Department of Electronic & Telecommunication Engineering, University of Moratuwa, Sri Lanka.

Electric Guitar Pedals

by Team ToneSmiths

Group Members:

220162T	Fernando C.S.R.
220420J	Nawarathne M.A.A.K.
220163X	Fernando D.S.
220200K	Gunawardana I.M.P.T.

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Contents

1 Introduction and Functionality

This analog electric guitar pedal project focuses on enhancing the tonal versatility and creative potential of musicians by designing and building three essential effects: distortion, wah, and phasor pedals. The main goal is to create high-quality, analog circuitry that provides precise control and rich sound characteristics while preserving signal integrity. Unlike digital alternatives that might introduce latency or lack the warmth of analog processing, our project employs carefully engineered analog components, such as operational amplifiers (Op-Amps) and filters, to create effects with unique sonic qualities. Each pedal is crafted to integrate smoothly into a guitarist's setup, delivering responsive performance and minimal signal degradation, ensuring that the nuances of the player's technique are accurately captured.

The key functionality of our analog guitar pedal project lies in delivering high-fidelity sound effects while preserving the integrity of the guitar's signal. Each pedal is meticulously designed to achieve specific sonic characteristics: the distortion pedal shapes the signal with adjustable gain and clipping to produce a rich, over-driven tone; the wah pedal employs a resonant filter controlled via a foot pedal, creating dynamic tonal sweeps; and the phasor pedal modulates the phase of the signal to produce a swirling, spatial effect. By using analog components such as operational amplifiers, precision filters, and low-noise circuitry, these pedals ensure minimal signal degradation and responsiveness to the player's touch, providing reliable and expressive performance for both live and studio applications.

2 System Architecture

2.1 Distortion Pedal

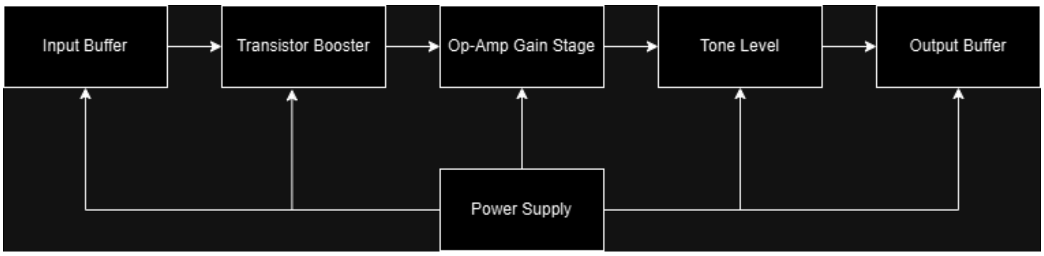

Figure 1: Block Diagram of Distortion Pedal

A distortion pedal is a fundamental tool for electric guitarists, designed to modify the instrument's signal by adding harmonic and inharmonic overtones, resulting in a "distorted" sound that is richer and more aggressive. The architecture of a typical analog distortion pedal, such as the Boss DS-1, comprises several key stages:

1. Input Stage

Input stage is a JFET in common collector configuration with unity gain and high input impedance to preserve signal quality and eliminate tone sucking (high-frequency loss).

- The capacitor C1 isolates the guitar from any pedal dangerous DC level and filters the inaudible low-frequency signals with a cut frequency of 7.2Hz
- The R2 input series will protect the base of the transistor from surge currents (electrostatic discharges from the guitar jack tip).
- R1 is just a moderate high-value resistor that biases the base of the transistor to 4.5V.
- R3 is the emitter resistance, 10K is a pretty standard value for an Emitter Follower buffer.

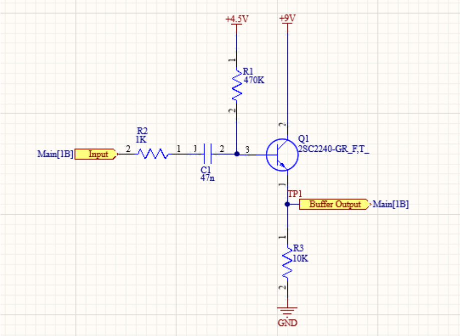

Figure 2: Input Stage

Input Impedance Calculation

$$Z_{\text{in}} = R_2 + (R_1 \parallel \beta R_3) = R_1 = 470\,\text{k}\Omega \tag{1}$$

The simplification $Z_{\text{in}} \approx R_1$ is valid because:

- The resistor R_2 is too small compared to R_1: $R_2 = 1\,\text{k}\Omega \ll R_1 = 470\,\text{k}\Omega$, so R_2 can be neglected in comparison.
- The term βR_3 is much larger than R_1: $\beta R_3 = 200 \cdot 10\,\text{k}\Omega = 2\,\text{M}\Omega \gg R_1 = 470\,\text{k}\Omega$. Therefore, the parallel combination simplifies as:

$$R_1 \parallel \beta R_3 \approx R_1 \tag{2}$$

2. Transistor Booster Stage

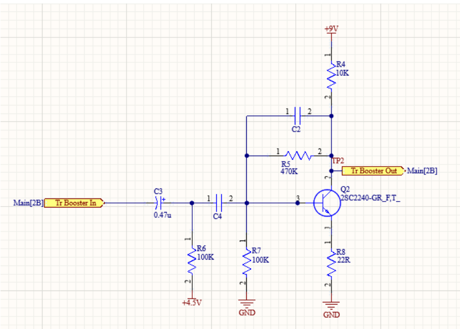

Figure 3: Transistor Booster Stage

This stage applies some frequency filtering and signal boosting before the op-amp stage. The first part of this stage are 2 consecutive high pass filters:

- C3 and R6 with a cut frequency of 3.3Hz
- C4 and R7 with a cut frequency of 33Hz.

The basic idea behind this filters is to remove the excess of bass before the (next) distortion stage, a guitar signal with too much bass harmonics could make the distortion slow, dumped or muddy.

The transistor stage is a Common Emitter (CE) amplifier.

The approximate voltage gain (A_v) in this topology is determined by the ratio of the collector resistance (R_C) to the emitter resistance (R_E), given by:

$$A_v \approx \frac{R_C}{R_E} \tag{3}$$

Substituting the given values:

$$R_C = 10\,\mathrm{k\Omega}, \quad R_E = 22\,\Omega$$

$$A_v = \frac{10\,\mathrm{k\Omega}}{22\,\Omega} = 454 \approx 53\,\mathrm{dB} \tag{4}$$

However, the effect of the feedback resistor (R_7) and capacitor (C_4) must be taken into consideration(Shunt Feedback Resistance). Feedback reduces the overall gain, resulting in a practical voltage gain of approximately:

$$A_v \approx 35\,\mathrm{dB}$$

However, a gain of 36dB (56 times) is a huge amount of it, if we have a guitar input signal of 200mVpp, after the transistor booster the signal level is 11.2Vpp, the waveform will be distorted because the pedal supply is 9V. This gain will create a clipping that looking at the image below is asymmetric (cycles have a slightly different duration) and has a soft knee or soft clipping:

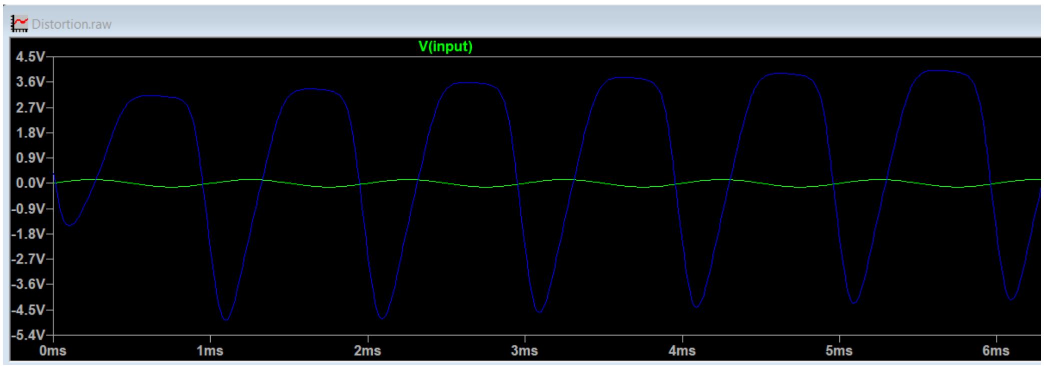

Figure 4: Waveform After Transistor Booster Stage

3. Op-Amp Gain Stage

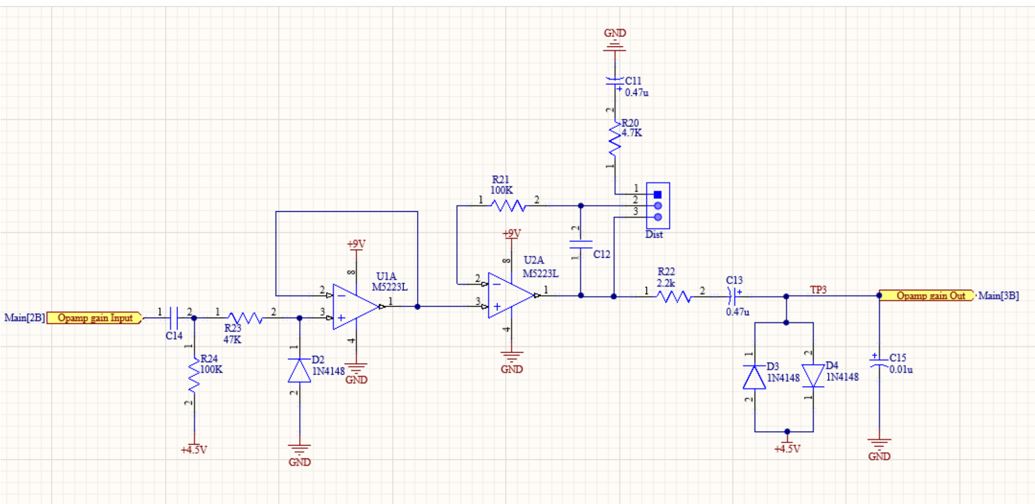

Figure 5: Op-Amp Gain Stage

The Operational Amplifier block serves as the core of the circuit, functioning as a variable non-inverting amplifier. It incorporates two diodes to generate the clipping or distortion effect and employs passive RC filters (a combination of low-pass and high-pass filters) to define the clipping characteristics and control the frequency range where the distortion occurs.

At the beginning of the stage, there is an RC network (C_14 and R_{24}) that forms a high-pass filter. The cutoff frequency (f_c) of this filter is determined by the formula:

$$f_c = \frac{1}{2\pi RC} \tag{5}$$

Substituting the values for R_{24} and C_14, the cutoff frequency is calculated as:

$$f_c = \frac{1}{2\pi R_{24}C_14} = 23\,\text{Hz}$$

This high-pass filter is not an intentional filter; it arises from the need for:

- A coupling capacitor (C_14) to connect the output of the previous transistor gain stage.
- A moderately high resistor (R_{24}) to bias the + pin of the op-amp at virtual ground ($+4.5\,\text{V}$).

Biasing and Protection:

- R_{24} is a high-value resistor that biases the input of the op-amp at $+4.5\,\text{V}$.
- Diode D_2 is placed to protect the op-amp input. Signals at the op-amp input float around $+4.5\,\text{V}$, biased by R_{24}.
- If a signal from the previous stage tries to drive the op-amp input below the negative rail ($-0.7\,\text{V}$, the forward voltage of the diode), D_2 will conduct and clip the signal, preventing dangerous voltages at the + pin.

Collector Bias and Diode Protection:

- The transistor Q_2's collector is biased around $+5.8\,\text{V}$.
- When Q_2 saturates, without D_2, pin 3 of the op-amp (U_1) would be driven to $-1.3\,\text{V}$. This can cause significant issues for the op-amp, such as:
  - Permanent damage to certain op-amps.
  - Latch-up in some op-amps.
  - Recovery delays in the input stage of most op-amps, affecting performance and degrading sound quality.

Key Points About D_2:

- By the time D_2 starts conducting, the op-amp is already clipping. Thus, D_2 does not contribute to asymmetrical clipping or modify the guitar signal in any way.
- Its sole purpose is to protect the op-amp from over-voltage conditions.

Role of R_{23}: The resistor R_{23} limits the current into the + pin of the op-amp, providing additional protection to the input. The second half of the M5223L is a non-inverting amplifier that will boost the signal up to 22.3 times (26.5 dBs) following the formula:

$$G_{v_{\text{op-amp max}}} = 1 + \frac{V_{R1}}{R_{20}} = 1 + \frac{100K}{4.7K} = 22.3 \text{ (26.5dB)}$$

$$G_{v_{\text{op-amp min}}} = 1 + \frac{0}{R_{20}} = 1 + \frac{0K}{4.7K} = 1 \text{ (0dB)}$$

The clipping stage defines the distortion signature sound, it is built using 2 back to back diodes that shunt the signal to AC ground (4.5V). This kind of clipping technique gives a “hard-clipping” sound.

With the 26.5 dB of gain, the audio signal will be bigger than the V_F of the diode that is around 0.7V in any position, creating a hard clipping action.

Playing with the distortion potentiometer, the edge of the waveform can be softened but, in any case, the overall look is pretty squared and distorted.

Capacitor C12 (100pF) reduces the high harsh harmonics at the very top of the audio spectrum. It controls it by allowing highs through the feedback loop. The high-pass filter created by C11 and R20 (and part of the VR1 pot depending on its position) will remove frequencies below 72Hz (or lower depending on the VR1 position):

$$f_{c_{\max}} = \frac{1}{2\pi C_8 R_{20}} = \frac{1}{2 \times 3.14 \times 0.47\mu \times 4.7K} = 72\text{Hz}$$

$$f_{c_{\min}} = \frac{1}{2\pi C_8 (R_{20} + VR_1)} = \frac{1}{2 \times 3.14 \times 0.47\mu \times 104.7K} = 3\text{Hz}$$

At max distortion, harmonics over 72Hz get the full gain of the distortion stage, and everything below it gets progressively less gain and distortion. Bass notes are less clipped, so the distortion is frequency selective.

As mentioned above, the diodes D3 and D4 will clip when the amplified signal goes over/below the forward voltage (VF), which is around 0.7V.

4. Tone/Level Stage

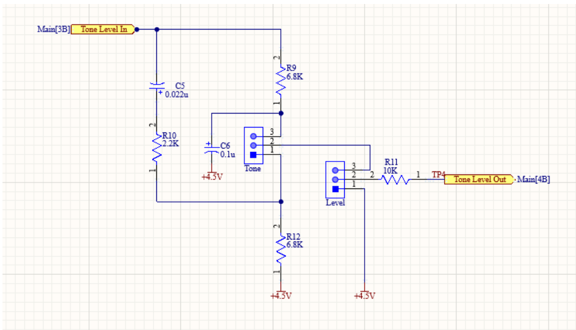

Figure 6: Tone/Level Stage

The Boss DS-1 uses a passive Big Muff Pi style tone control, which scoops the mids and attenuates the lows or highs, depending on which way you turn the knob. The circuit consists of a simple fixed -6dB/oct low pass filter (formed by R9 and C6 with an $f_c = 234$Hz) and a fixed -6dB/oct high pass filter (formed by C5 and R10 with an $f_c = 1063$Hz) using the VR3 pot to mix the two signals. The cut-off points of both filters are calculated so that their interweaving effect creates a frequency scoop/notch around 500Hz when the tone control is set to the middle position.

- After the initial tone shaping carried out by the first part of the circuit and the VR3, the VR2 pot regulates the level by bleeding part of the signal to AC ground.

5. Output Buffer Stage

The output buffer has exactly the same circuit as the input buffer. Its task is to keep a low output impedance for better signal integrity in the guitar-pedals-amp chain. Like the Input Stage, this unity gain buffer is implemented with a plain Emitter Follower with a 10K emitter resistor R16, biased from the 4.5V source with R13 in parallel with R14 ($1M//1M = 500K$).

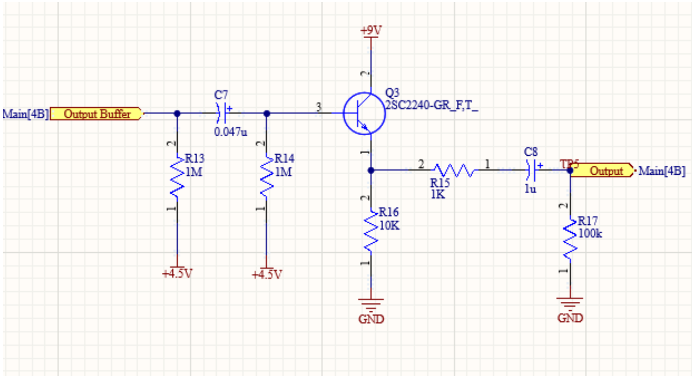

Figure 7: Output Buffer Stage

- The input capacitor C13 and R20 create a high pass filter with $f_c = 3.4$Hz ($f_c = \frac{1}{2\pi RC}$), the idea is just to remove the DC levels so the transistor can be correctly biased.
- R16 is the emitter resistance, 10K is a standard value for an Emitter Follower buffer.
- C8 and R17 form a high pass filter with an $f_c = 1.6$Hz below the audio spectrum. The purpose of this filter is just to remove the DC levels from the final output signal.

2.2 Wah Pedal

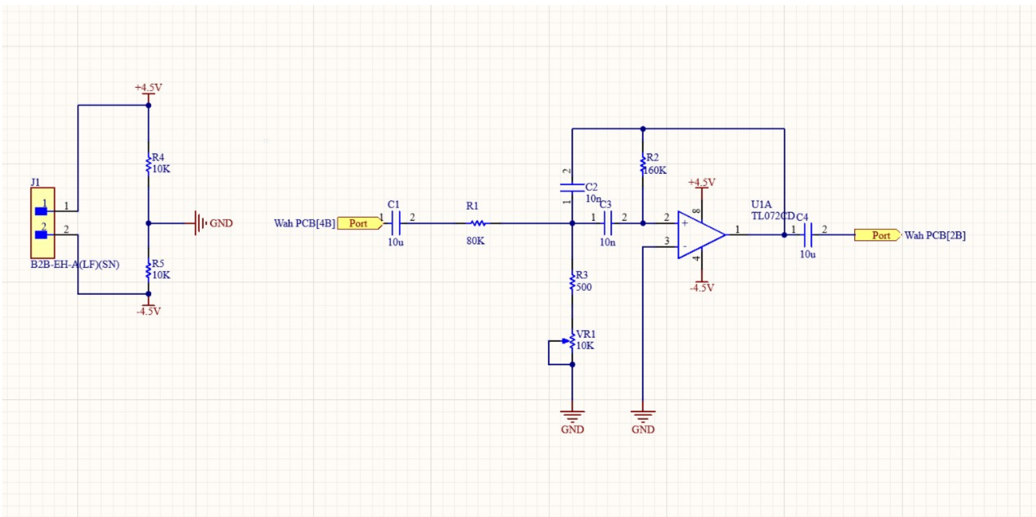

Figure 8: Schematic of Wah Pedal

A wah-wah pedal, or simply wah pedal, is a type of effects pedal designed for electric guitar that alters the timbre of the input signal to create a distinctive sound, mimicking the human voice saying the onomatopoeic name "wah-wah". The pedal sweeps a band-pass filter up and down in frequency to create a spectral glide.

The circuitry of Wah Pedal is relatively less complex compared to Distortion Pedal and Phasor Pedal.

- C3 and R1 form a highpass filter of cutoff frequency 0.159Hz - This is used to cut-off the DC level signal.

- Then we have second order resonant band-pass filter to isolate the band. By varying the potentiometer(R_a) we can change the band to create the wah wah sound.

$$f_{c_{\max}} = 1.78\text{kHz}$$

$$f_{c_{\min}} = 536.5\text{Hz}$$

- The quality factor of the band-pass filter is,

$$Q = \frac{R3}{R4} = 320$$

2.3 Phasor Pedal

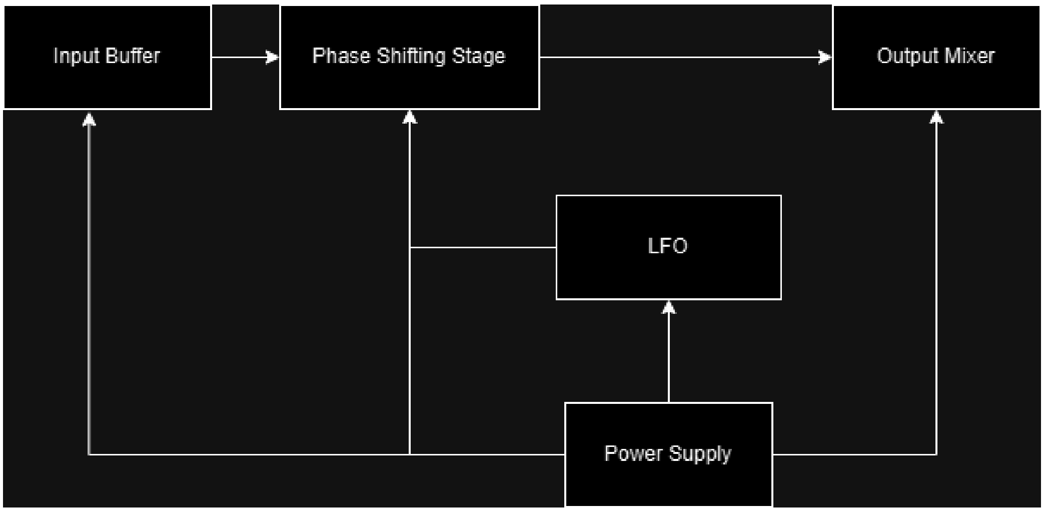

Figure 9: Block Diagram of Phasor Pedal

A Phaser Effect pedal splits the guitar signal into two copies: the first copy suffers a phase shift of 180° (is inverted) at a certain frequency f_{phaser}, the second copy is the same as the original. Both signals are recombined into a single signal; as a result, a notch (signal cancellation) at f_{phaser} is created.

Input Impedance

The input impedance can be calculated as:

$$Z_{\text{in}} = R_3 + \left(\frac{R_4 \parallel Z_{\text{in op-amp}}}{R_4 + Z_{\text{in op-amp}}} \right) = R_3 + R_4 = 480\,\text{K}$$

Note: 480K ohms can be considered a decent input impedance, sufficient to avoid tone sucking. However, in pedal design, the best practice is to keep the input impedance at least at 1 MΩ.

90 Phase Shifting Unit

Using the Elementary Shifting Unit concept, the Phase 90 uses an inverting operational amplifier with the RC shifter at the (+) input. In the image below, the circuit is presented with the signals at the key points. The phase shift of 90° will take place at the $f_{\text{phaser}} = f_{\text{cut-off}}$ of the RC network.

- The **Blue** waveform V_{in} is the input signal, for the example a unitary signal is used (module 1, phase 0°).

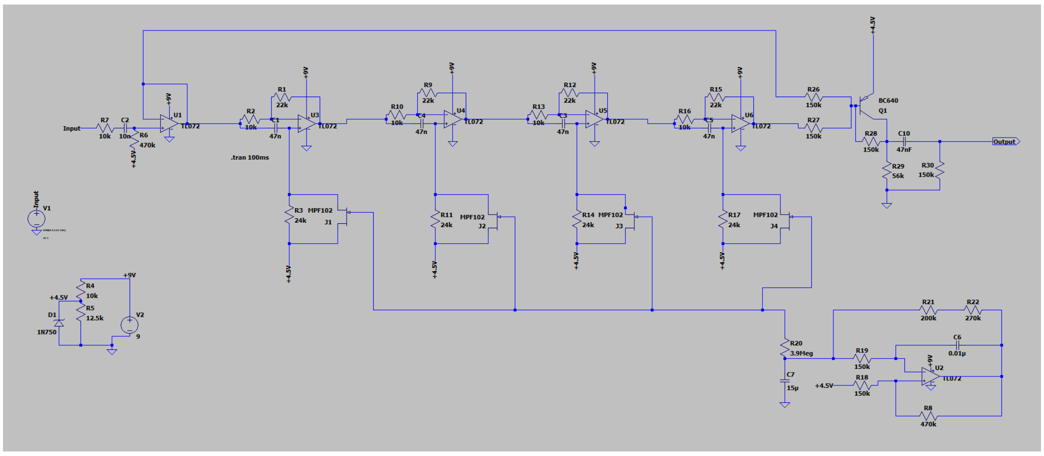

Figure 10: Phasor Pedal Schematic

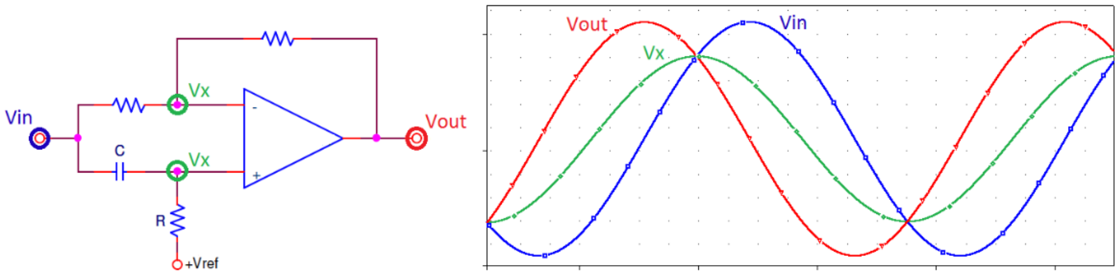

Figure 11: Phase 90 Shifting Unit

- The Green waveform V_X is the signal at the (-) or (+) op-amp inputs. Considering the RC as a standard high-pass filter, because $+V_{\text{ref}}$ is virtual ground and can be considered as the GND point. The $f_{\text{cut-off}} = \frac{1}{2\pi RC}$ with a 45° phase shift and the amplitude is $V_{\text{in}} - 3\,\text{dB}$ or, in other words, $\frac{1}{\sqrt{2}}$ (which is why the green waveform is smaller than the blue and the red).
- The Red waveform V_{out} is the output signal, with a magnitude of 1 and a phase shift of +90°.

3 Component Selection

Table 1: Op-Amp Selection

Property	**What we need**	**TL072**(WAH Pedal and Phasor Pedal)	**M5223L**(Distortion Pedal)
Slew Rate	0.02 V/μs	13 V/μs	0.5 V/μs
Bandwidth	5 kHz	3 MHz	1 MHz

So, it is evident that the Op-Amps we selected satisfy the required conditions for a pedal board.

4 Schematics

For the ease of understanding and to view the design at a modular level, the schematics of Distortion and Phaser effects were created using the hierarchical method in Altium.

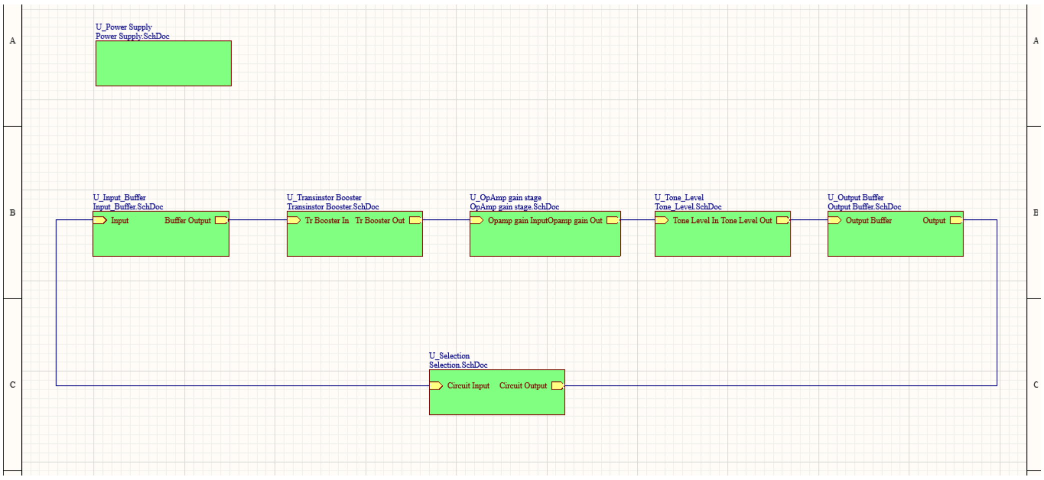

Figure 12: Distortion Pedal Schematic

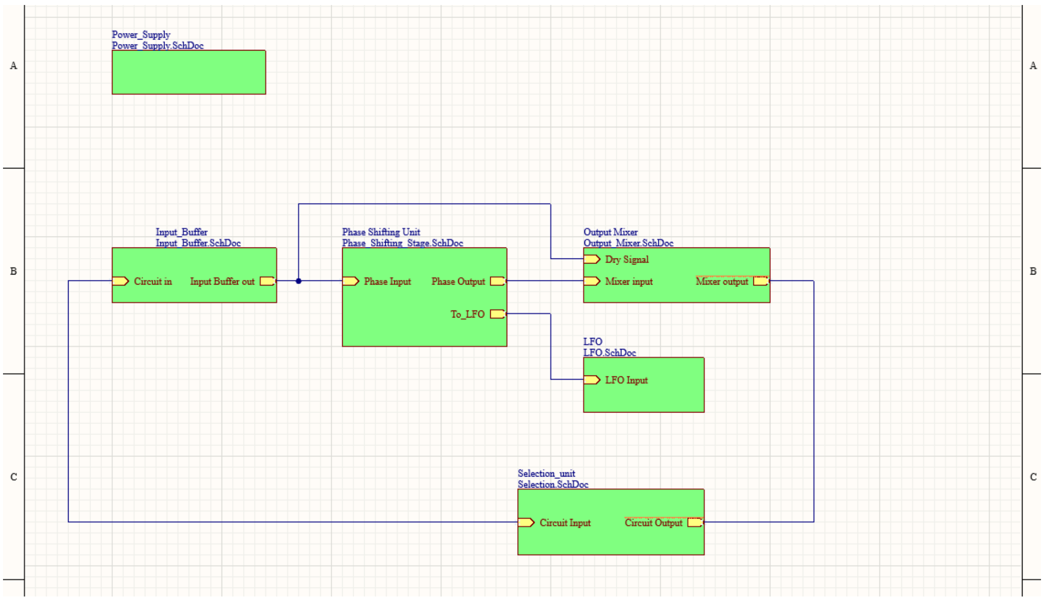

Figure 13: Phasor Pedal Schematic

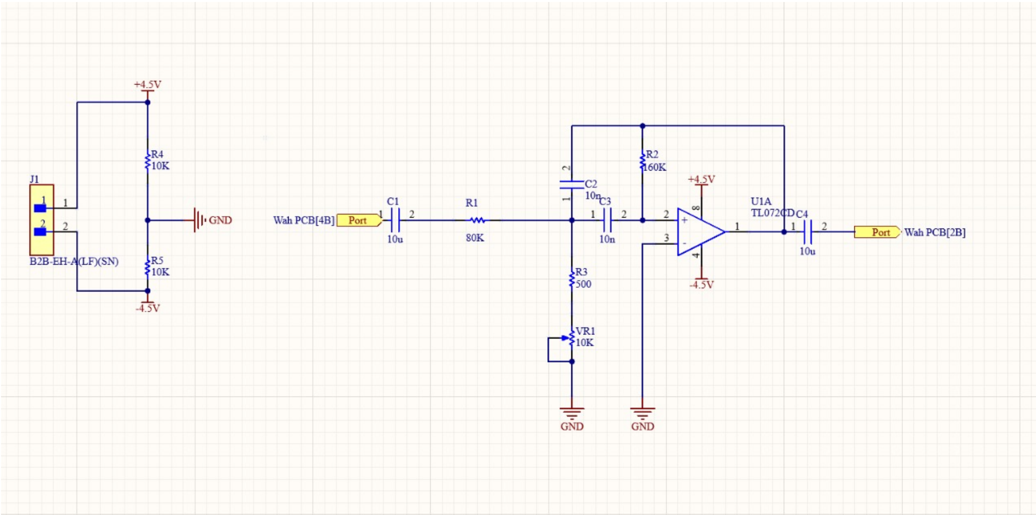

Figure 14: Wah Pedal Schematic

As suggested by the lecturers, an LED indicator was included to show whether the effect is switched on or off, and both standard 9V DC and battery power options were provided to meet the multiple power supply requirements. Schematic for this is given above.

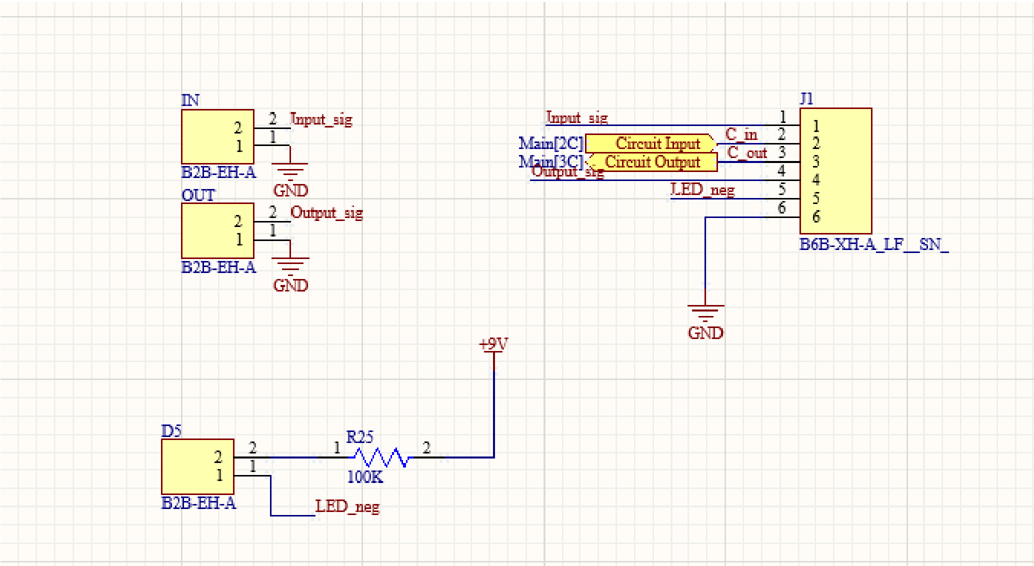

Figure 15: Selection Schematic

5 PCB Design

Due to time constraints, we had to print the PCBs for the wah and phasor effects in Sri Lanka as single-layer PCBs. However, due to the complexity of the phasor effect, we were unable to route it on a single layer, so it was not implemented on a PCB.

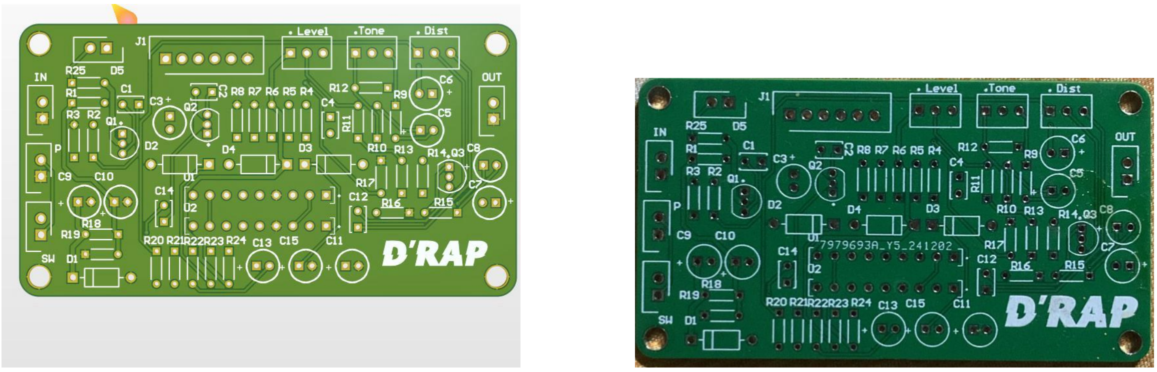

Figure 16: Distortion PCB

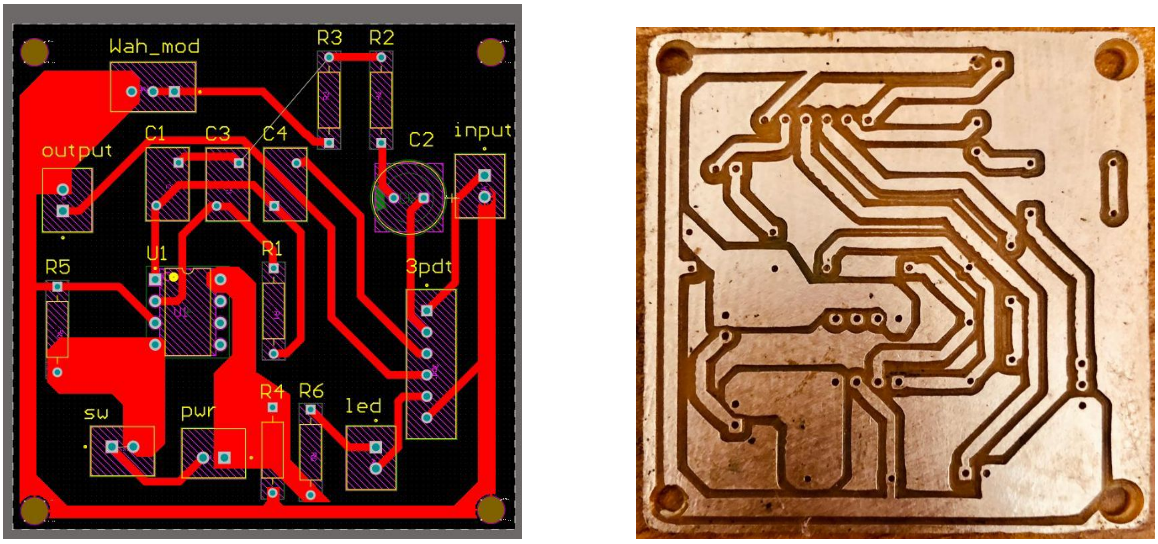

Figure 17: Wah PCB

6 Enclosure Design

The enclosure design was done in autodesk fusion 360. We designed two enclosures for the Distortion pedal and the Wah pedal.

6.1 Distortion

The knobs were taken from from grabcad, an open source website to import premade models. The distortion pedal was inspired by the popular MXR distortion pedal brand. It was a very simple compact design. Comparatively the distortion pedal was much easier to make.

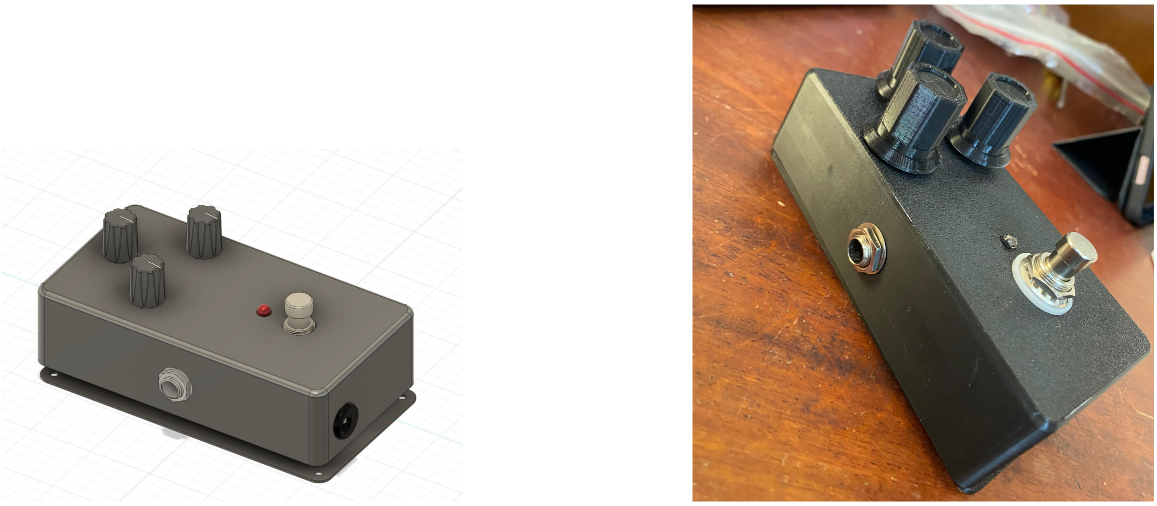

Figure 18: Enclosure-Distortion

6.2 Wah

The wah pedal was inspired by a DIY project on the internet.
This was quite challenging to make due the expected mechanism of this enclosure. In the wah pedal

you have to be able to control the potentiometer by pressing on the pedal. This was done using the a gearwheel mechanism as shown in the images. We came up with it by analyzing a few existing designs.

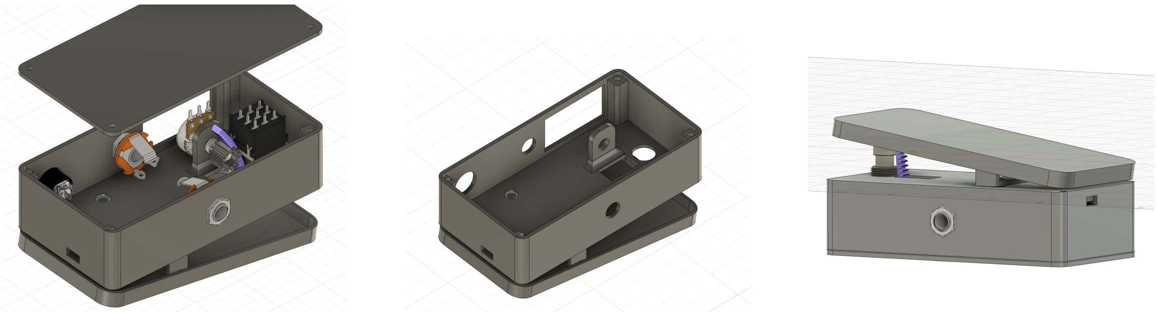

Figure 19: Enclosure-Wah

7 Software Simulation and Hardware Testing

7.1 Simulation

We used LTspice software to simulate the schematics and obtain the relevant results. It helped to verify the components and the circuitry.

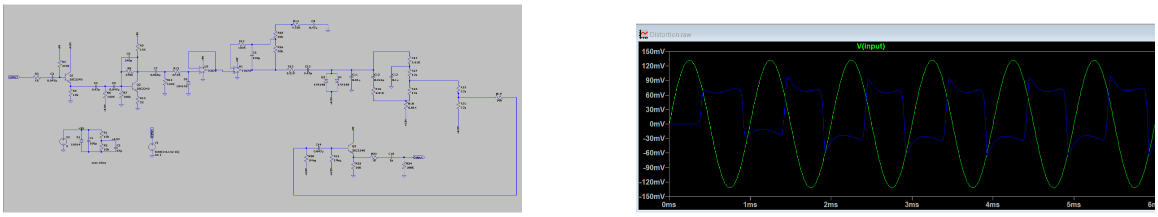

Figure 20: Simulation results-distortion

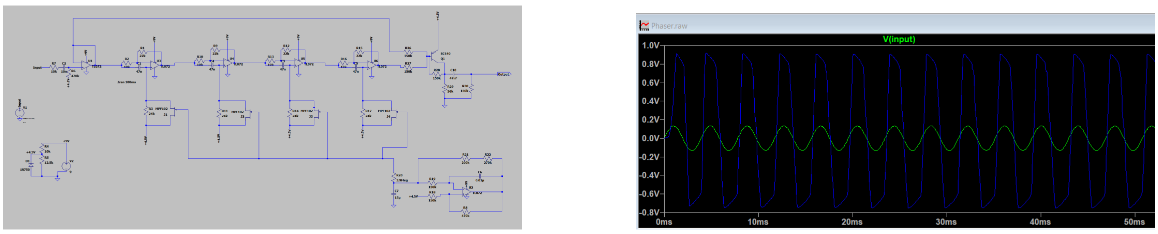

Figure 21: Simulation results-Phaser

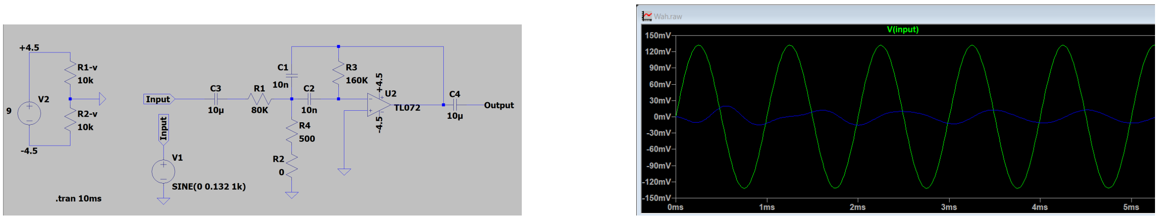

Figure 22: Simulation results-Wah

7.2 Hardware Testing

First, we implemented the circuit on the bread board and calibrated the components until getting successful results for all three pedals. Then we designed the PCB for distortion and wah pedals and did a PCB testing using the multimeter by checking the output voltage. Finally, we have attached every component to our enclosure and did a testing and got successful results for distortion and wah pedals.

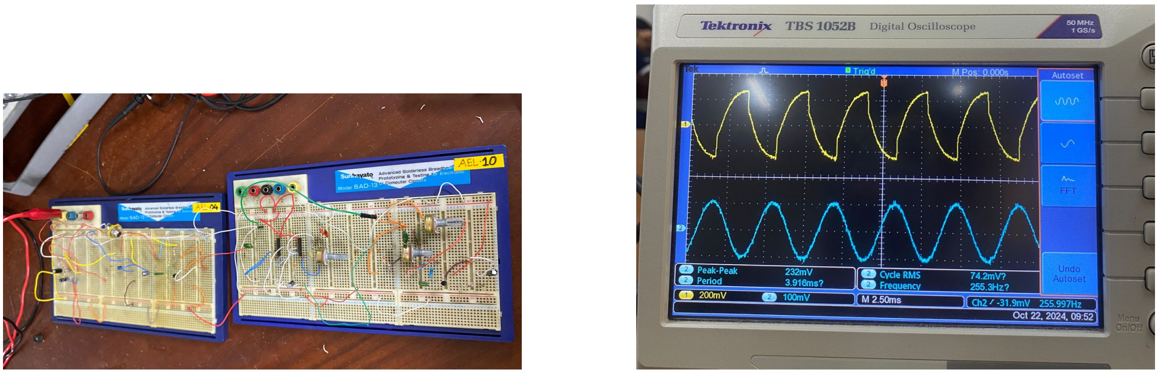

Figure 23: Distortion

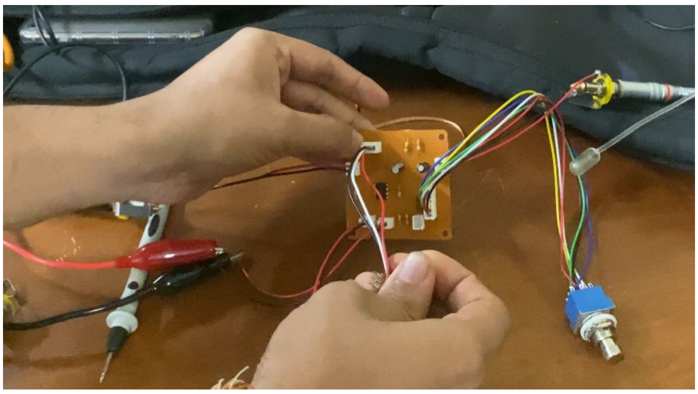

Figure 24: Wah

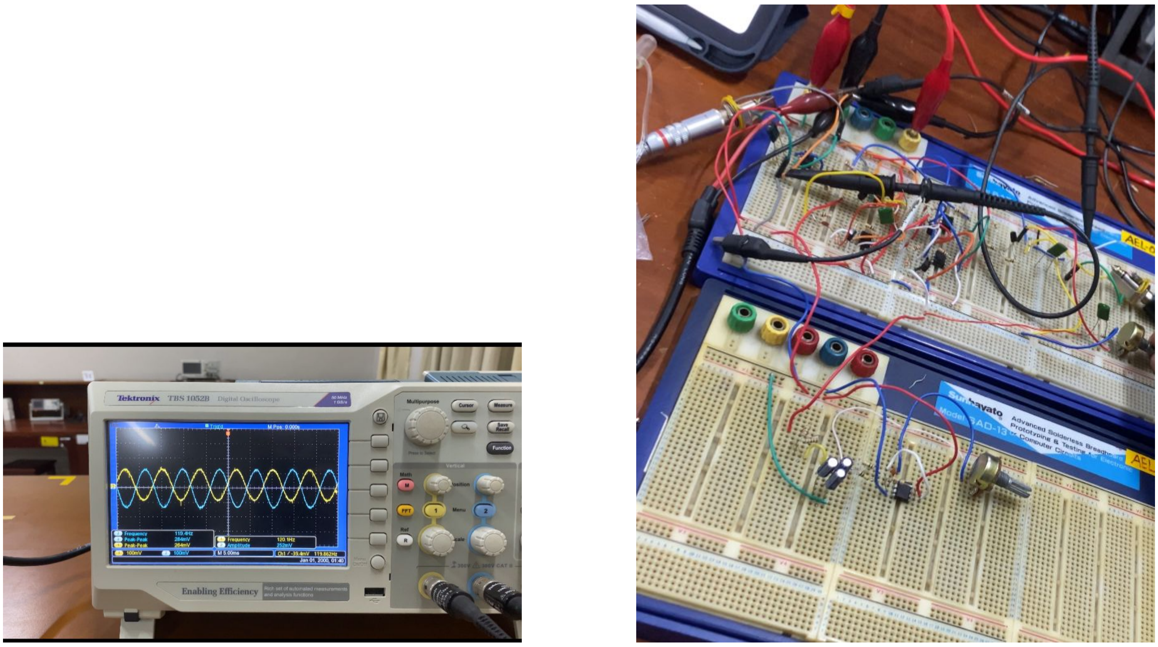

Figure 25: Phaser

8 Conclusion & Future Works

In conclusion, our analog electric guitar pedal project has demonstrated the effectiveness of analog methods in creating unique and high-quality sound effects. By utilizing analog circuitry rather than digital processing, we have developed a fresh approach to shaping guitar sounds through operational amplifiers, filters, and other analog components. The combination of distortion, wah, and phasor pedals has resulted in a versatile setup that delivers a wide array of tones with impressive clarity and character.

The process of converting analog signals through various stages of amplification and filtering showcases the adaptability of analog methods in shaping guitar sounds. Features such as adjustable gain for distortion, sweep control for the wah pedal, and phase modulation for the phasor contribute to a pedal board that is both versatile and user-friendly.

Looking ahead, there are numerous opportunities for improvement and exploration. Fine-tuning component values and optimizing the analog circuitry could enhance the pedals' responsiveness to different playing styles and genres. Investigating alternative analog components and circuit designs may further boost performance. Additionally, developing power-efficient designs and considering battery-powered options could extend the pedals' lifespan and increase portability.

By continuing to refine and innovate in the realm of analog guitar effects, we aspire to provide musicians with tools that spark creativity and elevate their performances.

9 Contribution of Group Members

It was a great team work and everyone hauled day and night to make this project a success.

Index Number	Name	Contribution
220162T	Fernando C.S.R.	Wah PCB, Distortion PCB
220163X	Fernando D.S.	Phasor PCB, Simulation
220420J	Nawarathne M.A.A.K.	Enclosure Design,Wah PCB
220200K	Gunawardana I.M.P.T.	Distortion PCB, Simulation

Table 2: Team Member Contribution

10 References

- Premier Guitar. (n.d.). *Boss DS-1 Mods.* Retrieved from `https://www.premierguitar.com/diy/pedal-projects/boss-ds-1-mods`
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