



EN 2091: Laboratory Practice and Projects

SLAP Innovators

Analog Function Generator

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1 Introduction and Functionality

Function generators are capable of generating analog waveforms and are used in a variety of applications. In this project, we implement some basic functionalities of a function generator using analog components such as transistors, resistors, potentiometers, op-amps, and capacitors. We were able to generate the analog waveforms square, triangular, sawtooth, and sine waves for a wide range of frequencies with adjustable amplitudes. Frequency and amplitude variation were achieved by adjusting the capacitor and resistor values in the corresponding sections of the circuit. A thorough analysis was needed for component selection to reconcile factors such as market availability, product requirements, and affordability. In the following sections, we discuss the construction of the circuit, schematic, PCB design, enclosure design, simulation and hardware testing results, and component selection.

2 Requirements

- **Waves:** square, triangle, sawtooth, sine
- **Frequency variation:** 20Hz– 20kHz
- **Variable duty cycle for square wave:** 1%–99%
- **Ability to drive a minimum load of 50Ω**

3 System Model

3.1 Block Diagram

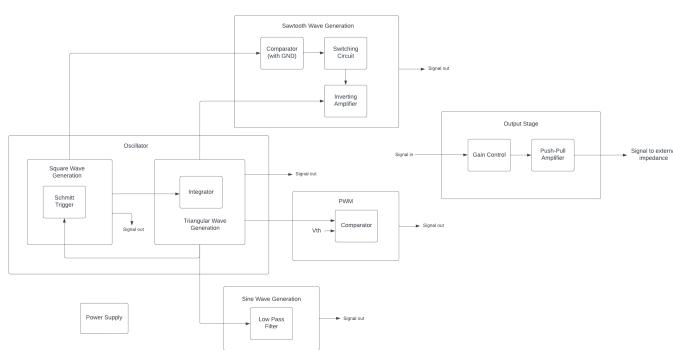


Figure 1: Block diagram

3.2 Waveform Generation

3.2.1 Square and Triangle Waves

Using the hysteresis property of a Schmitt trigger, we generate square and triangle waves. Assume that the Schmitt trigger initially is at VDD. This creates a negative ramp across the integrator, which is fed back to the Schmitt trigger. Once the ramp passes the lower threshold (LTP) of the trigger, the output

is inverted to VSS, creating a positive ramp across the integrator. Once this voltage reaches the upper threshold (UTP) of the trigger, the voltage inverts once again to VDD, creating a cycle. Therefore, the square/triangle generator doubles as the oscillator for our function generator.[1]

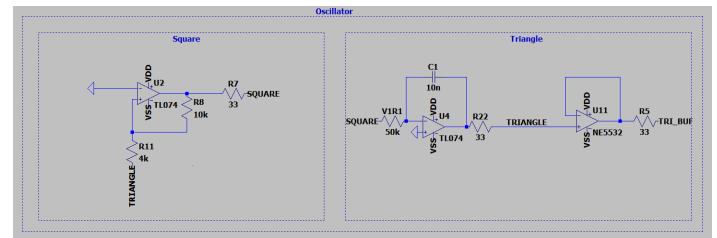


Figure 2: Oscillator

$$V_+ = \frac{R_8}{R_8 + R_{11}} V_{TRIANGLE} + \frac{R_{11}}{R_8 + R_{11}} V_{sat}$$

$$V_+ = 0$$

$$V_{O+} = -\frac{R_{11}}{R_8} V_{sat}$$

$$V_{O-} = \frac{R_{11}}{R_8} V_{sat}$$

$$V_{PP} = 2 \frac{R_{11}}{R_8} V_{sat}$$

$$V_{PP} = -\frac{1}{(V1R1)C_1} \int_0^{T/2} V_{in}(t) dt$$

1

$$f = \frac{R_8}{4(V1R1)R_{11}C_1}$$

Amplitude

$$V_{PP} = 2 \frac{R_{11}}{R_8} V_{sat}$$

Frequency

$$f = \frac{R_8}{4(V1R1)R_{11}C_1}$$

3.2.2 Sine Wave

We obtained the sine wave by filtering the triangle wave. For this, we implemented a 4th-order Butterworth low-pass filter by cascading two second-order filters.

¹VXRY denotes variable resistors. Resistors of equal X are part of the same ganged-potentiometer. Y denotes independent resistors within the same ganged-potentiometer.

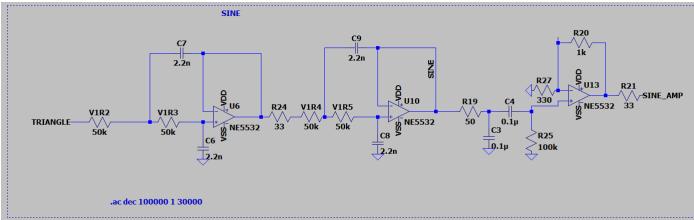


Figure 3: Sine wave generation

Cut-off Frequency

$$f = \frac{1}{2\pi RC}$$

[2]

Design

We can obtain the following relationship between

C₁ and *C*

$$f = \frac{R_8}{4(V_1 R_1) R_{11} C_1} = \frac{1}{2\pi R C}$$

By using a 5-ganged potentiometer, we can control *R* and *R₁₁* together. Note that there are 4 resistors of the same value, *R*, in the filter. Now we can obtain a relationship between *C₁* and *C*. Once again, note that there are 4 capacitors of the same value, *C*, in the filter.

This ensures that the cut-off of the filter follows the frequency of the generator, ensuring a sine of almost constant THD across all frequencies.

Through these methods, we obtained a sine wave of approximately 0.765% THD at 300Hz, which was the highest THD value we obtained over multiple tested frequencies.

We used the following formula to calculate THD;

$$\text{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}}{V_1}$$

where:

- *V₁* is the RMS value of the fundamental harmonic.
- *V₂, V₃, ..., V_n* are the RMS values of the harmonic components.

3.2.3 PWM Wave

The PWM wave was generated by comparing the triangular wave with a threshold using an op-amp comparator. First, we give the triangular wave generated by the oscillator to an inverting amplifier

to adjust its amplitude for the comparison against a voltage varying from -12V to +12V i.e. VTH. U1 acts as the comparator. When the value of the triangular wave is greater than VTH the comparator saturates at VDD; otherwise, it saturates at VSS since the value of the triangular wave is less than VTH. By varying VTH using a potentiometer, we vary the duty of the resulting square wave to an arbitrary percentage value to achieve pulse width modulation.

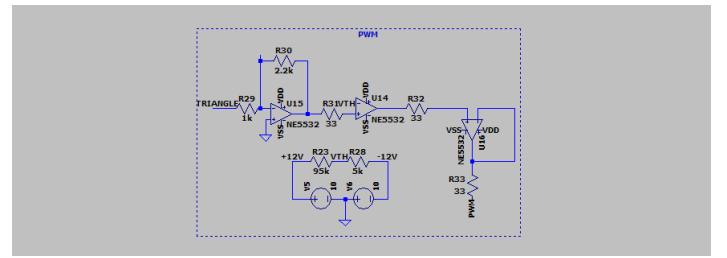


Figure 4: PWM

3.2.4 Sawtooth Wave

We generate the sawtooth wave using the square and triangle waves from the oscillator. It is important that both waves have the same frequency and phase. The square wave controls the MOSFETs, turning them on and off. When the MOSFETs are on, they ground the non-inverting input of the op-amp, causing the op-amp to act as an inverting amplifier with unity gain. This inverts the input triangle wave during these half cycles. When the MOSFETs are off, the op-amp passes the triangle wave without any change.

The result is a waveform where every alternate ramp of the triangle wave is inverted. This produces a continuous sawtooth waveform at the output.

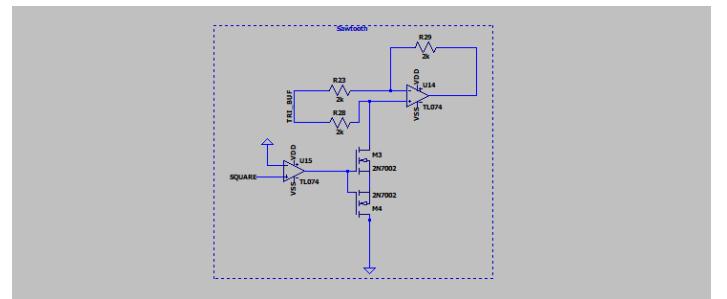


Figure 5: Sawtooth wave generation

3.3 Output Stage

The output stage consists of a voltage buffer followed by an inverting amplifier that adjusts the amplitude of the waveform between 0V and 10V. The gain of the inverting amplifier is given by,

$$A_v = \frac{R26 + V2R3}{Rin}$$

Afterward, it's followed by a push-pull amplifier that provides the necessary current to drive the load without waveform distortion or excessive power loss. This ensures the waveforms appear across a low impedance such as 50Ω without distortion. Here we use a complementary pair of transistors: an NPN transistor (Q2) and a PNP transistor (Q3) to provide symmetrical output drive capability. The two diodes D1 and D2, establish a small voltage drop of approximately 0.7 V each to bias the bases of the transistors, ensuring that both Q2 and Q3 turn on at the appropriate points in the input waveform, reducing crossover distortion. The resistors R1 and R2 help set the bias conditions for the diodes and transistors by providing a current path between the supply voltage (VDD) and ground (VSS).

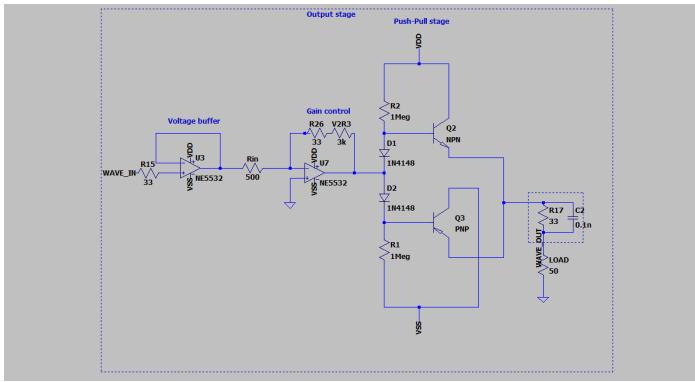


Figure 6: Output stage

3.4 Design Parameters

Parameter	Value
Frequency Range	20 Hz to 20 KHz
Output Voltage (Peak-Peak)	0 V to 10 V
THD (Sine)	0.765% (300 Hz)
Duty (PWM)	1% to 99% (10kHz)
Symmetry (Square, Triangle)	$\pm 1\%$
Minimum Output Impedance	550Ω
Power Supply Voltage	$\pm 12\text{V}$
Power Consumption	2.5 W (Max)

Table 2: Design Parameters for a Function Generator

3.5 Frequency Select

For selecting various frequency ranges, we must switch the capacitors in both the oscillator and the filter. For this, we use multi pole, multi throw switches. The following table denotes the capacitance used for each frequency range as well as the potentiometer resistance values required to obtain end-frequencies of the relevant range.

Frequency (Hz)	Capacitance (μF)	Resistance ($k\Omega$)
8	1	50
130	1	3.3
130	0.1	50
1.3k	0.1	5
1.3k	0.01	50
20k	0.01	2.5

Table 4: Capacitances and Resistances for frequency Select

4 Schematic

Developing the schematic and all the simulations are done using LTspice

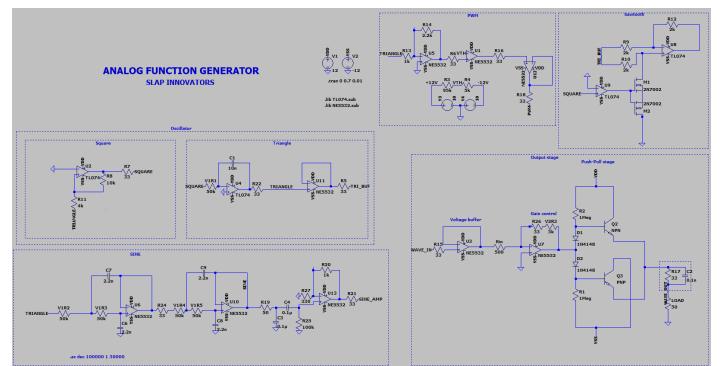


Figure 7: Schematic

Note that the 33Ω resistors are for the series termination of opamps. This aims to reduce signal reflections, preserve signal integrity, and minimize the effect of high frequency noise.

5 PCB Design

The circuit was designed onto a 10x10cm PCB using Altium Designer. The 2-layer design consists of 3mm traces and a ground plane for optimal electrical performance and heat dissipation. Additionally, layer crossings by signal-carrying traces are avoided to ensure minimal noise effects.

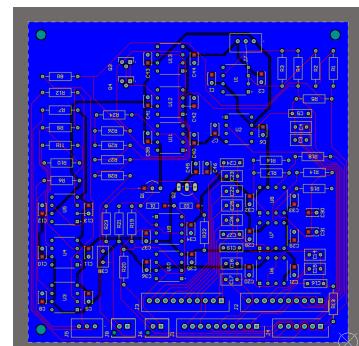


Figure 8: PCB Layout

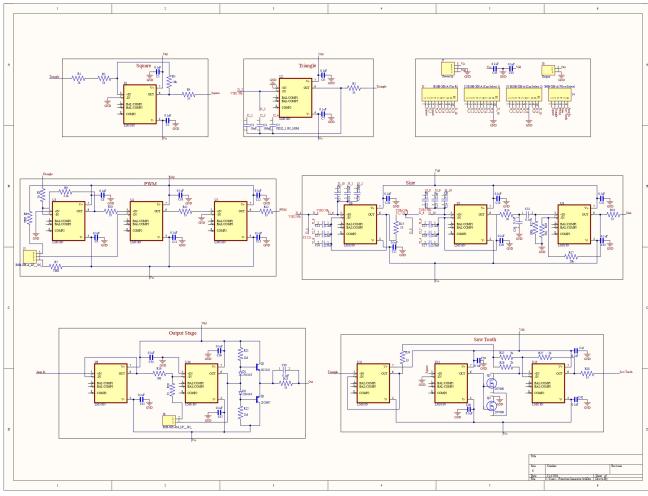


Figure 9: PCB schematic

6 Enclosure Design

Enclosure was designed using Solidworks. It facilitates banana connectors for electrical connections, a power on/off switch, frequency and amplitude adjusting knobs, a waveform selection knob and frequency range (respective capacitances) selection knobs.

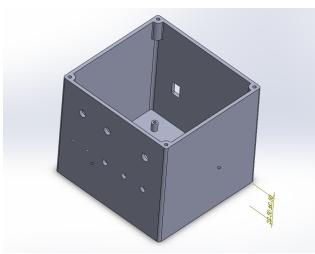


Figure 10

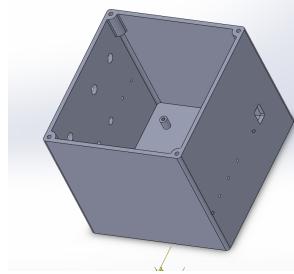


Figure 11

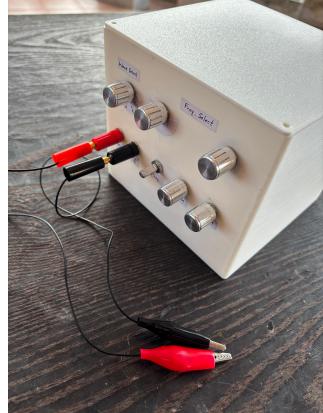


Figure 12

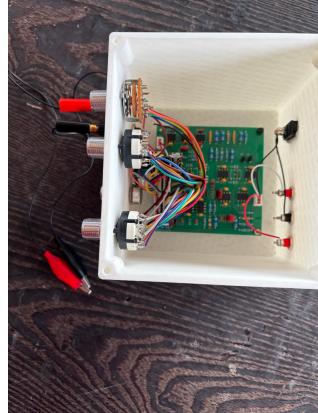


Figure 13

8 Testing

When designing analog circuits, it is crucial to verify proper functionality of the circuit physically, as practical results and simulated results could vary dramatically. For this, we built the circuit on a breadboard and verified its functionality using an oscilloscope.

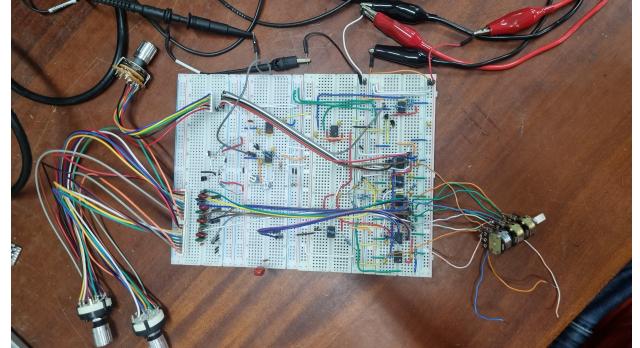
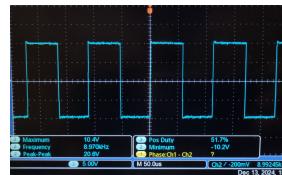
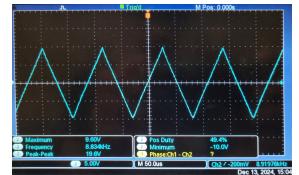


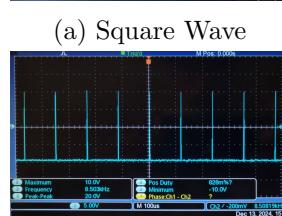
Figure 14: Breadboard Implementation



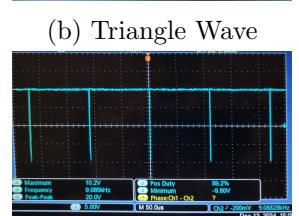
(a) Square Wave



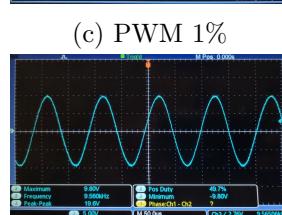
(b) Triangle Wave



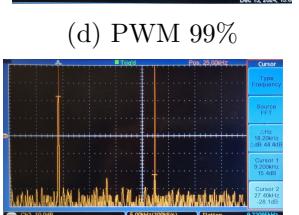
(c) PWM 1%



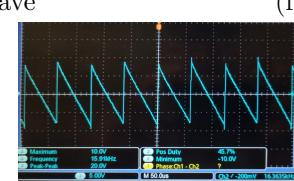
(d) PWM 99%



(e) Sine Wave



(f) Sine FFT



(g) Sawtooth Wave

9 Component Selection

9.1 Op-Amp selection

We have used the op-amp LM318N in our circuit since its characteristics align with the requirements of the function generator. It has a slew rate of $70 \text{ V}/\mu\text{s}$ that allows us to generate square, sawtooth waveforms without significant distortions at high frequencies. The

7 Simulation

As the initial stage of designing our product, we used LTspice to simulate and verify that our circuits were able to accurately generate the required functions while meeting the performance criteria.

Gain Bandwidth Product of the op-amp is 15MHz which also allows us to amplify the waveforms without distortion. It also has a very low Total Harmonic Distortion of 0.008% which makes it preferable when it comes to the precision of the generated waveforms. [3]

9.2 Transistor selection

For the sawtooth generation stage of our circuit, we chose the transistor 2N7000 which is an N-channel, enhancement-mode MOSFET. Here we focused on the characteristics that affect the switching functionality in the sawtooth wave-generating process. The transistor has low input and output capacitances of 60pF and 25pF respectively. The turn-on delay time and turn-off delay time are both 10ns. These characteristics make it suitable to generate the sawtooth wave with significant accuracy [4].

For the push-pull stage of our circuit, we chose the transistors 2N2222 (NPN) and 2N2907 (PNP). The characteristics of the two transistors agree with each other to act as a complementary pair which is crucial for the proper functionality of the push-pull stage. [5] [6]. //

Parameter	2N2222	2N2907
Peak Collector Current	800mA	-800mA
Total Power Dissipation	400mW	500mW
Collector-Emitter Saturation Voltage	400mV	-400mV
DC Current Gain	≈ 100	≈ 100
Transition Frequency	250MHz	200MHz

Table 6: Comparison of the characteristics of 2N2222 and 2N2907

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 - Circuit Design, Implementation, Testing and Debugging
- Perera A.L.C.K. - 220459K
 - Output Stage Design, Enclosure Design, Documentation

12 Conclusion and Future Works

Even though the circuit is implemented using a 2-layer PCB design, noise and distortions can be further reduced by a 6-layer PCB design with separate layers for GND, Vss and Vdd. However, there's a tradeoff with a significant increase in the cost of production.

The sawtooth waveform tends to overshoot at peaks. This is due to the low output impedance of the high slew rate opamp not being matched properly at the load. We attempted to fix this by adding 33Ω termination resistors to unloaded opamp outputs [7]. However, this did not fix it. In the future, we plan to add a small capacitor in the negative feedback loop to feed high frequency ringing to back into the input.

We were unable to find the 5 pole 4 throw switches required for the capacitor selection circuit at a reasonable price. Instead, we use two 3 pole 4 throw switches which need to be adjusted together. We intend to use 5 pole 4 throw switches for bulk production since they're available at far lower rates in bulk.

10 Power Supply

The circuit should be powered up with a 12V dual power supply capable of providing a maximum power of 2.5W. The design excludes this power supply and the device must be powered externally.

11 Contribution Report

- Attanayake A.Y. - 220051D
 - PCB Design, Soldering, Debugging
- De Zoysa A.S.I. - 220106D
 - Switching Circuit Design, Enclosure Design, Soldering

13 References

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