Wave Generation and Shaping

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Abstract—This project details the design, construction, and testing of a voltage-controlled oscillator (VCO) as the foundational component for a future analog synthesizer. The VCO generates a tunable periodic waveform, the basic building block of musical sound, with its output frequency controlled by an applied voltage. The successful realization of this circuit lays the groundwork for developing a more comprehensive synthesizer system capable of generating a wider variety of electronic sounds.

keywords—*Analog Synthesizer, VCO, Wave Shaping, Waveform Design*

Contents

1. Introduction

This is the lab report for our Final Lab Project for the course EE1201. We were asked to experiment with some circuits, and then design and implement a circuit of our choice.
This report documents the investigation into the fundamental principles of sound synthesis and waveform generation. The project focused on designing and implementing a Voltage-Controlled Oscillator (VCO), a core element responsible for generating sound based on an applied control voltage. Additionally, waveshaping techniques, which manipulate the characteristics of a waveform, are presented.
Sound synthesis and wave shaping are fundamental building blocks in various fields, including electronic music production, where they enable the creation of a vast array of sonic textures. VCOs offer a versatile way to generate sound with controllable pitch, while wave shaping allows further sculpting of the sound characteristics. Understanding these techniques provides a strong foundation for understanding the core principles of sound manipulation.

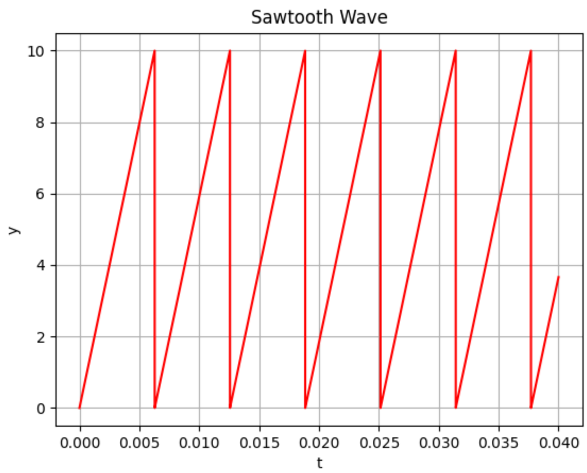
2. Design of the System and List of Components

2.1. The Art of Wave Shaping

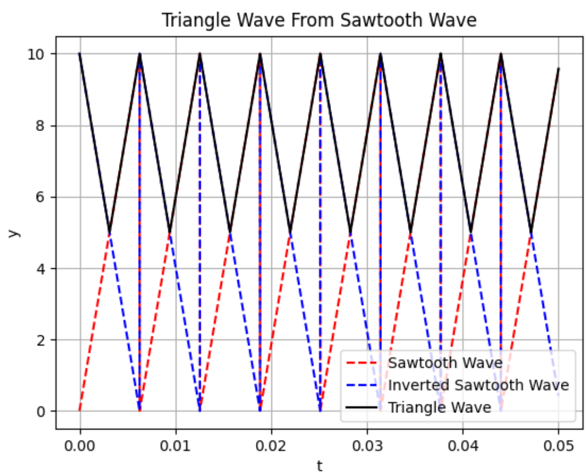
Waveform synthesis lies at the heart of electronic sound generation. Through mathematical operations like summation, filtering, and amplitude modulation, existing waves are combined and transformed to generate different waves. For our lab project, we chose to create the following waves.

- Square
- Triangle
- Saw-Tooth
- Sine

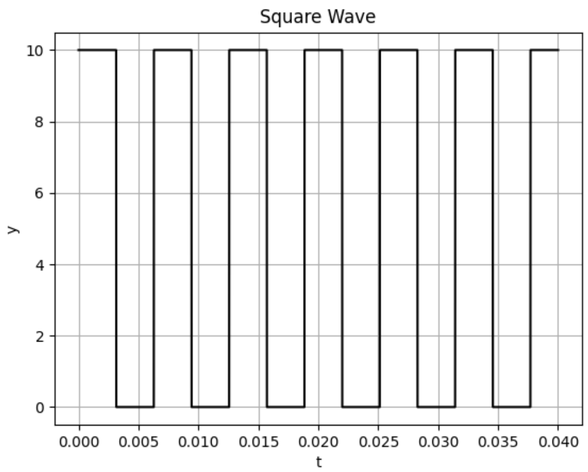
We start with the generation of the Saw-Tooth wave, as the basic constituent of all the waves.



Using the Sawtooth wave, a triangle wave can be generated by taking the maximum of the saw, and its inverse.



Generating a square wave from either the sawtooth or the triangle is a simple comparison with $\frac{V_{pp}}{2}$ $w.r.t$ V_{min}, where V_{pp} is the peak-to-peak voltage, and V_{min} is the minimum voltage of the wave.



An RC phase shift oscillator is used here to generate a quasi-sinusoidal waveform from a square wave.

2.2. Generating the Saw-tooth Wave

The basic idea behind generating such a wave is the charging and discharging of a capacitor. We use a 555 timer IC, to achieve the wave. The following circuit was used as a reference:

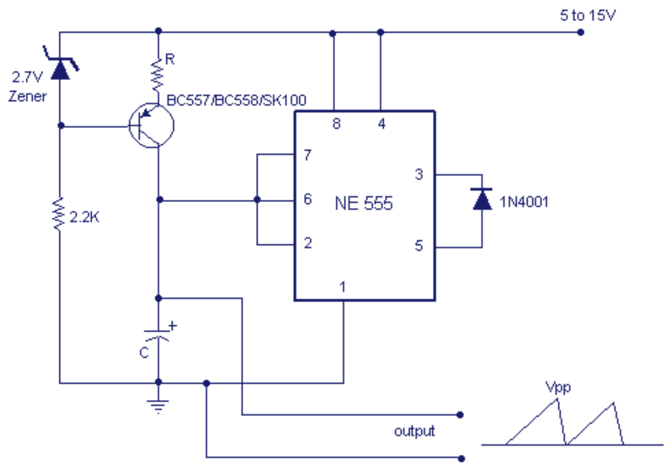


Figure 1. Circuit used for Sawtooth Generation

The resistors, transistor and the Zener Diode collectively form a constant current source, which is used to charge the capacitor C. If the capacitor is initially discharged, the voltage across the capacitor is zero and the 555's output is high because of the internal comparators connected to the pin 2. The capacitor starts charging to supply voltage. The 555 timer operates in astable mode by utilizing an internal voltage divider to establish two voltage thresholds. During the charging phase, the output transitions low when the voltage on the timing capacitor C rises above two-thirds (2/3) of the supply voltage (V_{cc}). Conversely, during the discharging phase, the output transitions high when the voltage across C falls below one-third (1/3) of V_{cc}. Consequently, the capacitor undergoes a continuous charging and discharging cycle between these two voltage thresholds, defining the oscillation period.

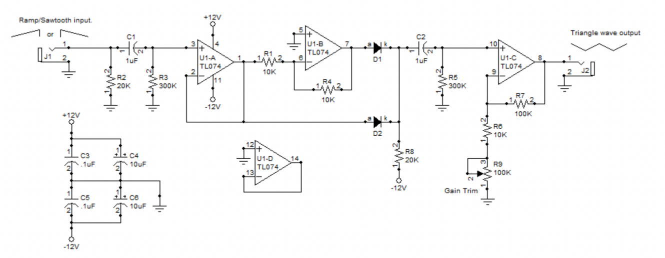
Component	Quantity
NE555	1
Zener Diode	1
BC557	1
$2.2k\Omega$	1
$1\mu F$	1
1N4007	1

Table 1. Components Used

2.3. Wave Shaping

2.3.1. Sawtooth to Triangle Wave

The following reference circuit creates the triangle wave.



The sawtooth wave connects to the Input. Resistor R_2 ($20k\Omega$) reduces the signal level. Capacitor C_1 ($1\mu F$) blocks any DC offset from the signal and couples it to the non-inverting input of an Op-Amp. The reference for this Op-Amp is set to ground. However, the AC coupling of C_1 and R_3 limits low-frequency signals (below 20Hz) distorting the resulting triangle wave. The signal first passes through a buffer and a rectifier circuit. The buffer creates an inverted copy of the signal, while the rectifier removes the negative portion of the waveform. A capacitor blocks any DC offset from reaching the next stage. The original and inverted/rectified signals are then summed and amplified to create a triangle wave. A slight imperfection appears in the final output due to the limited speed of the original signal's transitions. This imperfection is negligible for human hearing. Finally, the triangle wave is amplified again to adjust its overall strength before being output.

Component	Quantity
TL074	1
1μF	2
0.1μF	2
10μF	2
$20k\Omega$	2
$300k\Omega$	2
$10k\Omega$	3
$100k\Omega$	1
$100k\Omega$	1
IN4007	2

Table 2. Components Used

2.3.2. Sawtooth to Square Wave

The following circuit was designed to convert a sawtooth wave into a square wave. (Here, V_{ref} is $\frac{V_{cc}}{2}$) The comparator circuit compares the incoming sawtooth waveform to a preset reference voltage (V_{ref}). As the sawtooth voltage transitions between ground (GND) and the

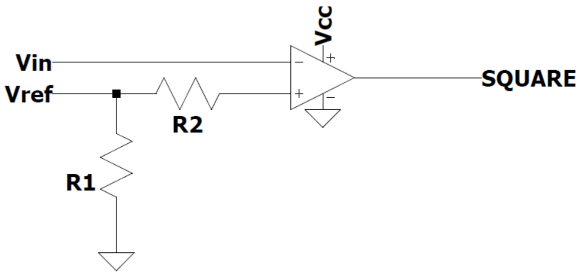


Figure 2. The Comparator

supply voltage (v_{cc}), the comparator's output switches accordingly. During the rising edge of the sawtooth where the voltage exceeds the reference, the comparator output transitions to a high state. Conversely, when the falling edge of the sawtooth falls below the reference, the comparator output transitions to a low state. This results in a square wave output, with a 50% duty cycle. However, real-world considerations like input impedance can influence V_{ref} through loading effects. During the high state of the sawtooth waveform, current may flow from the reference voltage source to the comparator input, potentially causing a slight decrease in V_{ref}. This, in turn, leads to a duty cycle exceeding 50% in the comparator's output square wave.

2.3.3. Square to Sine Wave

An RC phase shift oscillator is used in this. It utilizes a network of resistors and capacitors to create a feedback loop. By carefully selecting component values, the circuit introduces a specific phase shift between the input and output signals, eventually producing a continuous oscillation. While not a perfect sine wave, the output wave resembles a sine wave, which is approximate enough for human auditory precision.

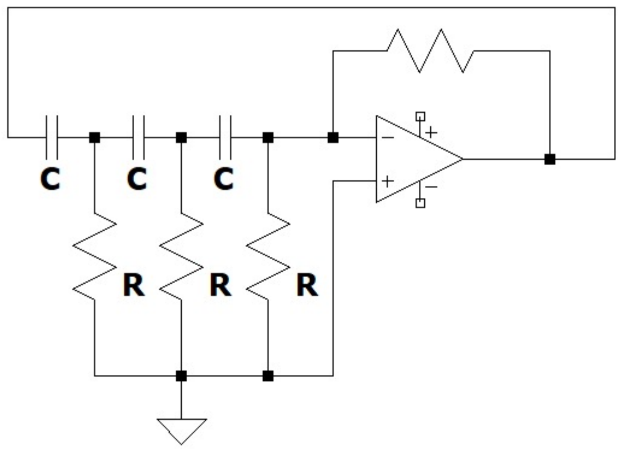


Figure 3. RC Phase Shift Oscillator

We connect a triangle / square wave as input instead of the feedback, for our purpose, and it generates an 'approximately sine' wave.

2.4. The VCO

"A voltage-controlled oscillator is an electronic circuit that generates a signal at a frequency that can be controlled by applying a voltage." For this project, we built a basic VCO, that generates triangle and square waveforms. The following circuit is a modified version of an existing circuit.

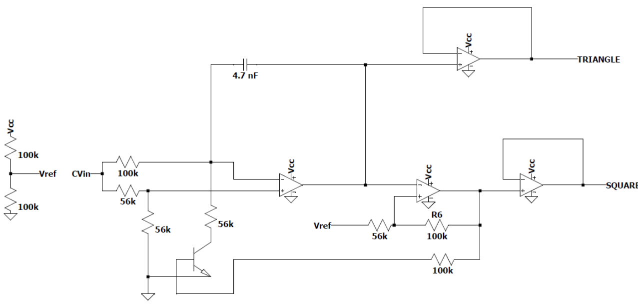


Figure 4. VCO Design

The circuit has the following stages:

- Integrator Circuit
- Schmitt Trigger
- Reset Circuitry (A single Transistor)

2.4.1. The Integrator

The first part of the VCO is the integrator, whose output voltage V_{out} is related to V_{in}, by the following relation

$$V_{out} = \alpha \int_0^t V_{in}(t)dt$$

Here V_{in} is a DC input. Therefore

$$V_{out} = \alpha \int_0^t V_{in}dt = \alpha \left[V_{in} \cdot t\right]_0^t = kt$$

where k is some constant dependant on the input voltage. If left unregulated, the output would linearly increase, and hit V_{cc}

2.4.2. The Reset Circuit

The reset circuit has the following characteristics.

- If the base input is high then the transistor will be on.
- If the base input is low (0V) then the transistor will be off.

2.4.3. The Schmitt Trigger

The Schmitt trigger circuit derives its name from its ability to maintain its output state (high or low) until the input voltage undergoes a specific change, triggering a switch in the output. Unlike a standard comparator with a single threshold, the Schmitt trigger employs a non-inverting configuration characterized by hysteresis.

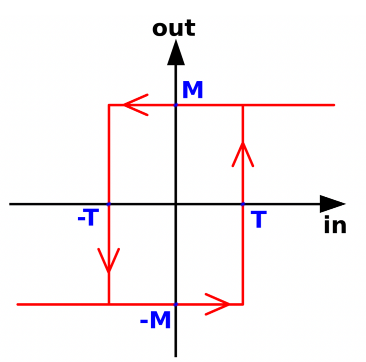


Figure 5. Schmitt Trigger Transfer Function

2.4.4. Working of the Circuit

Initiated by the transistor being on, the integrator's output steadily climbs. Upon reaching the upper threshold of the Schmitt trigger, a rapid change occurs. The Schmitt trigger flips, forcing its output to 0V. This transition turns the transistor off, causing the integrator's voltage to decline. As the integrator's output dips below the lower threshold of the Schmitt trigger, another abrupt shift takes place. The Schmitt trigger switches back to 5V, consequently turning the transistor back on, restarting the cycle. These steos are listed below:

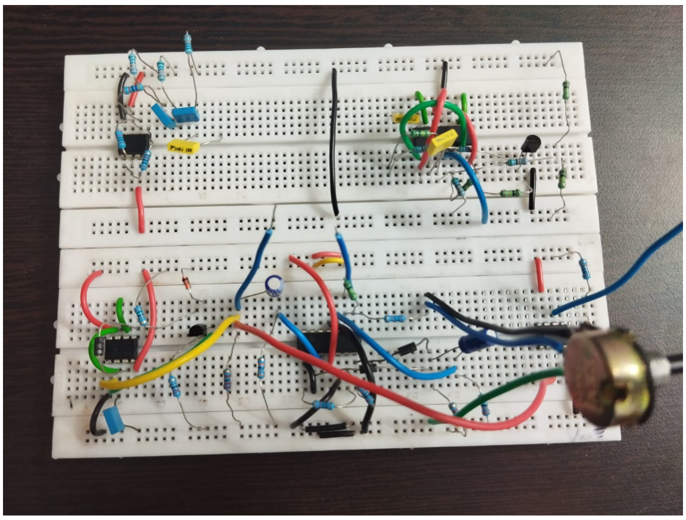
1. The transistor is on and so the integrator's output rises.
2. The integrator's output eventually crosses the Schmitt trigger's upper threshold.
3. The Schmitt trigger's output now switches to 0V.
4. The transistor is now off and so the integrator's output begins to fall.
5. The integrator's output eventually falls below the Schmitt trigger's lower threshold.
6. The Schmitt trigger's output now switches to 5V.
7. The transistor now turns on (so go back to step 1).

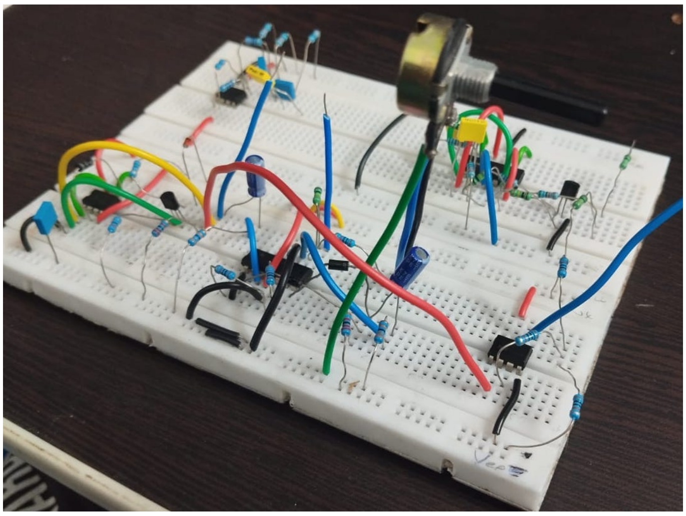
Component	Quantity
LM324	1
BC548	1
$100k\Omega$	5
$56k\Omega$	4
$100nF$	2
$4.7nF$	1

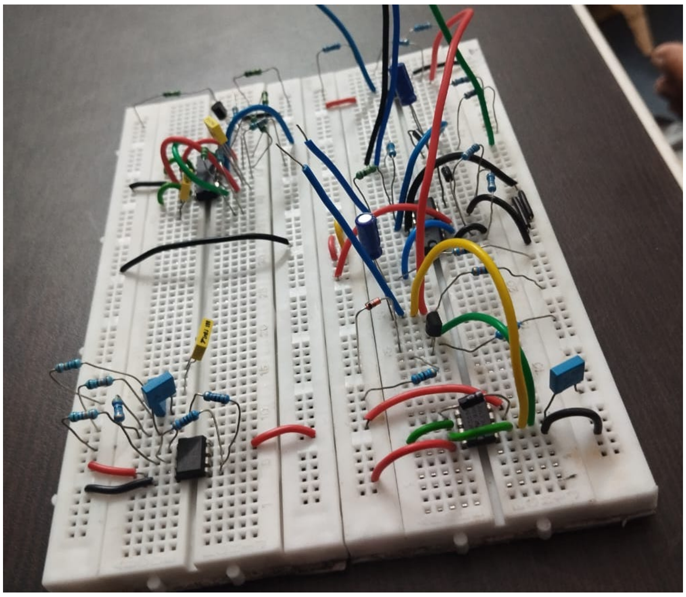
Table 3. The VCO

3. Our Work

The circuit built by us is shown below.







4. The Observations

4.1. Testing the Wave Shaping circuitry

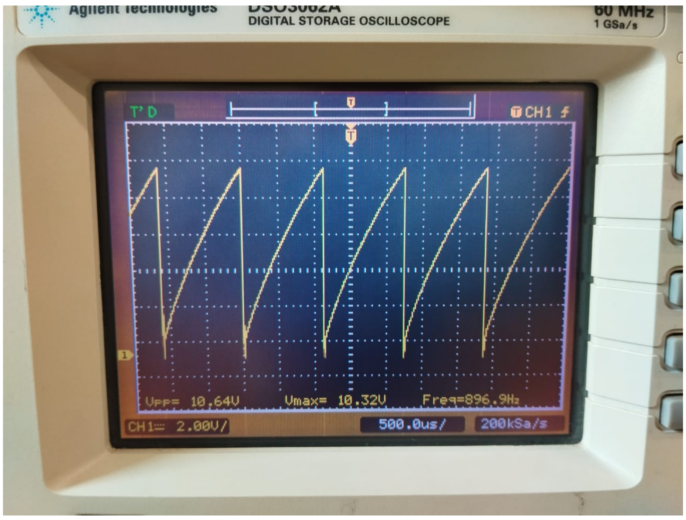


Figure 6. The Generated Sawtooth Wave

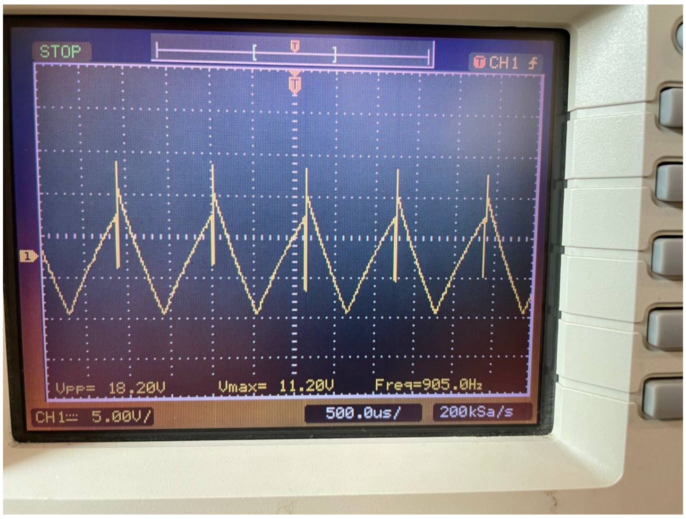


Figure 7. Triangle wave generated from the Saw-Tooth wave

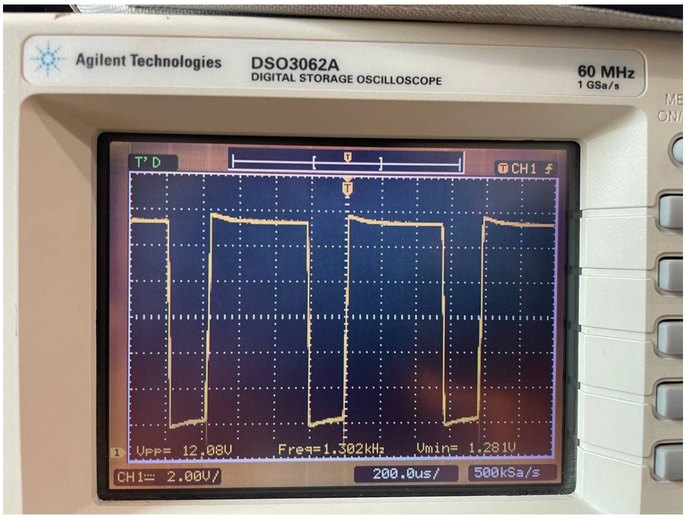


Figure 8. Square wave generated from the Saw-Tooth wave

By increasing the maximum voltage, we get the following output

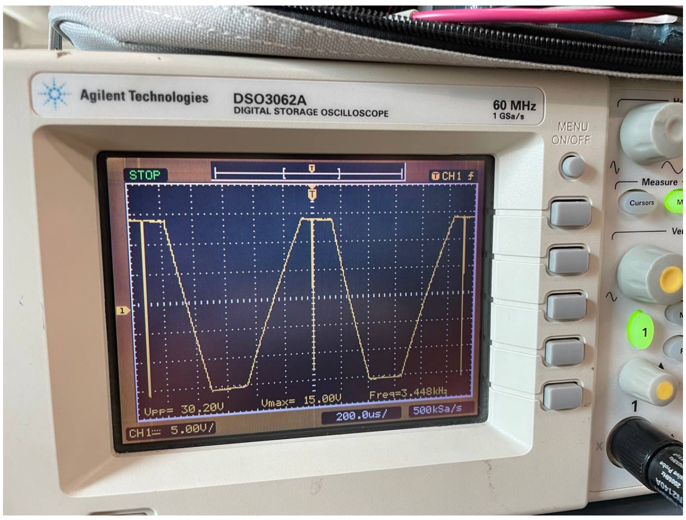


Figure 9. Triangle wave generated from the Saw-Tooth wave, distorted

4.2. Testing the VCO

The following pictures show the output generated by the VCO, at various control voltages.

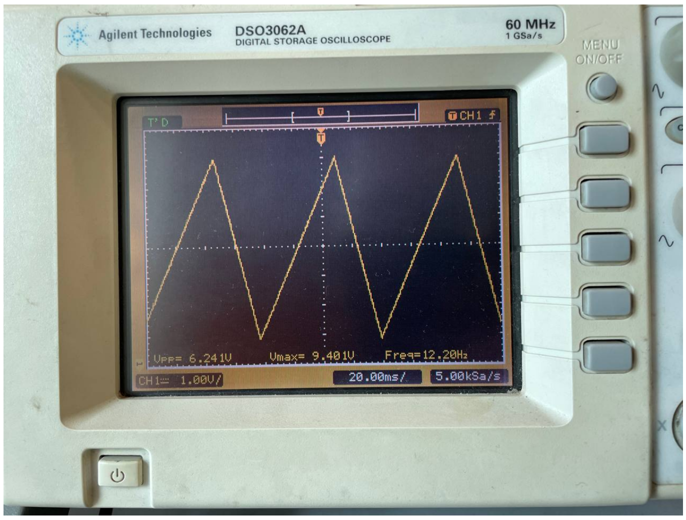


Figure 10. The Frequency of the waveform at $V_{in} = 0.1V \approx 12Hz$

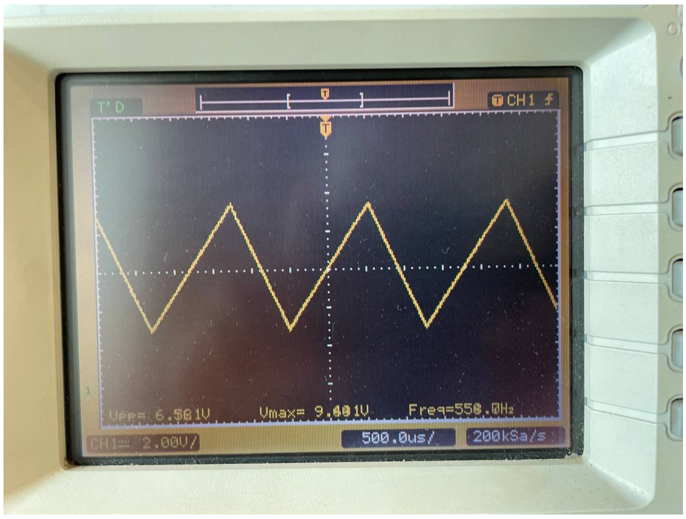


Figure 11. The Frequency of the waveform at $V_{in} = 0.7.9V \approx 560Hz$

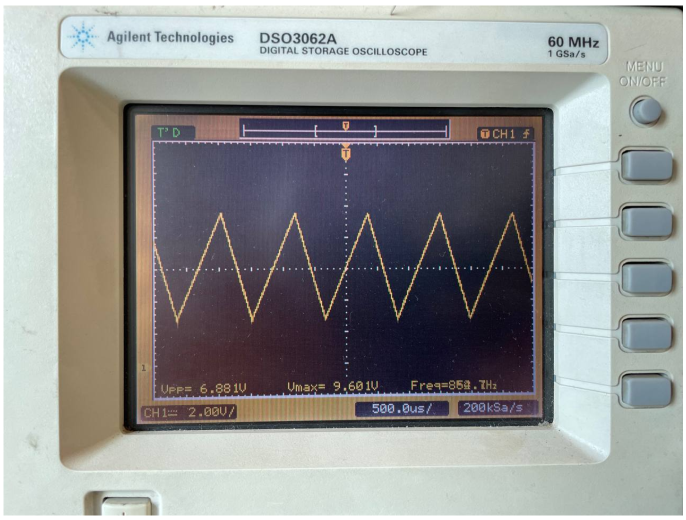


Figure 12. The Frequency of the waveform at $V_{in} = 12.6V \approx 860Hz$

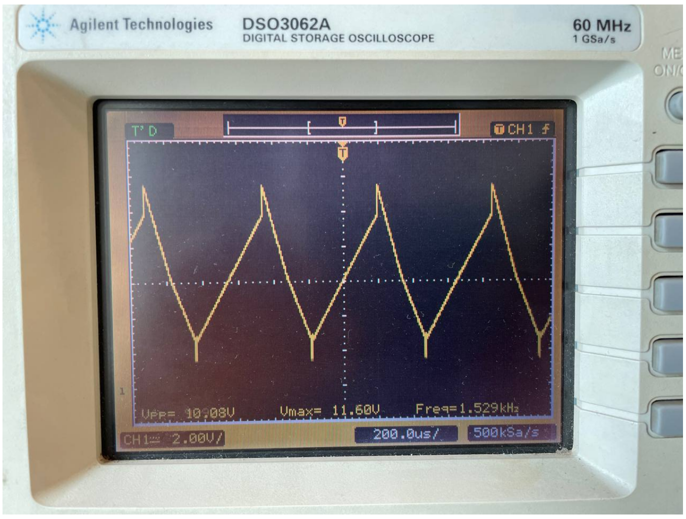


Figure 13. The Frequency of the waveform at $V_{in} = 24.2V \approx 1.6kHz$

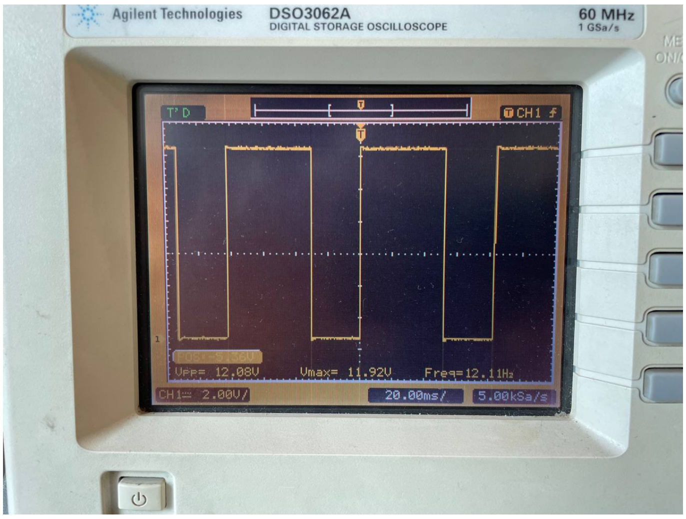


Figure 14. The Frequency of the square waveform at $V_{in} = 0.1V \approx 12Hz$

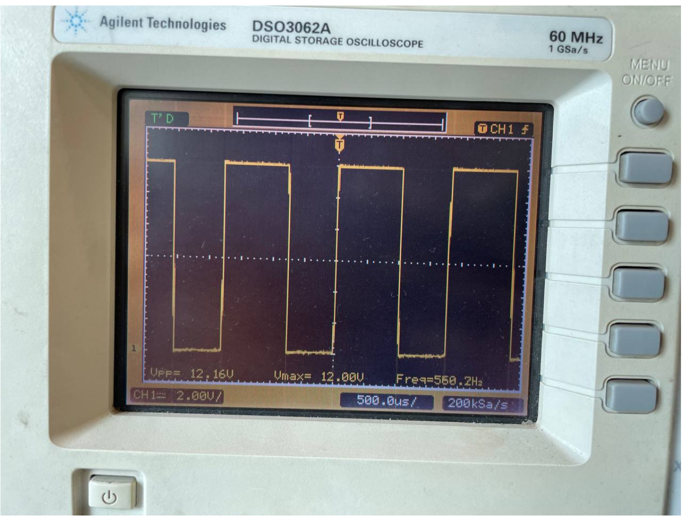


Figure 15. The Frequency of the Square waveform at $V_{in} = 0.7.9V \approx 560Hz$

Figure 16. The Frequency of the Square waveform at $V_{in} = 12.6V \approx 860Hz$

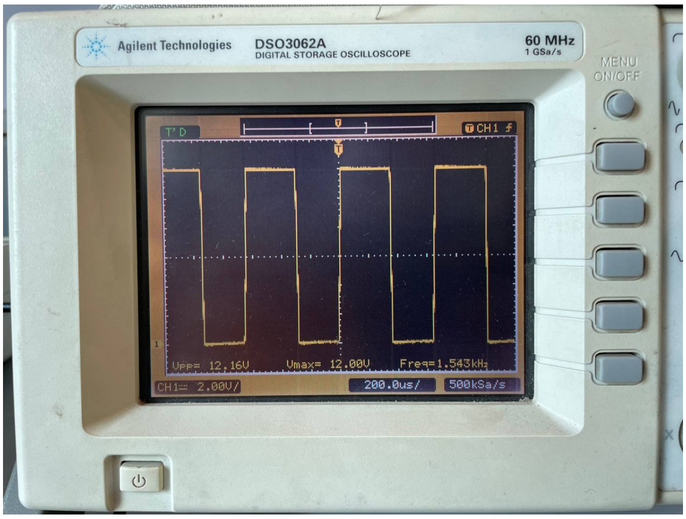


Figure 17. The Frequency of the Square waveform at $V_{in} = 24.2V \approx 1.6kHz$

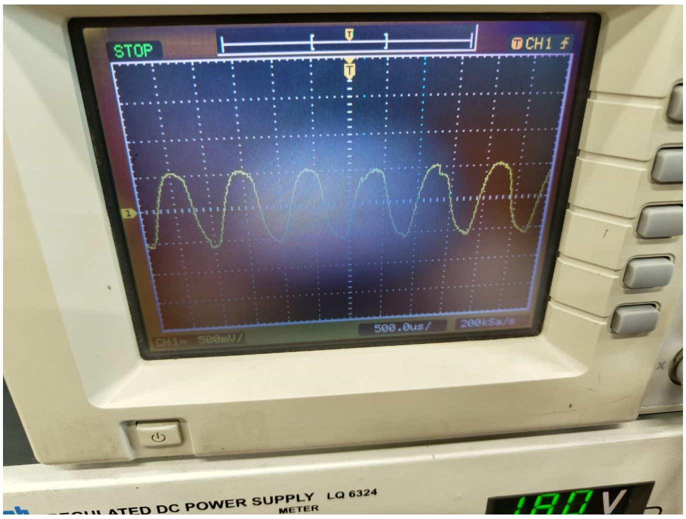


Figure 18. Sine Wave from the Triangle wave using RC Phase Shift Oscillators

Frequency scaling

Approximatey Linear scaling is found between the input voltage and the oscillation frequency.

5. Some Errors

1. The output of the actual circuit from 7 vs the theoretic output varies because of small delays in the circuit, which cause imperfect superposition of the 2 waves.
2. The duty cycle of the square wave generated by the comparision of the sawtooth with a reference voltage from 8 is greater than 50%.

6. Conclusion

This lab report documented the successful design, construction, and testing of circuits for wave shaping and voltage-controlled oscillation (VCO). We explored the conversion of a sawtooth waveform into triangle and square waves, demonstrating the capabilities of basic circuit techniques like comparators and operational amplifiers. Additionally, we built a VCO capable of generating both triangle and square waves, showcasing the control of frequency and waveform through voltage manipulation.

The experimental results confirmed the theoretical principles behind each circuit, with successfully generated triangle, square, and VCO-produced waveforms.

Overall, this project provided a practical understanding of fundamental wave shaping principles and VCO operation. The acquired knowledge can be applied to various applications in electronic music production, sound effect design, and other fields that utilize controlled and manipulated waveforms. Future endeavors could involve exploring more advanced wave shaping methods or delving deeper into VCO design to achieve higher fidelity outputs.