure 5.3: Hardware Buffer Simulation

confirms the function of the buffer circuit. Due to noise in the circuit, the output hovers around 270 mV rather than 250 mV (peak-to-peak). However, this difference is negligible in the function of the overall circuit. Therefore, it can be concluded that the buffer circuit hardware design matches the intended function demonstrated in the theoretical section.

### 5.2.2 Validation: Gain Stage with Hard Clipping

Next, the validation of the gain stage with hard clipping was done using several simulations with varying gain potentiometer values. Recall, a 1MΩ potentiometer connected to the feedback path of the op. amp is responsible for dialing in the gain for the circuit. The lowest possible gain setting in this case being when the potentiometer is set to 1MΩ.

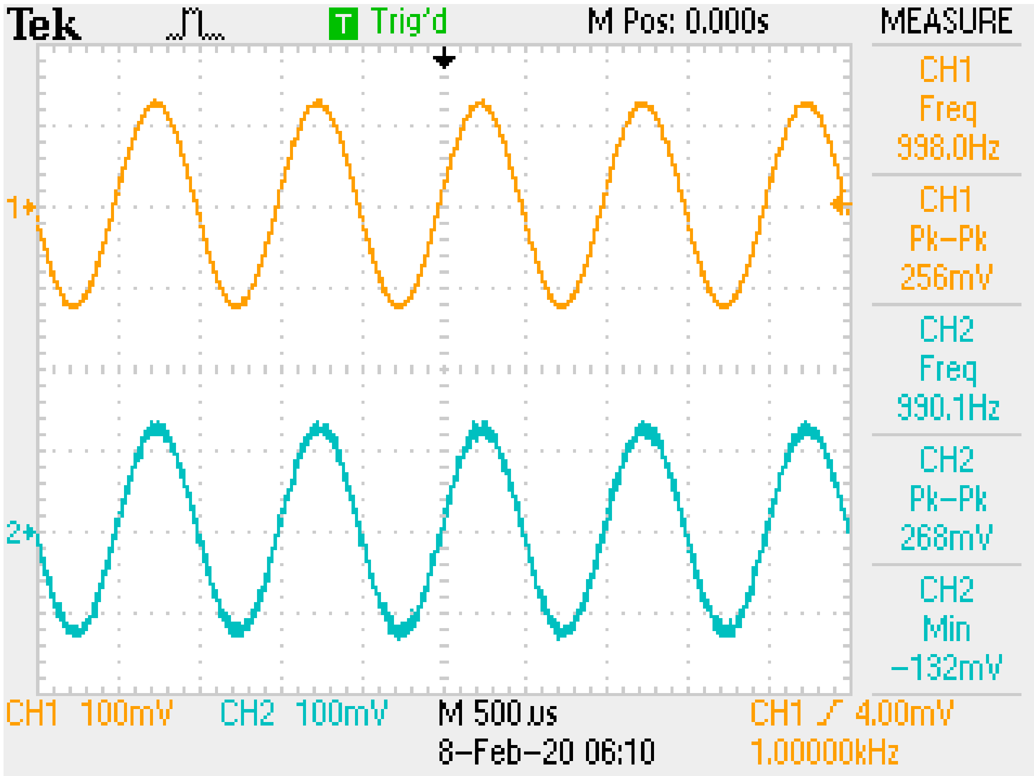


Figure 5.4: Hardware Gain Simulation: 1MΩ Potentiometer

In the theoretical section of this paper, it is shown that as the potentiometer resistance decreased, an increasing amount of gain was applied to the signal. As shown in Fig. 5.4, 5.5, and 5.6, this same trend is visable, which validates the function of the gain stage of the circuit. When the gain potentiometer is set to higher gain levels such as 10kΩ and 4.7kΩ., the output signal experiences hard clipping as predicted in the theoretical section. The hard clipping effect becomes more apparent as the resistance of the potentiometer approaches zero. This is demonstrated in the latter two figures. These simulations conclude the hardware verification of the gain and hard-clipping stages.

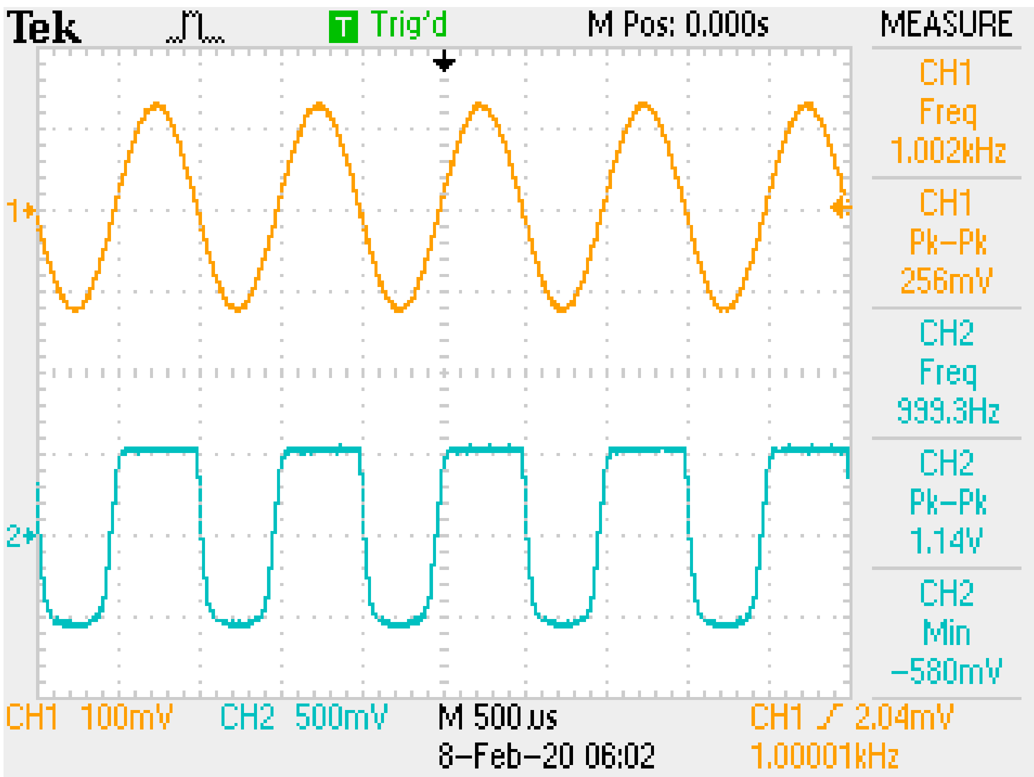


Figure 5.5: Hardware Gain Simulation: 10kΩ Potentiometer

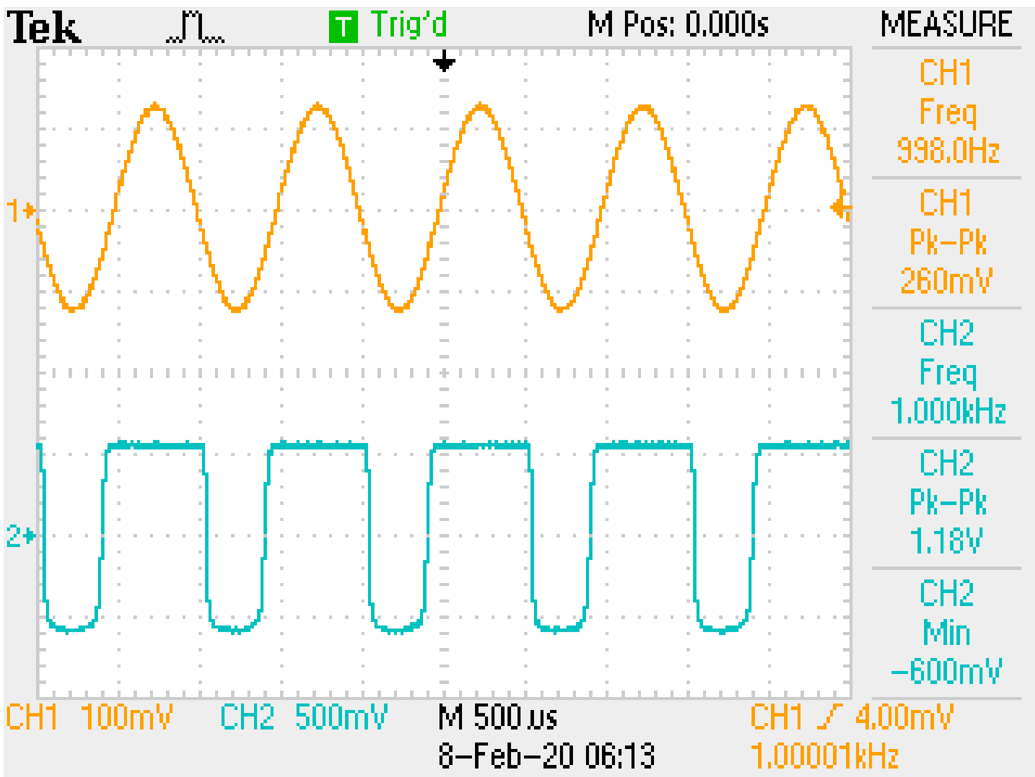


Figure 5.6: Hardware Gain Simulation: 4.7kΩ Potentiometer

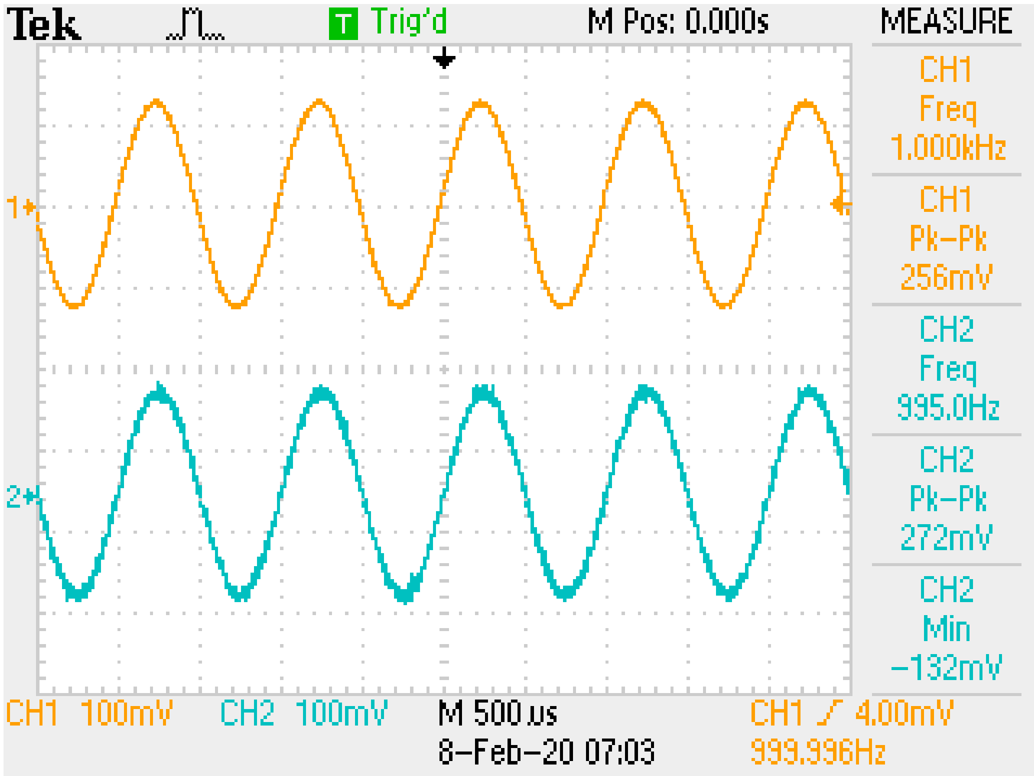


Figure 5.7: Hardware Tone Control Simulation

### 5.2.3 Validation: Tone Control Stage

The tone control stage was validated using a hardware simulation just as the previous stages were. Recall that this stage was intended only to affect the frequency response of the overall circuit. The unity gain op-amp configuration was simulated in the theoretical section of the paper and shown to apply no gain to the signal. In Fig. 5.7, the circuit returns a near-identical signal at the output, which confirms that the circuit is not applying gain to the signal. This result matches the predicted result from the theoretical section. This concludes the functionality of each individual stage of the overall system.

### 5.2.4 Validation: Complete Circuit

After verifying each stage of the circuit individually, the complete circuit was constructed and tested as a whole. Three simulations were done to confirm that the circuit was properly applying gain to the signal. These simulations, ideally, should be close to identical to the simulations done in Section 5.2.2.

As shown in Fig. 5.8, 5.9, and 5.10, three simulations were performed with varying potentiometer values. As anticipated, by decreasing the resistance of the potentiometer, more gain is applied to the signal. When the signal amplitude surpasses the forward voltage of the selected diodes, the signal experiences a hard clipping effect. These simulations provide justification for the overall design. From these simulations, it can be concluded that the analog distortion pedal design is valid.

## 5.3 Modeling of Diodes

This section aims to verify that different types of diodes can distort the signal differently, and thus affect the characteristics of the sound. Section 5.3.1 demonstrates different hard clipping configurations and compares simulations performed on several common industry diodes. Section 5.3.2 demonstrates different soft clipping configurations and compares their corresponding simulations.

### 5.3.1 Diode Hard Clipping Profiles

In the following figures, several different types of industry diodes were simulated and tested to examine the different clipping profiles produced by each diode. Each diode clipped the signal slightly differently than the others. As a result, each diode produced its own unique flavor of

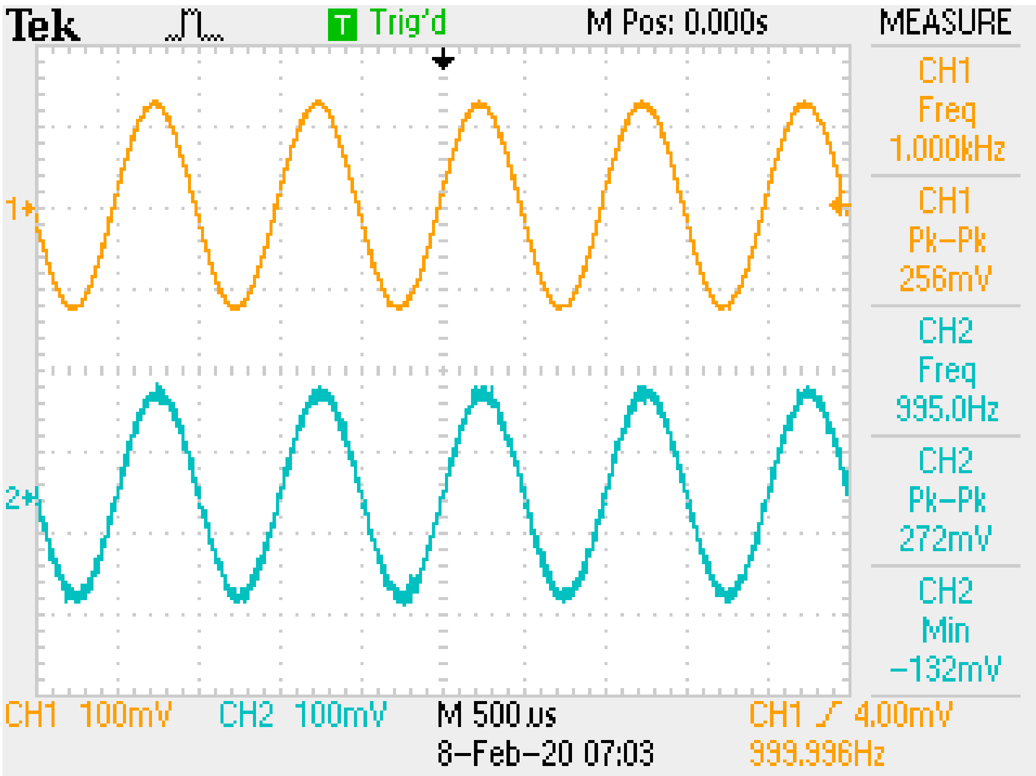


Figure 5.8: Hardware Gain Simulation: 1MΩ Potentiometer

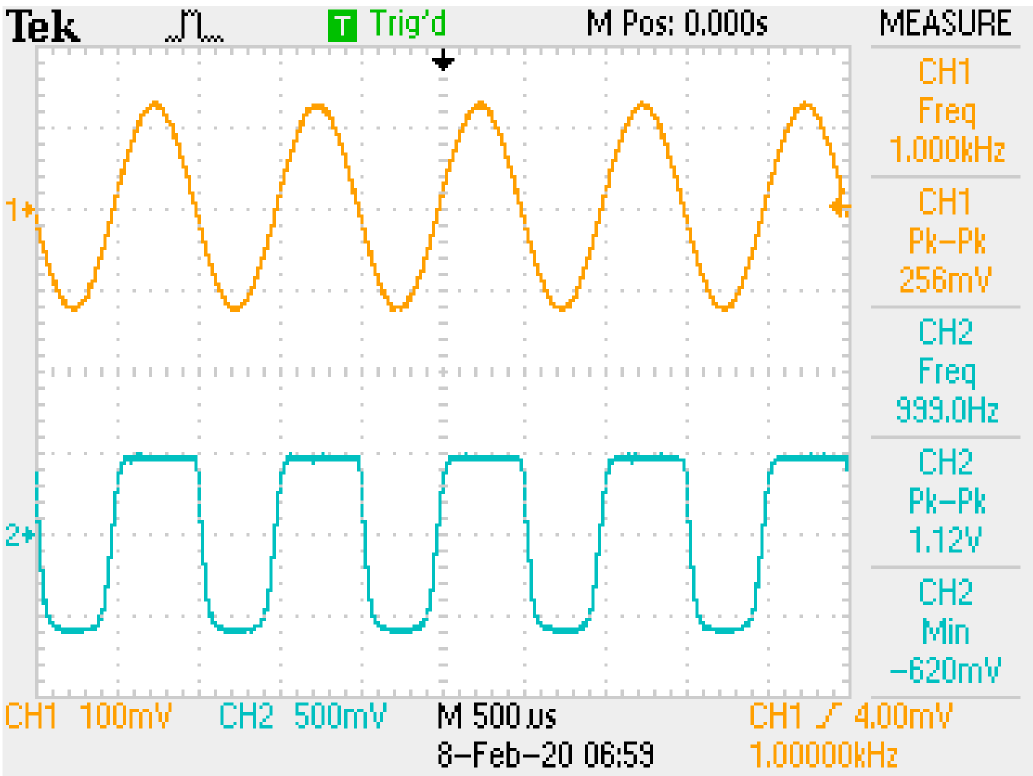


Figure 5.9: Hardware Gain Simulation: 10kΩ Potentiometer

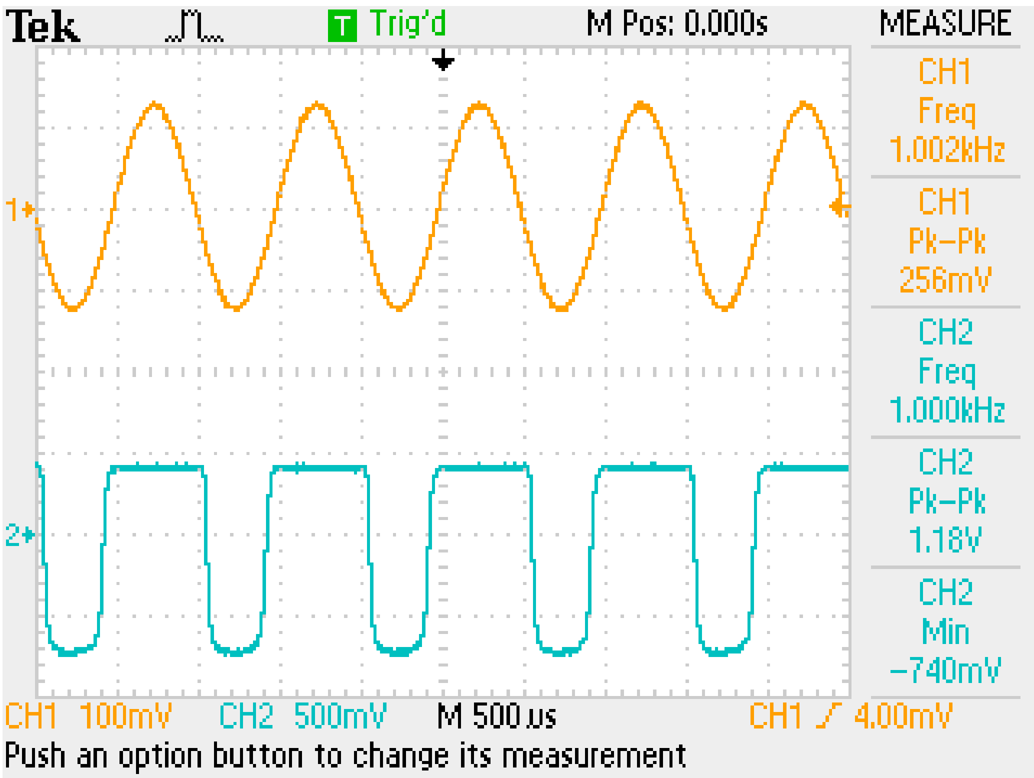


Figure 5.10: Hardware Gain Simulation: 4.7kΩ Potentiometer

distortion [12]. The differences between the diodes were subtle overall, but noticeable to any regularly practicing musician.

To minimize sources of error, each diode was tested using the same Gibson Les Paul, with the exact same amplifier settings. Doing this ensures that the tonal differences between each diode are accented. Additionally, the same guitar cable was also used to ensure that the inherent characteristics of the cable would not contribute to the tone differences for each trial [9] . In the following simulations, the pedal volume was kept at the maximum, and the gain was set to a high setting (20k) to properly demonstrate the clipping effect. A 1kHz signal with a 100 mV amplitude was used to simulate a guitar signal in each of the simulations below.

The first simulation in Fig. 5.11, was of the 1N4735. This is a common industry silicon zener diode with a nominal forward voltage of roughly 1.2 V (at the maximum current setting). The higher forward voltage of this diode caused the signal to clip in a less harsh manner compared to the other diodes with lower forward voltages, which resulted in a less fuzzy type of distortion. Generally speaking, the sound wasn't overly fuzzy, but didn't lack in fuzz either. A wide range of frequencies seemed to be present in the signal, and it seemed fairly balanced. Notice that the measured peak-to-peak voltage of the signal is roughly 1.34 V. This is higher than all of the other diodes tested in this section, which indicates that less of the signal is being hard clipped. Overall, the sound seemed to be fairly representative of a typical hard clipping sound profile that guitarists look for in classic rock.

The second simulation in Fig. 5.12, was of the 1N4148. This is another common silicon diode with a nominal forward voltage of 0.7-1 V (depending on the amount of current through the diode). This diode seemed to clip the signal at a lower level compared to the 1N4735, as indicated by the peak-to-peak voltage measurement of 1.11 V. Still, the sound profile seemed to represent a classic rock profile in a similar manner to the 1N4735. There were a lot of middle

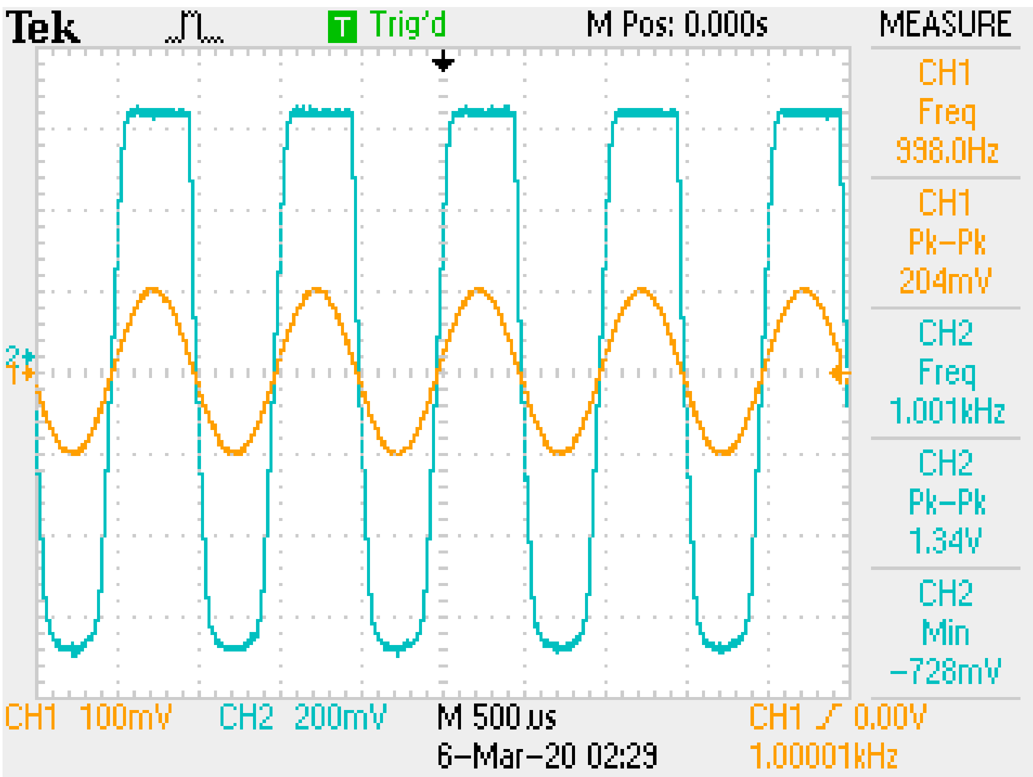


Figure 5.11: Simulation of 1N4735 Diode

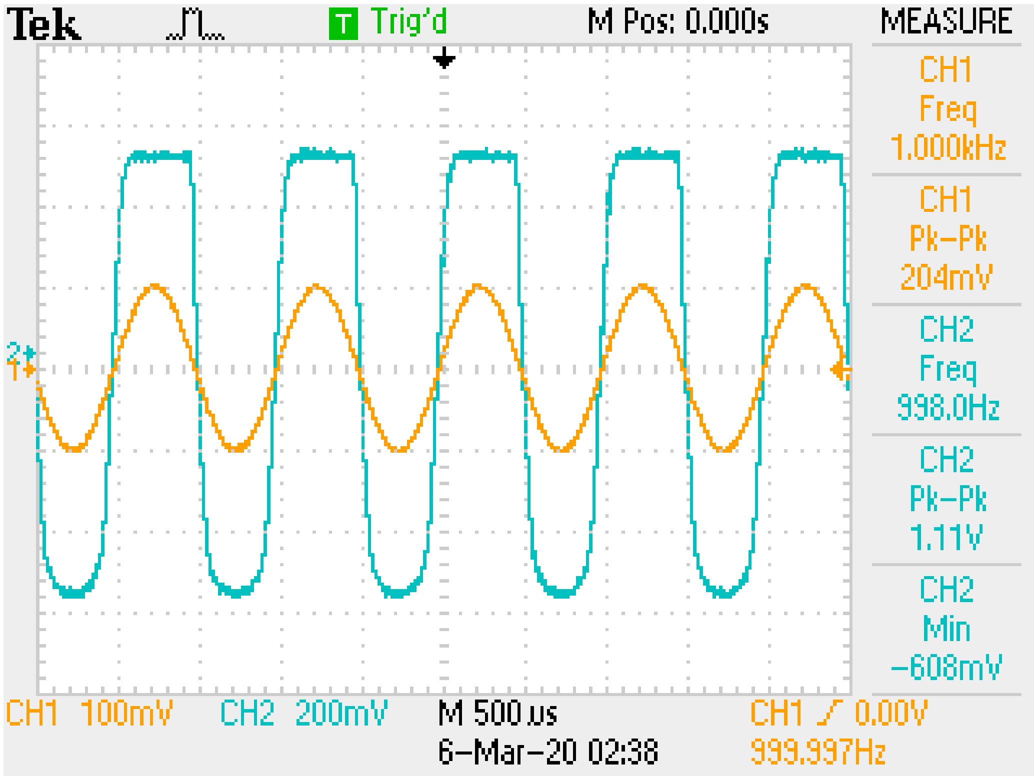


Figure 5.12: Simulation of 1N4148 Diode

frequencies present, which is likely mostly due to the filters in the analog circuitry. The tone felt fairly bright as well, but still had some subtle “fuzzier” characteristics. Overall, these diodes sounded harsh but satisfying; and they were very similar to the previous 1N4735 diodes.

The next simulation in Fig. 5.13, was of the 1N914. This diode typically has a forward voltage of 0.7 V and is fast compared to some of the other diodes simulated in this section. These diodes in the hard clipping configuration were my personal favorite in tone. The distortion created by these diodes was reminiscent of bands like Led Zeppelin, Deep Purple, and Black Sabbath. The sound had a fair amount of bass present, but it wasn’t quite what I would personally describe as a “fuzzy” tone. The bass was more precise than that of the 1N4004. The distortion felt slightly crunchier than the previous two diodes, but the sound was not excessively bright.

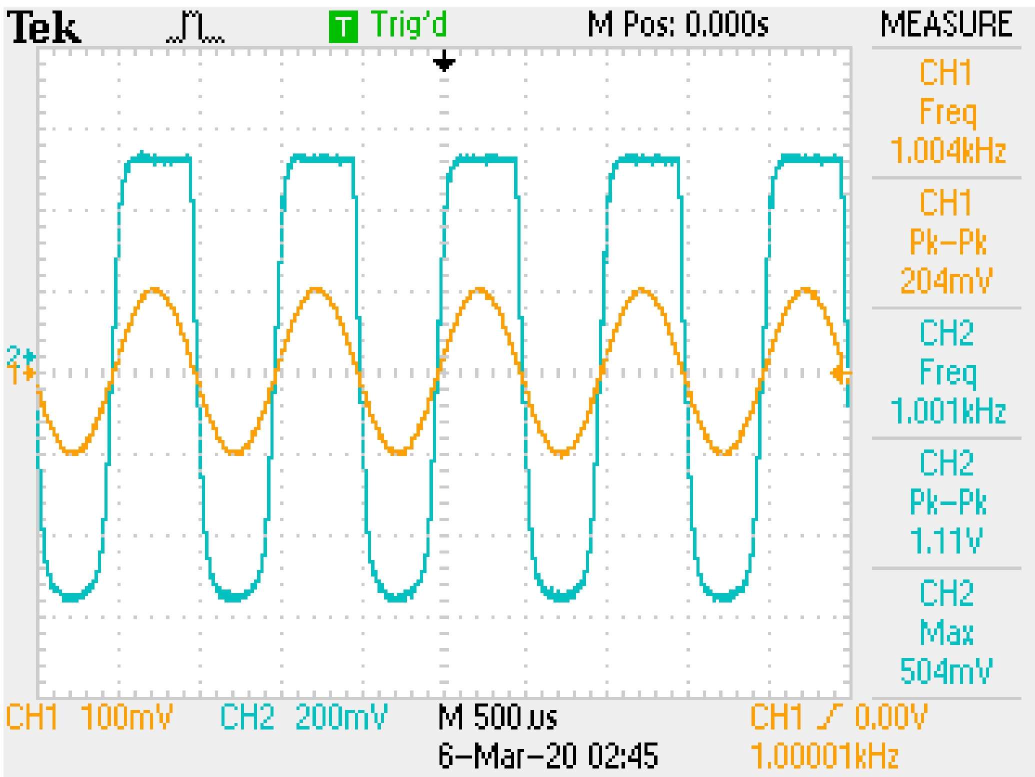


Figure 5.13: Simulation of 1N914 Diode

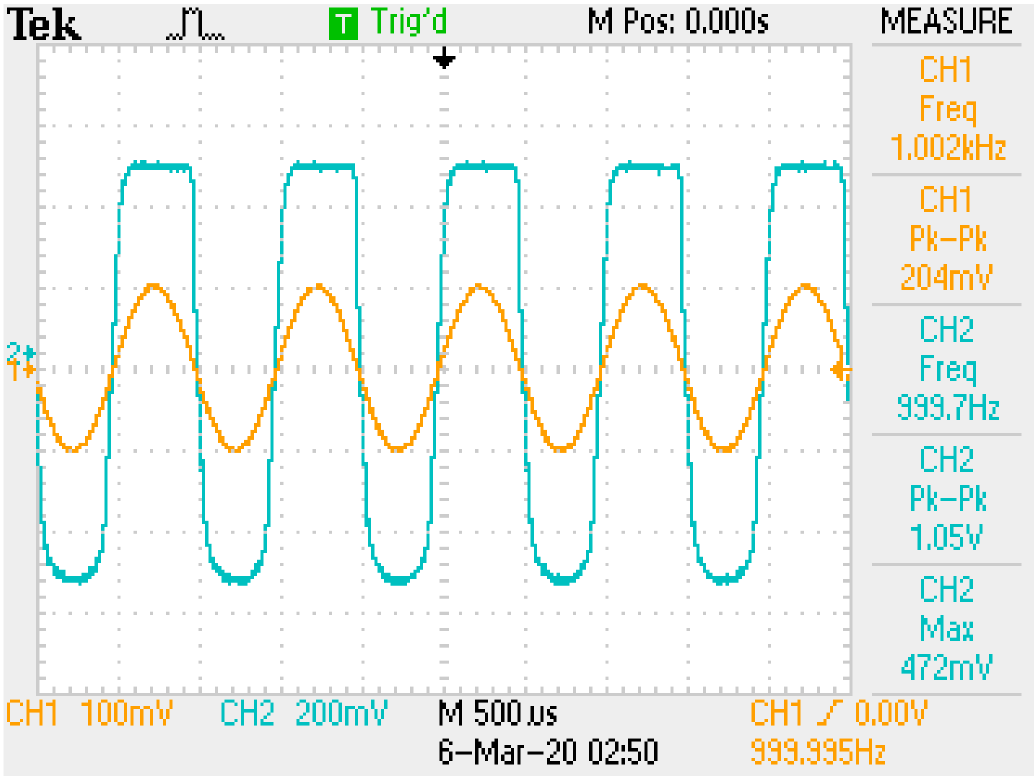


Figure 5.14: Simulation of 1N4004 Diode

The next simulation in Fig. 5.14, was of the 1N4004. This is a higher current diode , and as a result the typical forward voltage was not achieved for this simulation. Judging by the measured peak-to-peak voltage, the forward voltage across the diode was less than 0.7 V. The actual forward voltage was instead somewhere between 0.6-0.68 V. As a result, the peak of the produced in the simulation was very square. The near-square waves cause the tone of this diode to produce the fuzziest tone out of all the diodes tested. This tone would be perfect for the psychedelic rock made famous in the late 60's by guitarists like Jimi Hendrix.

The final diode simulated in this section was a typical red LED (Light Emitting Diode). This LED typically has a forward voltage somewhere between 1.7-2 V. This LED seemed to have a more "metal" or "hard rock" tone compared to the other diodes and would describe its sound as being more similar to 80's bands such as Guns n' Roses, Ratt, and the Scorpions. The tone

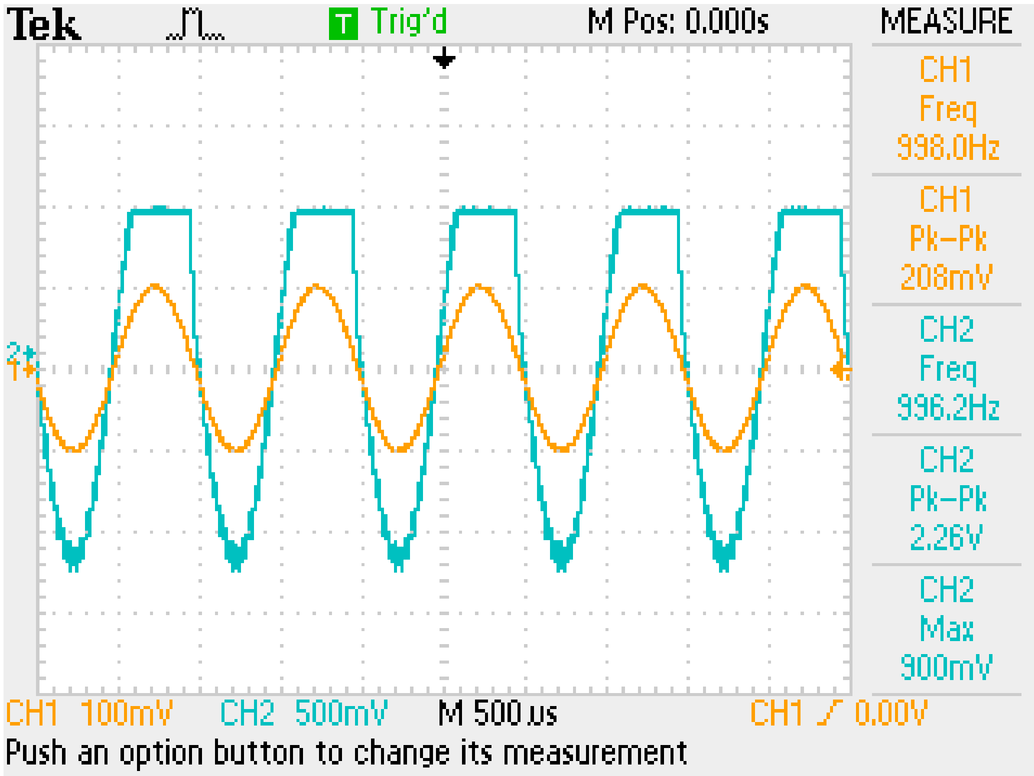


Figure 5.15: Simulation of Red LED

was heavier, and didn't at all feel fuzzy as compared to the previous diodes.Additionally, notice that the peak-to-peak voltage is 2.26 V. This is significantly higher than any of the other diode clipping simulations. Therefore, the clipping effect is less prevalent in this simulation than the previous ones, which can be a good or bad thing depending on the musician.

### 5.3.2 Diode Soft Clipping Profiles

In this section, some soft clipping profiles were explored that offered some different tonal qualities than the hard clipping configurations from the previous section. The same settings used in the hard clipping section were also used for this section to maintain the consistency of the experiment. The only difference between these simulations and the hard clipping simulations is that the diodes in this section were placed in the feedback path to attain the "soft slipping" effect.

When initially performing the soft clipping simulations, the signal contained excess amounts of noise and was not distorting the signal properly. To combat this problem, a parallel capacitor needed to be placed in the feedback path. After doing this, the noise was filtered out and the desired soft-clipped distortion was applied to the signal.

In Fig. 5.16, the 1N914 diodes were placed in the feedback path and simulated. The result was a crunchy, satisfying overdrive that could be described as being similar to bands like The Rolling Stones, Led Zeppelin, and Cream. This sound was one of the most satisfying configurations that was tested. The sound was full, and it provided a very good overdriven tone that any guitarist would expect from an analog pedal. Take note of how this signal clipped compared to Fig. 5.13. The peaks are overall smooth and round in the below figure, as opposed to being harshly clipped and square. This difference is what constitutes the rich mids and crunchy tone that describes overdrive in guitar signals [22].

In Fig. 5.17 the 1N914 diodes were placed in the feedback path and simulated. The 1N4004 clipped slightly more of the signal peak than the 1N914, but was overall very similar in tone. The overdrive produced by the 1N4004 was a much less aggressive form of clipping when compared to Fig. 5.14. The tonal difference between the hard clipping and soft clipping profiles of this diode are much more significant than the tonal differences between the other soft clipping profiles.

In Fig. 5.17 the red LED's were placed in the feedback path and simulated. These diodes seemed to soft clip the signal in an asymmetric manner. Much less of the signal was clipped for this simulation due to the LED's high forward voltage. Therefore, the overdrive was less obvious than the 1N914 or the 1N4004. To get a similar amount of crunchy overdrive to the 1N914, the

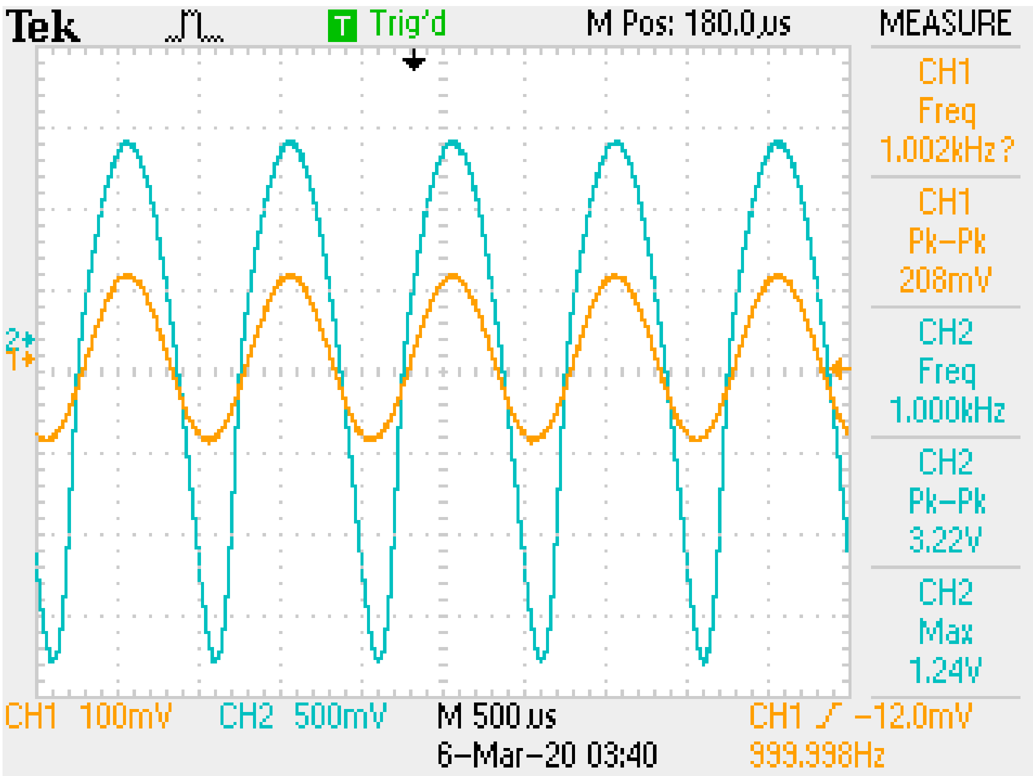


Figure 5.16: Simulation of 1N914 Diode

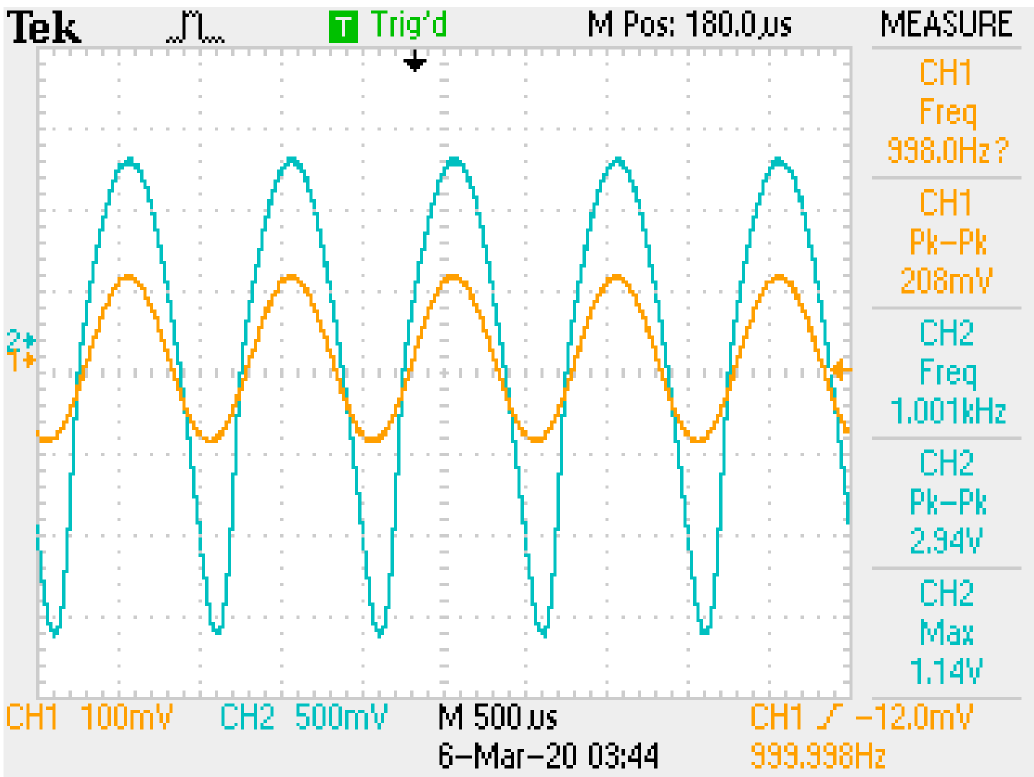


Figure 5.17: Simulation of 1N4004

gain dial would need to be turned up more for the red LED. Even though the overdrive for the LED was more subtle, it still produced a unique tone that some musicians may prefer over the other diodes. Perhaps it could have a role in music that requires smaller amounts of overdrive such as blues.

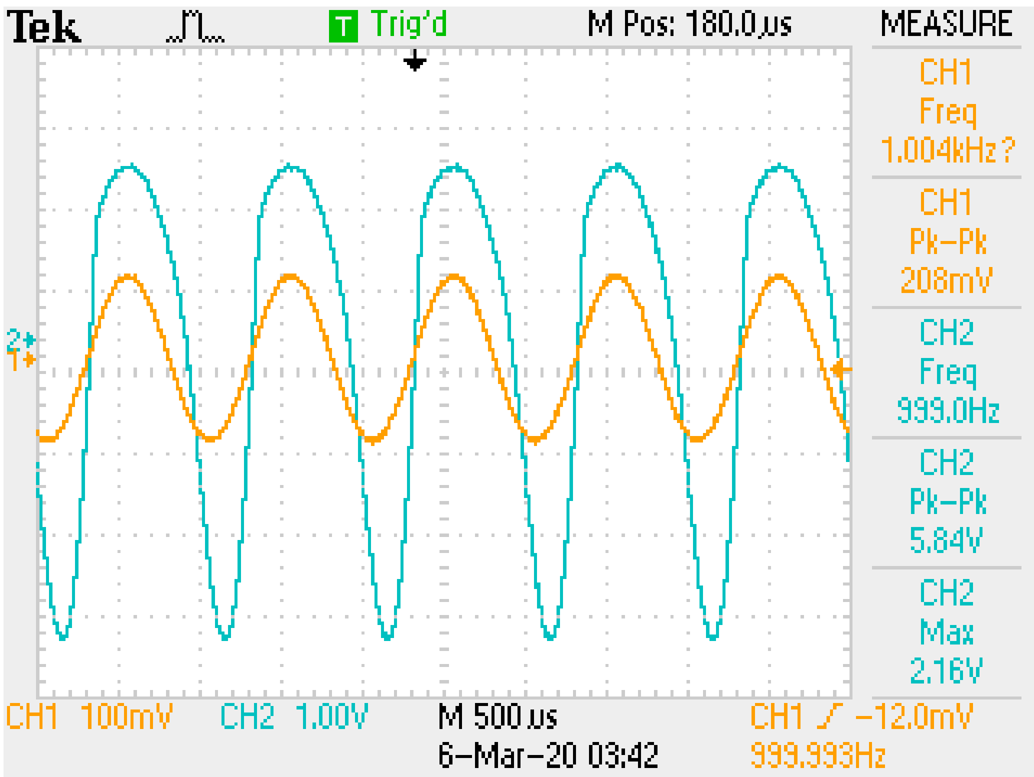


Figure 5.18: Simulation of Red LED

# Chapter 6

# Conclusions

This chapter summarizes this research project and presents possible future work associated with the project.

## 6.1 Summary of Results

The analog distortion circuitry designed in this project functioned as expected, and the distortion created by the circuit was both distinct and satisfying. The final pedal design was simple, yet versatile. The gain dial offered many different levels of distortion which any future user can change as needed. The tone dial provided some filtering for some of the higher frequencies produced during distortion. Lastly, the volume dial ensured that the user could adjust the amount of the signal being output to accommodate for different auditory levels. The diodes tested in the hardware chapter provided some examples of how different diodes can clip the signal differently. Some musicians may be striving for a fuzzier, more square distortion, which the 1N4004 was well suited for. Other musicians may prefer the classic crunchy tones of the Rolling Stones and Deep Purple, which the 1N914 represented well. Overall, the pedal exceeded expectations. The audio quality of the distortion was up to par with other standard analog pedals on the market.

## 6.2 Outlook and Future Work

While the project was successful in producing its promised deliverables, there are some modifications that could further improve the versatility of the pedal. In a future project, it would be beneficial to add a three band equalization, which would allow for further customization of the frequency response. Additionally, the PCB was intentionally left with unpopulated diode terminals. The user can modify the pedal manually by swapping out the clipping diodes.

Outside of this specific project, some other related future work could include designing other types of guitar pedal effects such as chorus, delay, and reverb. Many of these effects also rely on analog circuitry to alter the signal from a guitar. Using the knowledge basis that this project has provided, many other guitar-related engineering projects could be explored further.

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# Appendix I

# Appendix

Presented are images of various distortion pedals and the metal enclosure selected for the project.

## I.1 Ibanez Tube Screamer


Figure I.1: Ibanez Guitar Pedal

## I.2 BOSS DS-1


Figure I.2: BOSS Guitar Pedal

## I.3 Pedal Enclosure

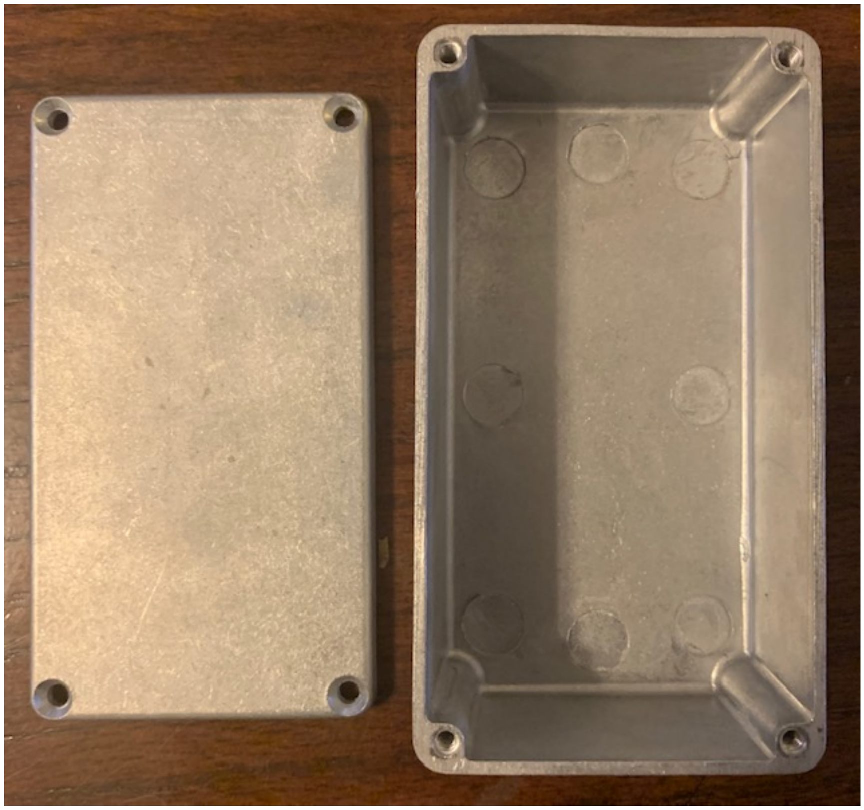

Figure I.3: Enclosure for Custom Analog pedal