Major design Project

Linear Voltage-controlled Function Generator (VCFG)

November 5th 2024

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Abstract

This project involved designing a Voltage-Controlled Function Generator (VCFG) to generate square and triangular waveforms over two frequency ranges: 100 Hz–3800 Hz and 20 Hz–760 Hz, with a control input of 0.1–5 V and up to 8 V peak-to-peak output amplitude. The design used LM741CN and LM318N operational amplifiers, a 2N3904 BJT, diode and zener diodes, potentiometer and passive components like resistors and capacitors. The project milestones included creating a stable fixed-frequency generator, setting voltage limits, developing a DC to ±DC converter, and achieving frequency and gain control. Design stages were simulated using Multisim and then tested in the lab, with occasional adjustments to align experimental and theoretical results. The final circuit was successful in producing a proper square waveform, but failed to present a correct triangular waveform and the frequency of the generator was not linearly proportional to DC input voltage without any side effects.

Objectives

The objective of this project is to design and implement a Voltage Controlled Function generator (VCFG) to output symmetrical square and triangular waves over two assigned ranges of frequency while also obtaining the following specifications:

- A Frequency Range:
    - Range 1: 100Hz to 3800 Hz
    - Range 2: 20Hz to 760Hz
- Input d.c. Voltage Control Range, Vc
    - 0.1V to 5V.
- Output Amplitude Control Range for two output waves
    - 0 to 8 Vp-p (its amplitude is in the range 0 to 4 V)

The components that were used throughout the project consist of:

- LM741CN op-amp
- LM318N op-amp
- Zener diode
- Rectifier diode
- BJT 2N3904
- Resistors
- Capacitor
- Potentiometer

Introduction

In the field of electronics, a versatile waveform generator that can adapt its output frequency based on an external control signal, such as voltage, can be of great use. These devices are often referred to as Voltage-Controlled Oscillators (VCOs), which are crucial in applications like electronic music synthesis, automatic control systems, and data encoding. The primary objective of a VCO is to vary the output frequency linearly with respect to the input voltage, allowing for accurate and controlled frequency adjustments.

This project involves the design and development of a Linear Voltage-Controlled Function Generator (VCFG), specifically designed to generate triangular and square waveforms. To successfully achieve this goal, many theoretical concepts need to be well understood , which is why this project was carried on throughout 5 weeks in order to fully understand how voltage controlled function generators can be created. Each week is designed for a certain stage of the project and finally it all comes together when combined into one circuit. Throughout each step, multiple characteristics were implemented and each design was simulated on Multisim then implemented and tested in the laboratory.

The project was divided into 4 stages, also named milestones;

1. Design a Fixed frequency Waveform Generator, with a frequency of 3800 Hz
2. Design the Fixed Frequency waveform generator but with precise L+ /L- voltage output value, and designing a DC to +/- DC converter
3. Implement the Linear Voltage Controlled waveform generator incorporating the DC to +/- DC converter, the Integrator and the Inverting Bistable
4. Incorporating "Frequency Range control" and "Gain control" to the Linear Voltage Controlled waveform generator to cover all required specifications.

Each stage was analyzed separately to make sure each part works well and gives us the expected results. Then slowly they are assembled together to finally produce the correct outputs. All results were compared with the theoretical calculations and simulation results. Any discrepancies were discussed and analyzed.

Theory

To produce a triangular waveform and a rectangular waveform, a bistable multivibrator and an integrator have to be implemented in the VCFG. The integrator circuit utilizes an op-amp with a capacitor in the feedback loop which allows the circuit to act in its integrating properties. The mathematical relationship between the input voltage signal, the output voltage voltage signal, and its corresponding components can be described by the following equation:

$$v_o(t) = -\frac{1}{RC}\int_0^t v_i(t)dt + V_c$$

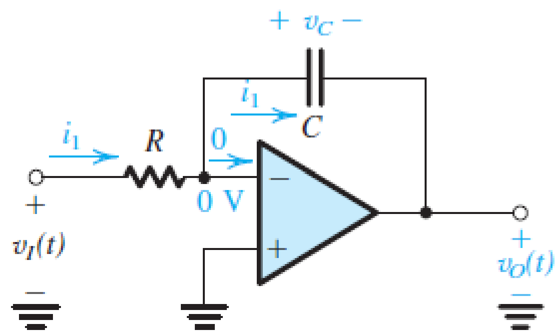


Figure 1: Inverting Integrator Circuit

The output waveform in the integrator being used in this design project is a triangular wave. In our design, the integrator is fed with a square wave. When the input is positive, the capacitor charges through resistor R. As a result, the output waveform of the integration circuit becomes a triangular wave with positive slope. When the square wave switches to negative voltage, the capacitor discharges which then results in the negative slope of the triangular wave.

Given that an inverting bistable has a positive feedback loop, the output voltage would saturate to either +Vcc or -Vcc. To ensure that the output voltage doesn't change until the input voltage reaches specific values, a resistor on the positive terminal and the feedback loop can be utilized. Since the integrator's output serves as the bistable's input in this project, those specific values correspond to the integrator's threshold voltages. As a result, the threshold voltages of the integrator, the bistable's saturation voltages, and its two resistor values have the following relationship:

$$V_{TH} = \frac{R_1}{R_1+R_2} \cdot L^+$$

$$V_{TL} = \frac{R_1}{R_1+R_2} \cdot L^+$$

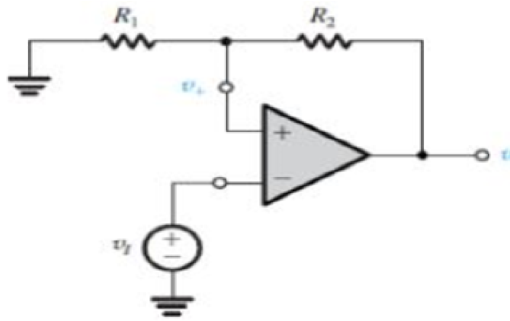


Figure 2: Inverting Bi-stable circuit

When both circuits are combined, with the integrator connected to the bistable, with their output terminals connected into their input terminals, we are able to create a fixed frequency waveform generator. The fundamental frequency of a fixed frequency waveform generator can be determined by the equation:

$$f_o = \frac{L^+}{2\left(V_{TH} - V_{TL}\right)RC}$$

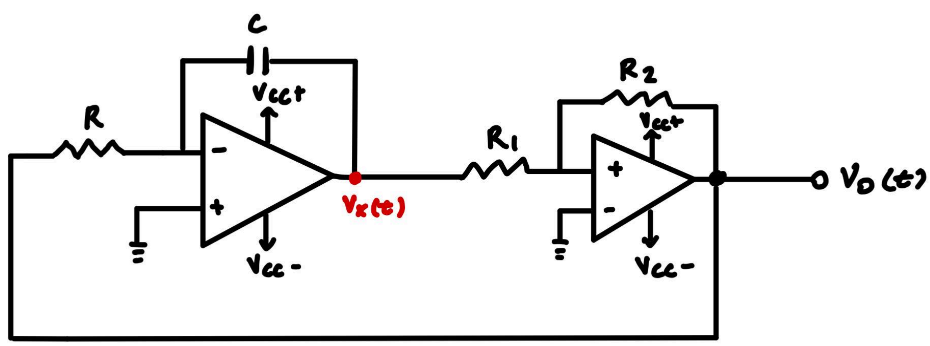


Figure 3: Fixed Frequency Waveform Generator

The DC to +/-DC Converter uses a resistor in the negative terminal, positive terminal, and feedback loop in order to produce the input voltage at the output. It is also able to control the polarity of the output which depends on the position of a switch in the positive terminal. The DC to +/- DC Converter utilizes a digital switch. The digital switch will be constructed using a 2N3904 Bipolar Junction Transistor. There are two modes of operation for the BJT; saturation and cutoff. During Saturation, the transistor acts as a short circuit. A diode and extra resistors are added to the digital switch to reduce the effects of potential voltage spikes from the input waveform. Another resistor is added near the positive terminal of the op amp to ensure that the terminal is not damaged in case the BJT malfunctions.

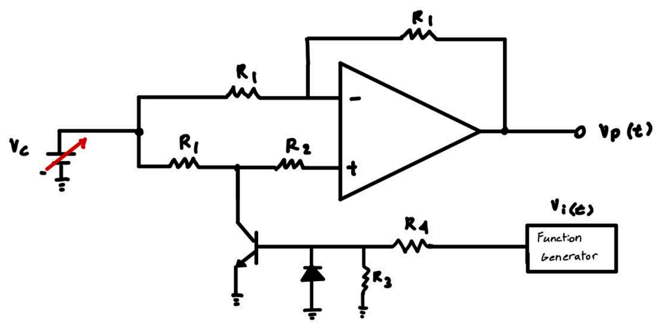


Figure 4: DC to -/+ DC Converter Circuit

When combing the DC to +/- DC converter with the fixed frequency waveform generator, we are able to control the value of the fundamental frequency f_o from its maximum value to a lower frequency, by increasing or decreasing the DC input voltage V_C. This in turn makes the circuit a linear voltage controlled waveform generator. Zener diodes and regular diodes are used at the output terminal of the inverting bistable to reduce the amplitude of the output signal. This is needed since the BJT of the digital switch has a maximum voltage at the emitter, which the bistable exceeds if no diodes are used.

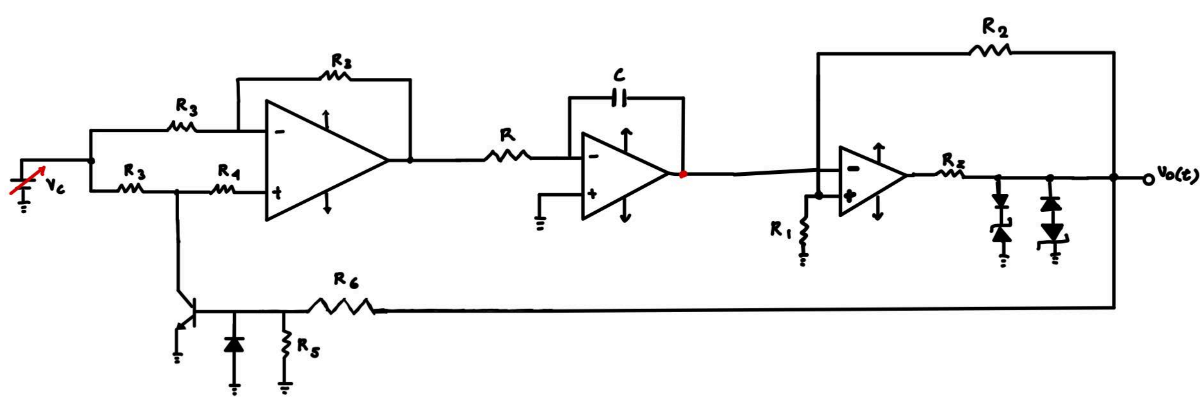


Figure 5: Linear Voltage Controlled Waveform Generator

Design analysis

Milestone 1:

For the first milestone, we were tasked to design a Fixed frequency Waveform Generator, with a frequency of 3800 Hz. Therefore to produce a triangular waveform and a rectangular waveform, a non-inverting bistable multivibrator and an inverting integrator have to be designed and put to the test.

VTH and VTL were set values of +4V and -4V respectively and L+ was set to 10.5V while L- was set to -10.5 V. We also know our fx to be 3800 Hz. By plugging our givens into the equation derived earlier:

$$V_{TH} = -\frac{R_1}{R_2} \cdot L^-$$

We can solve to find the values of R1 and R2 seen in **Figure 2** and get R1= 10kΩ and R2=3.3kΩ. Next the derived equation:

$$f_o = \frac{L^+}{2\left(V_{TH} - V_{TL}\right)RC}$$

Was used to calculate the value for R which was found to be R= 20kΩ. The multisim simulation can be seen below, however as will be discussed later on, by using the LM318N instead of the LM741CN for the second stage, we were able to reduce the apparent limitation on the output rectangular waveform.

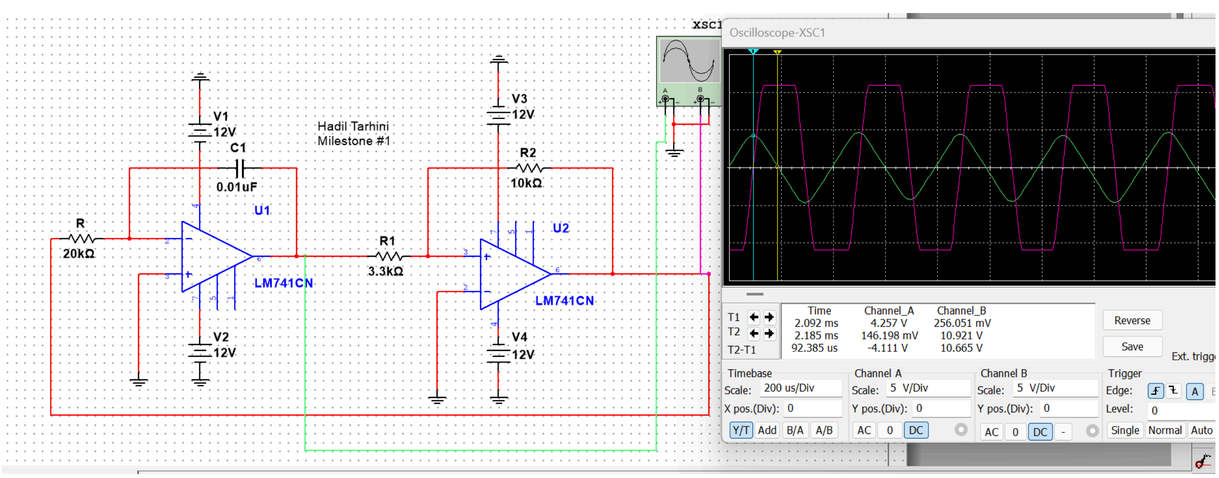


Figure 6: Multisim circuit design using two LM741CN op-amps and the waveforms obtained

As can be seen, the triangular waveform is the signal seen from the output of the inverting integrator, which also serves as the input of the non-inverting Bistable Multivibrator.

Furthermore, the square waveform is the waveform seen from the output of the non-inverting Bistable Multivibrator (also noted as the input of the inverting integrator).

Milestone 2:

The objective of the second milestone was to design and test a fixed frequency waveform generator to produce the same fx value of 3800 Hz but with +6.3V/-6.3V limits set using a limiter circuit design integrated in the bi-stable comparator. Next a DC to +/- DC converter was designed using an external 6.3V peak function generator.

As mentioned in the theory part above, the Zener diodes and regular diodes are used at the output terminal of the inverting bistable to reduce the amplitude of the output signal to 6.3V. In order to get the 6.3V value, the zener diodes were chosen to be 5.6 V and placed in series with the 0.7V diodes to sum up to a value of +/- 6.3 as the Vo. Next the value of Rz as seen in **Figure 5** needed to be calculated and this was done with a simple ohm's law equation while setting Iz to be 10mA (ensuring we do not exceed the 45mA Imax of the IN474A zener diode). Hence the Rz was calculated to be 0.57kΩ and the rest of the circuit as seen in milestone 1 was kept as is.

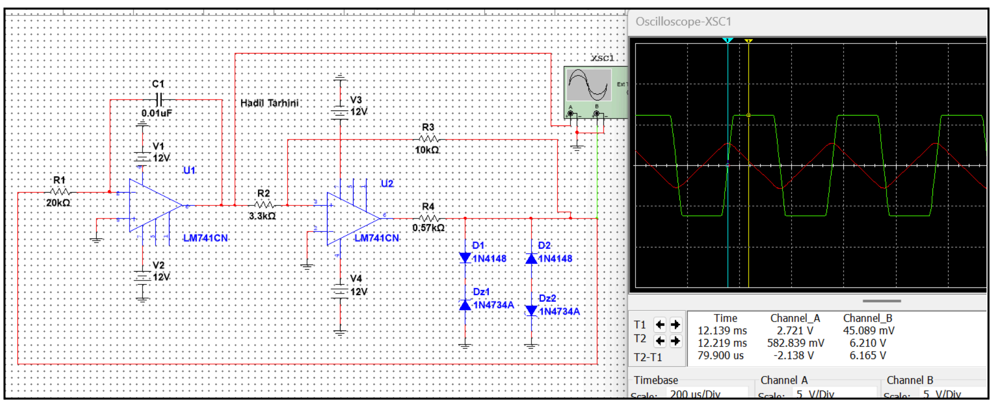


Figure 7: Fixed Frequency Waveform Generator with Limiter

Milestone 3

The third milestone consisted of implementing the Linear Voltage Controlled waveform generator by now incorporating the DC to +/- DC converter, the Integrator and the Inverting Bistable into one circuit. The components seen in the previous milestones were slightly adjusted to obtain the desired fo vs Vc transfer function specifications of Range #1.

In order to achieve an f_o of 760Hz for Range 1, we must adjust the R value of the integrator's input seen in **Figure 5**. This can be done by isolating the following equation for R:

$$f_o = \frac{L^+}{2(V_{TH} - V_{TL})RC}$$

$$R = \frac{L^+}{2(V_{TH} - V_{TL})f_o C}$$

By plugging in the values, we get a resistance value of 9.491kΩ but 10kΩ was chosen as the closest component available in the lab kit.

The DC Converter which would incorporate an automated switch using a Bipolar Junction Transistor was also designed. The BJT was placed in parallel with a diode and a resistor (as well as a resistor placed in series with the two which was added in the last milestone). By having this set up connected to the BJT and the bistable multivibrator, an automated switch was created for the DC converter.

Furthermore, since we've connected a DC to +/- DC converter, it will cause the signal to invert, for that reason, an inverting bistable was used, as opposed to milestone #1, to invert it back. The values of R1 and R2 were therefore adjusted. By applying the following equation:

$$V_{TH} = \frac{R_1}{R_1 + R_2} \cdot L^+$$

And since we know VTH to be 4V and L^+ to be 6.3V, we were able to solve for R1 and R2 and finally chose the resistances to be R1= 5.6kΩ and R2= 10kΩ as seen in the design and simulation below.

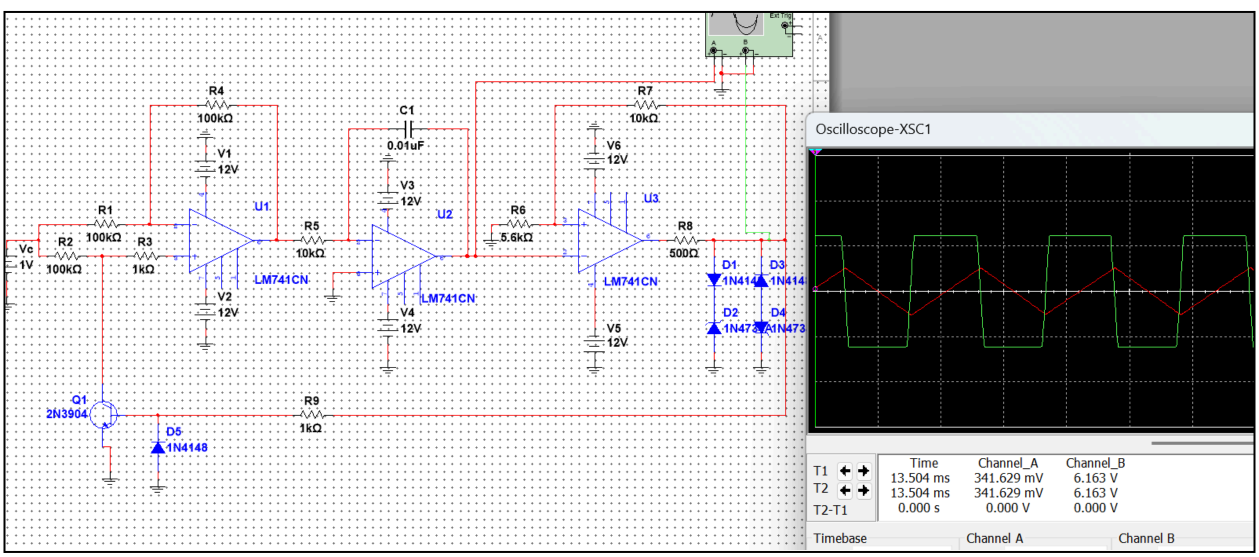


Figure 8: Multisim simulation of a Linear Voltage controlled waveform generator

In **Figure 8,** we see that the triangular waveforms illustrate the signal at the output of the inverting integrator, which also acts as the input for the non-inverting bistable multivibrator. Likewise, the square waveforms represent the signal output from the non-inverting bistable multivibrator, which, in this setup, connects to the switch of the DC converter.

Milestone 4:

The final milestone consisted of Incorporating the "Frequency Range control" and "Gain control" to the Linear Voltage Controlled waveform generator to cover all required specifications. In order to control the peak voltage without affecting the frequency, potentiometers were added at the outputs of the integrator and bistable. This results in implementing the Gain control in the Linear Voltage controlled waveform generator. The potentiometer values were carefully chosen to be high enough to minimize the loading effects but also low enough to allow minimum control over the adjustments. The potentiometers were chosen therefore to allow impedance of up to 10kΩ.

In order to switch between Range #1 and Range #2, a switch as seen in **Figure 9**, will allow you to select the frequency ranges desired. The resistors of range #1 and Range#2 needed to be calculated using the following equation:

$$R = \frac{Vc}{2\left(V_{TH} - V_{TL}\right) f_o C}$$

However in the prelab a total resistance value of 41.1kΩ was calculated which turned out to not give us the desired frequency and amplitudes therefore they were changed in the laboratory. As seen in the multisim simulation, the expected max frequency for Range #1 of 3800 Hz when the DC input voltage (Vc) was set at 5 V was not achieved, although as will be explained later, it was nearing our expected values in the laboratory. Any further discrepancies in the laboratory will be discussed later on. The figure below shows the simulation results on Multisim, when it is operating in Range#1 (closed switch) and in Range #2 (open switch) although once put to the test the obtained results are more accurate and will be discussed in the results and observation.

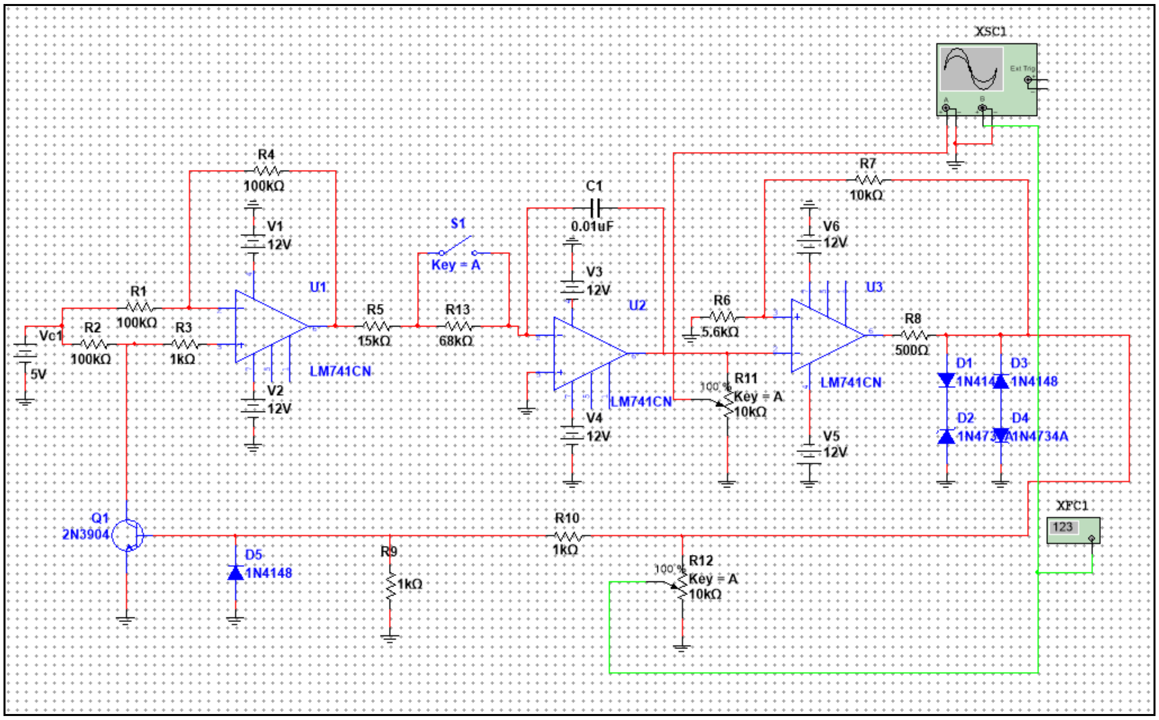


Figure 9: Multisim simulation of a Linear Voltage controlled waveform generator with "Frequency Range control" and "Gain control"

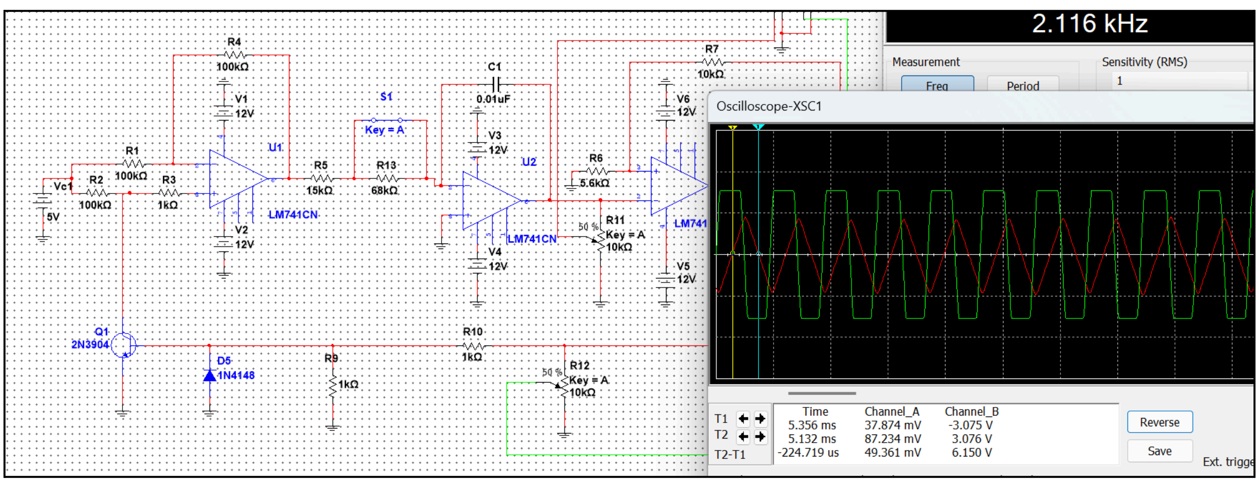


Figure 10: Multisim simulation when operating in Range #1 at Vc = 5V

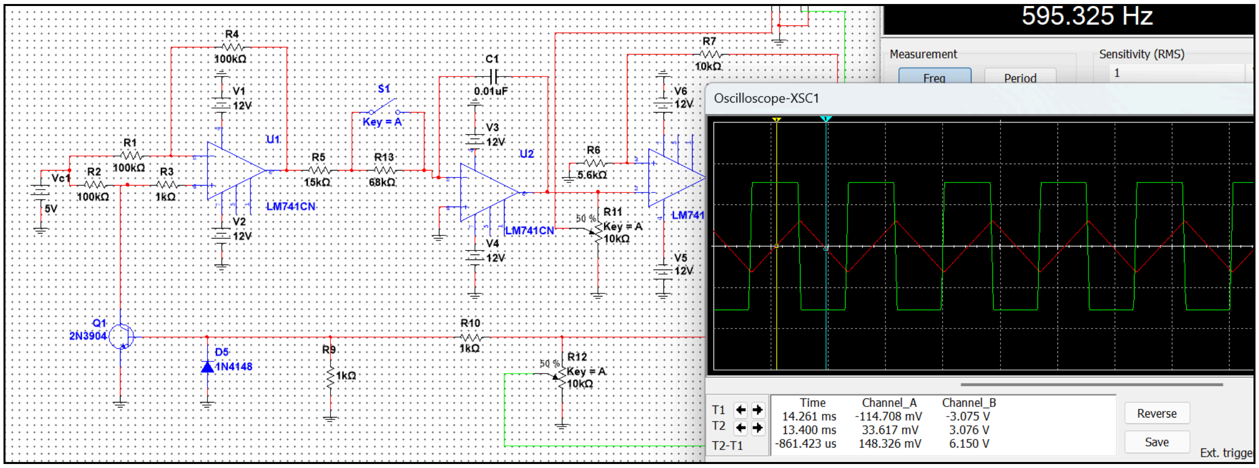


Figure 11: Multisim simulation when operating in Range #2 at Vc = 5V

Experimental procedure

The experiments typically follow four general steps. First, we design the circuit and choose the correct component values through calculations in order to get the desired output. Second, we use MultiSim to simulate the circuit and observe what results we get. In the third step, we assemble the circuit on a breadboard. Finally, we connect a power supply and an oscilloscope to test the circuit, measure the outputs, and see if it's working as expected. If at any point something doesn't work as planned, we begin the troubleshooting process.

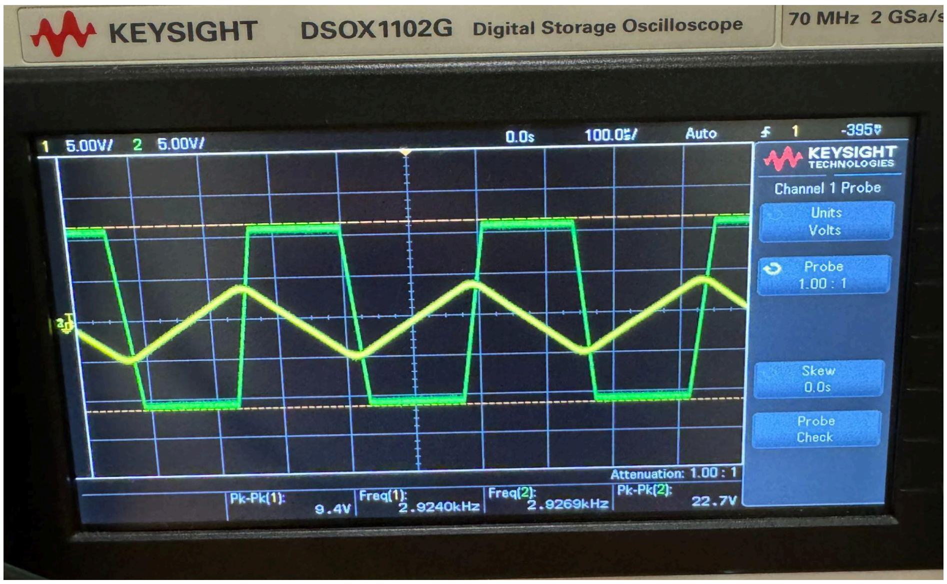
Troubleshooting can begin in the simulation phase, where we can fix any major issues without damaging components. Simulation also helps us check that the output frequency and voltage are right, ensuring the circuit should work under ideal conditions. Once we're confident it works in simulation, we can troubleshoot on the breadboard if necessary.

In-lab equipment such as the breadboard or components like the op-amps can present certain issues. The most common one is a poor connection, which happens if a pin or wire isn't making proper contact with the breadboard's internal plates. Another common issue is short circuits. For example, if two resistors are connected to the same voltage source but have separate connections on the other end, touching them together can accidentally short the circuit and cause problems. Components, like an Op-Amp, could also be flawed. Another frequent issue is simply connecting the components wrong which is why it is crucial to be very detail oriented and double checking the circuit at times. Another solution when in-lab discrepancies are presented is to use a multimeter because it allows us to measure voltages across the circuit. By comparing these measurements to expected values, we can narrow down where the problem is and focus on fixing that part of the circuit.

Results and Observations

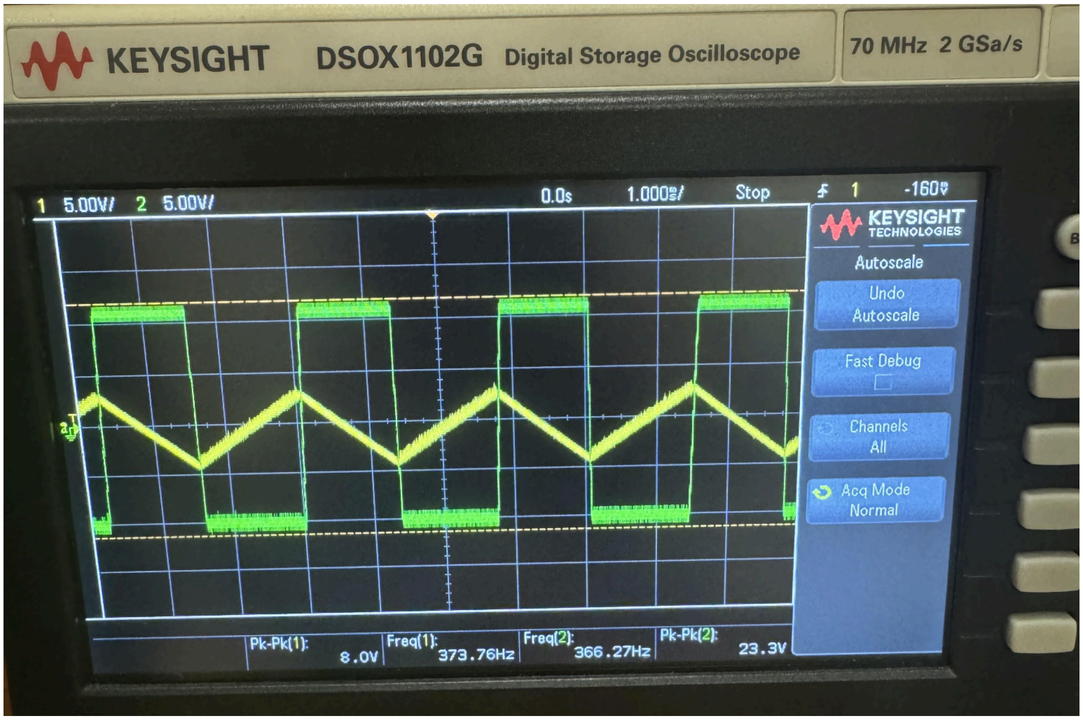
Milestone 1

We began by implementing the milestone 1 circuit on the breadboard but instead of using a 20 kΩ resistor, we used two 10 kΩ resistors in series. The obtained waveforms can be seen in Graph 1.



Graph 1: Waveforms for the circuit seen in Figure 1 built on a breadboard using two LM741CN op-amps

We switched the op-amp in the second stage to an LM318N and added two 0.1uF capacitors, one from the output terminal of the first op-amp to the ground, and another from the output to the ground; this had the goal of stabilizing the signal. Finally, the 0.01 uF in place of C seen in figure 3, was switched with a 0.1uF to further stabilize it. The purpose of switching the op-amp is to really notice the impact of the high slew rate present in the LM318N op-amp.

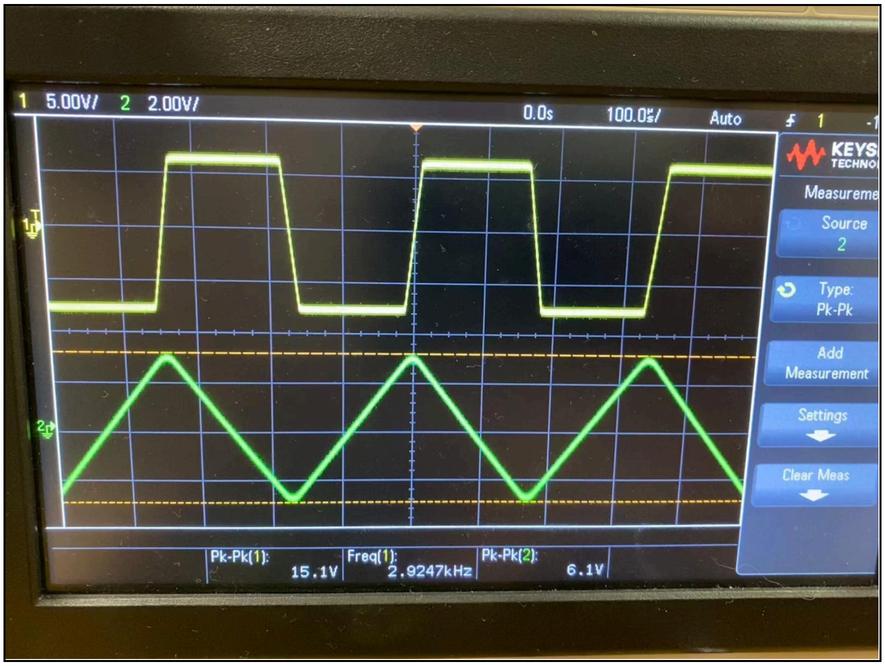


Graph 2: Waveforms for the circuit with LM741CN at the first stage and LM318N at the second stage

When comparing the waveforms of **Graph 1** and **Graph 2**, we can see that there is a clear and obvious difference between the rectangular waveforms. We can see that the slope for the LM318N op amp is much steeper than the LM741CN op amp. This is due to the fact that the LM318N op amp has a greater Slew rate, which allows the op amp to rapidly change the output signal, minimizing any limitations or distortions. The fundamental frequency in **Graph 1** is 2.9 kHz, even though the theoretical fundamental frequency should be 3800 Hz. This discrepancy may be due to circuit instability. Our peak-to-peak voltages for both waveforms are close to our specifications, mentioned in the objectives section.

Milestone 2

The fixed frequency waveform generator for milestone 2 was built on the breadboard but instead of the 570 ohm resistor, we used a 510 ohm as it was the closest available in our lab kit. When connecting the oscilloscope to the circuit, the waveform seen in **Graph 3** shows the results obtained in the lab.

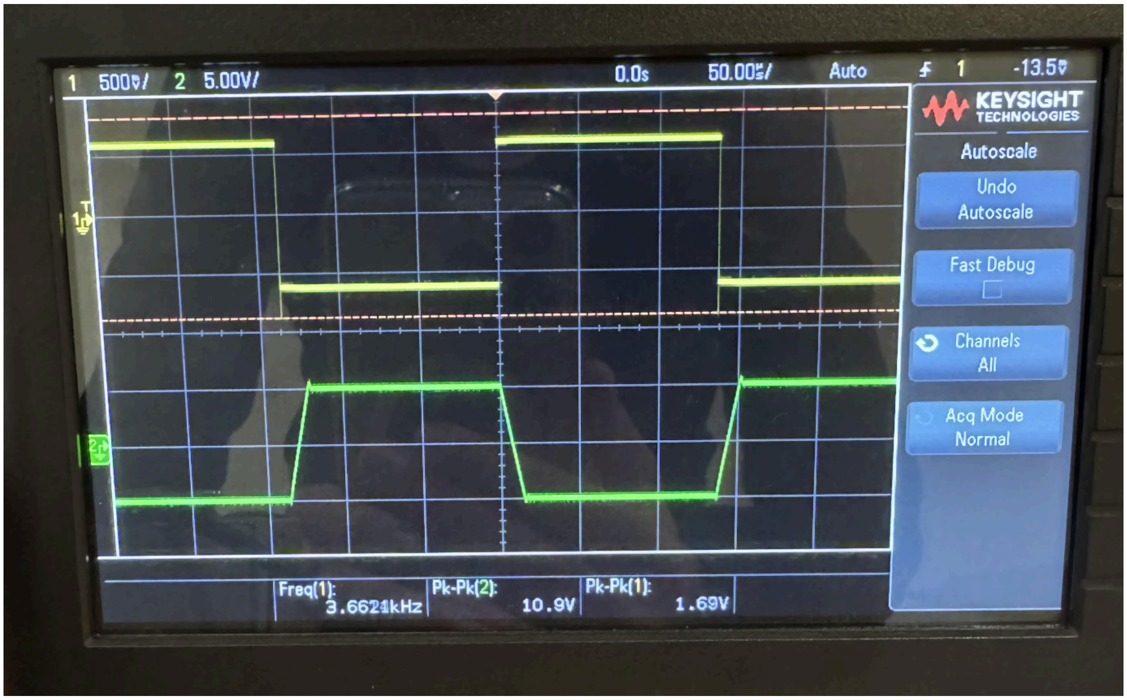


Graph 3: Waveforms of a fixed frequency waveform generator with limiter

Next, the DC to +/- DC converter was built on the breadboard and Vc was adjusted from 1 V to 5 V and ΔVo was determined from the waveforms and the results can be seen in Table Furthermore the waveform when Vc = 5v can be seen in **Graph 4**.

VC	ΔVo
1V	**3.22 Vp-p**
2V	**4.9 Vp-p**
3V	**6.8 Vp-p**
4V	**8.8 Vp-p**
5V	**10.8 Vp-p**

Table 1: Amplitudes of the output waveform at different Vc values



Graph 4: Waveforms of DC to +/- DC Converter for Vc = 5 V

When looking at the waveforms of the fixed frequency waveform generator with a limiter, the amplitude of the square wave is much lower, in comparison to the amplitude in milestone 1. The peak voltage with the limiter implemented in the design was 7.5 V, which is near its desired value of 6.3 V peak. This discrepancy could be caused by the diodes tolerances, or it might be the fact that the feedback resistor values are not high enough to reduce the gain to its expected value.

For our DC to +/- DC converter, we used a function generator to imitate our output voltage signal of our fixed frequency waveform generator with the limiter, with a controlled voltage source (Vc) connected to both terminals of the op-amp. We adjusted Vc to a wide range of values, from 1 V to 5V. The results show that the converter is able to adjust the amplitude of the output waveform.

<u>Milestone 3</u>

The fixed frequency waveform generator and the DC to +/- DC converter were combined to make a linear voltage controlled waveform generator, which was built on the breadboard. When connecting the oscilloscope, the waveforms seen in **Graph 5** show the results obtained in the lab.

Graph 5: Waveforms of the linear voltage controlled waveform generator when Vc = 5 V

Vc was adjusted from 1 V to 5 V and the frequencies as well as the ΔVo for both the waveform at the integrator terminal as well as the output voltage of the inverting bistable were determined and the results can be seen in Table 1.

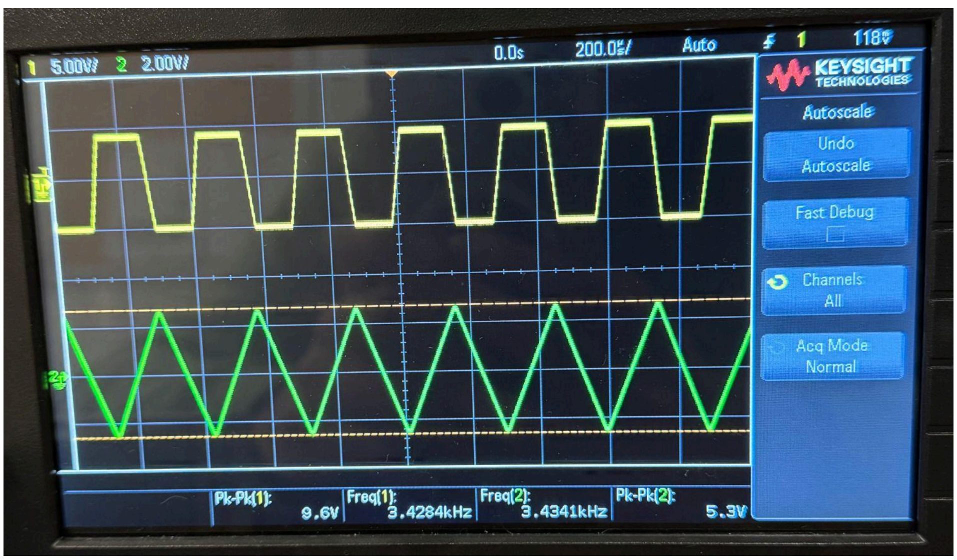
Vc	f	Vpp (triangular wave) (V)	Vpp (square wave) (V)
1 V	990Hz	5.8	14.1
2 V	1.83 kHz	6.4	14.1
3 V	2.47 kHz	7.0	14.1
4 V	2.98 kHz	7.4	14.1
5 V	3.4 kHz	8	14.1

Table 2: Frequency and amplitudes of the output waveforms at different Vc values

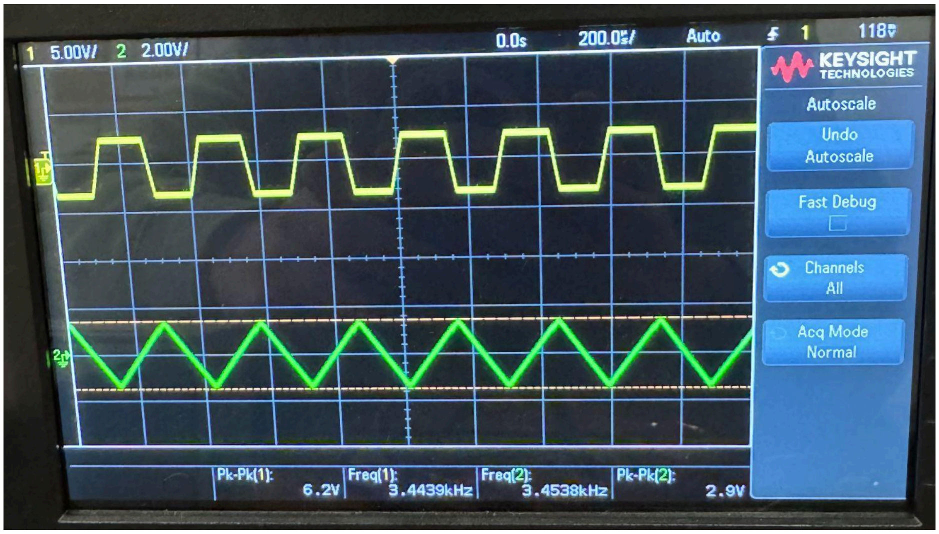
We can see that our integrated linear voltage controlled waveform generator is nearing our expected max frequency for Range #1 of 3800 hz when the DC input voltage (Vc) was set at 5 V. When looking at the table, we can see that there is a linear increase in the frequency when we change Vc from 1V to 5V. Our peak-to-peak voltage for the inverting bistable multivibrator for each Vc was around 14.1 volts, When adjusting the Vc, we can see that the peak-to-peak values for the triangular waveform are steadily increasing to 8.0 Vpp, even though it should constantly be around 8.0 Vpp. This discrepancy might be caused by potential instability in the circuit when the Vc values decrease.

Milestone 4

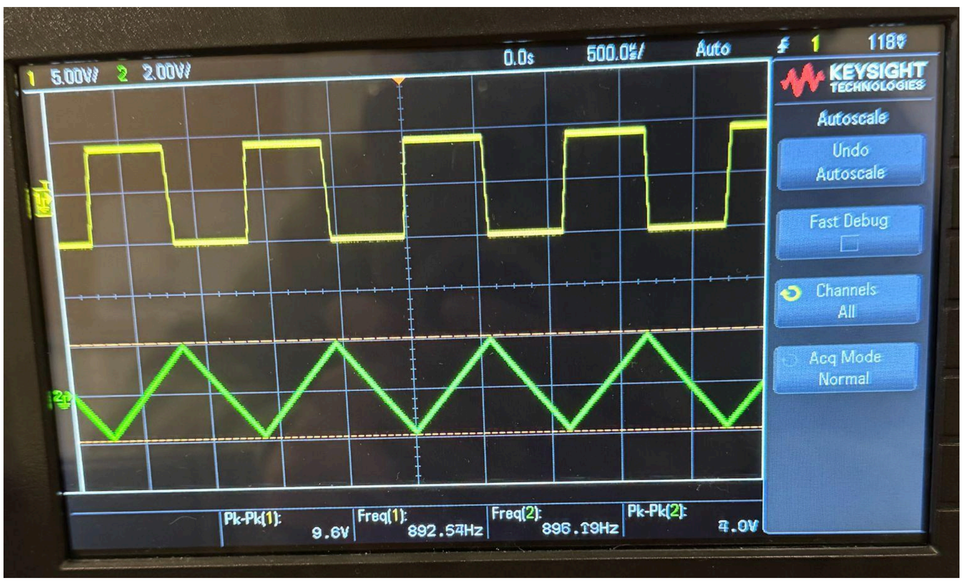
The linear voltage controlled waveform generator with frequency range control and gain control of milestone 4 was built on the breadboard. When connecting the oscilloscope to the circuit, the waveforms seen in **Graph 6** and **Graph 8** show the results obtained for **Range #1** and **Range #2** respectively when Vc was set to 5 V. Furthermore, **Graph 7** shows the change of amplitude of the waveforms when we adjust the resistance of the potentiometer by turning the wiper. The yellow waveform is the rectangular waveform connected to the second potentiometer at the output of the inverting bistable. The green waveform is the triangular waveform when connected to the potentiometer placed between the output of the integrator and input of the inverting bistable. Finally all reading values can be seen in **Table 3** for both Range #1 and Range #2 as well as the peak to peak voltage values for the triangular and rectangular waves.



Graph 6: Range #1 at Vc = 5V



Graph 7: Range #1 at Vc = 5V with adjusted Gain control



Graph 8: Range #2 at Vc = 5V

	Range 1 *(closed switch)* **Vpp (triangular): 3.74V** **Vpp(rectangular): 9.6v**	**Range 2** *(open switch)* **Vpp (triangular): 4.3V** **Vpp(rectangular): 9.8v**
Vc	**f**	**f**
1 V	**198 Hz**	**1kHz**
2 V	**383 Hz**	**1.81 KHz**
3 V	**559 Hz**	**2.46 kHz**
4 V	**732 Hz**	**3 kHz**
5 V	**891 Hz**	**3.4 KHz**

Table 3: Frequency and Amplitudes seen at different Vc values for Range #1 and Range #2

When close the switch (shorting the resistor by adding a wire), the waveform generator successfully selects Range #1. In **Table 3,** the waveform generator is nearing our expected max frequency for Range #1 of 3800 Hz when the DC input voltage (Vc) was set at 5 V. Furthermore, we can see that there is a linear increase in the frequency when we change Vc from 1V to 5V. When we open the switch (removing the wire), the circuit successfully selects Range #2. At Vc = 5V (**Table 3**), the max frequency is in the reasonable range of the specified max frequency of 760 Hz, with a clear linear decrease when the DC input voltage is reduced from 5V. However, to reach these specifications, the resistor values had to be increased significantly at the integrator. This might be due to the fact that the waveform generator becomes more unstable at lower resistor values.

Our peak to peak voltages for the triangular and rectangular waveforms for Range #1 and Range #2 are almost identical, which signifies the frequency range control has no effect on the amplitudes. When comparing **Graph 6** and **Graph 7**, we can see a substantial difference in amplitude at the same frequency. This proves the potentiometers are able to greatly change the amplitude of the waveforms without affecting the frequency.

Conclusion and Recommendations

After conducting the major design project and completing the milestones that led up to this point, some requirements were met while some were not. Firstly, the rectangular waveform produced a maximum voltage near 8 Vpp. Secondly, the waveform generator was successfully able to switch between our specified frequency ranges (up to 3800 Hz for Range #1, and up to

760 Hz for Range #2). The potentiometers were able to control output voltage amplitudes, without having any sort of impact on the frequency. The diodes at the bistable also worked as limiters by setting the output voltage of the bistable to 6.3V peak which would prevent variations of Vcc from affecting the output. However, one requirement that was not met was the linearity of the frequency, without affecting the amplitude. In Milestone 3, As the input of the DC input voltage (Vc) was decreased, the desired outcome was that the frequency would decrease linearly with Vc. However, the circuit ended up decreasing the amplitude of the triangular waveform, which was supposed to remain constant. Therefore, the frequency control feature did not work as intended, making the triangular waveform incorrect. This was likely due to miscalculation in digital switch values or component values in the DC converter. Another requirement that was not met was the maximum voltage of 8 Vpp for the triangular waveform. In Milestone 4, we can see the maximum peak-to-peak of around 4 Vpp. This major discrepancy is most likely caused by the feedback resistors for the inverting bistable not being set at their correct values for this scenario.

We can conclude the waveform generator was able to produce a proper square waveform and an incorrect triangular waveform and the frequency of the generator was not linearly proportional to DC input voltage without any side effects. A few recommendations to avoid these potential issues in the future include carefully selecting component values, as even theoretically correct values may not perform as expected in practical applications.

References and Biography

[1] A. Sedra and K. Smith, Microelectronic circuits. New York, NY: Oxford University Press, 2016.

[2] Kassam M.S,ELE504-MAJOR DESIGN PROJECT, Toronto Metropolitan University 2022.

Appendix

TEXAS INSTRUMENTS — LM741

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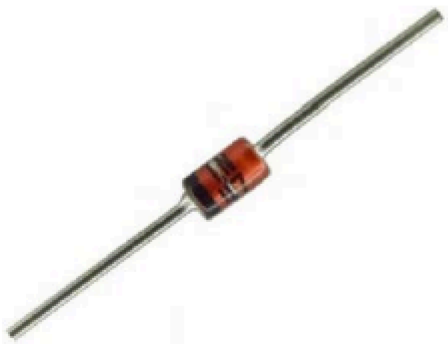
Electrical Characteristics[1] (continued)

Parameter	Test Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage Adjustment Range	T_A = 25°C, V_S = ±20V	±10				±15			±15		mV
Input Offset Current	T_A = 25°C		3.0	30		20	200		20	200	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			70		85	500			300	
Average Input Offset Current Drift				0.5							nA/°C
Input Bias Current	T_A = 25°C		30	80		80	500		80	500	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			0.210			1.5			0.8	μA
Input Resistance	T_A = 25°C, V_S = ±20V	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \le T_A \le T_{AMAX}$, V_S = ±20V	0.5									
Input Voltage Range	T_A = 25°C							±12	±13		V
	$T_{AMIN} \le T_A \le T_{AMAX}$				±12	±13					
Large Signal Voltage Gain	T_A = 25°C, $R_L \ge$ 2 kΩ										V/mV
	V_S = ±20V, V_O = ±15V	50									
	V_S = ±15V, V_O = ±10V				50	200		20	200		
	$T_{AMIN} \le T_A \le T_{AMAX}$,										V/mV
	$R_L \ge$ 2 kΩ,										
	V_S = ±20V, V_O = ±15V	32									
	V_S = ±15V, V_O = ±10V				25			15			
	V_S = ±5V, V_O = ±2V	10									
Output Voltage Swing	V_S = ±20V										V
	$R_L \ge$ 10 kΩ	±16									
	$R_L \ge$ 2 kΩ	±15									
	V_S = ±15V										V
	$R_L \ge$ 10 kΩ				±12	±14		±12	±14		
	$R_L \ge$ 2 kΩ				±10	±13		±10	±13		
Output Short Circuit	T_A = 25°C	10	25	35		25			25		mA
Current	$T_{AMIN} \le T_A \le T_{AMAX}$	10		40							
Common-Mode	$T_{AMIN} \le T_A \le T_{AMAX}$										dB
Rejection Ratio	$R_S \le$ 10 kΩ, V_{CM} = ±12V				70	90		70	90		
	$R_S \le$ 50Ω, V_{CM} = ±12V	80	95								
Supply Voltage Rejection	$T_{AMIN} \le T_A \le T_{AMAX}$,										dB
Ratio	V_S = ±20V to V_S = ±5V										
	$R_S \le$ 50Ω	86	96								
	$R_S \le$ 10 kΩ				77	96		77	96		
Transient Response	T_A = 25°C, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		μs
Overshoot			6.0	20		5			5		%
Bandwidth [2]	T_A = 25°C	0.437	1.5								MHz
Slew Rate	T_A = 25°C, Unity Gain	0.3	0.7			0.5			0.5		V/μs
Supply Current	T_A = 25°C					1.7	2.8		1.7	2.8	mA
Power Consumption	T_A = 25°C										mW
	V_S = ±20V		80	150							
	V_S = ±15V					50	85		50	85	

Zener Diode



Features:

- High reliability.
- Very sharp reverse characteristic.
- Low reverse current level.
- V_z-tolerance ±5%.

Application:

Voltage stabilization.

Absolute Maximum Ratings $T_j = 25°C$

Parameter	Test Conditions	Symbol	Value	Unit
Power dissipation	$T_{amb} \leq 50°C$	P_v	1	W
Z-current	-	I_z	P_v / V_z	mA
Junction temperature	-	T_j	200	°C
Storage temperature range	-	T_{stg}	-65 to +175	

Maximum Thermal Resistance $T_j = 25°C$

Parameter	Test Conditions	Symbol	Value	Unit
Junction ambient	l = 9.5 mm (3/8") T_L = constant	R_{thJA}	100	K/W

Stresses exceeding maximum ratings may damage the device. Maximum ratings are stress ratings only. Functional operation above the recommended operating conditions is not implied. Extended exposure to stresses above the recommended operating conditions may affect device reliability.

Electrical Characteristics $T_j = 25°C$

Parameter	Test Conditions	Symbol	Maximum	Unit
Forward voltage	I_F = 200 mA	V_F	1.2	V

ELE 504 Lab Kit

Item	Quantity	Part No.	Description
1	4	1N4148	Silicon, small signal diode
2	1	1N4734	Zener diode, 5.6V
3	1	J111	N-Channel Switch
4	1	2N3906	BJT, PNP
5	1	2N3904	BJT, NPN
6	6	LM318CN	OPAMP, High slew rate
7	1	LM555	Timer
8	6	741	OPAMP, General Purpose
9	4	100	¼ Watt 5% resistor
10	4	1k	¼ Watt 5% resistor
11	8	10k	¼ Watt 5% resistor
12	4	100k	¼ Watt 5% resistor
13	4	10M	¼ Watt 5% resistor
14	4	2k	¼ Watt 5% resistor
15	4	5k1	¼ Watt 5% resistor
16	2	1k	Mini-pot
17	4	10k	Mini-pot
18	2	100k	Mini-pot
19	2	0.01uF	Capacitor, ceramic 50V 103
20	4	0.1uF	Capacitor, ceramic 50V 104
21	2	0.022uF	Capacitor, ceramic 50V 223
22	2	10uF	Capacitor, electrolytic 35V

ELE 404 Lab Kit

Item	Quantity	Part No.	Description
1-4	2 each	10r, 100r, 1M0, 10M	¼ Watt 5% Resistor
5-8	2 each	910r, 9k1, 91k, 910k	¼ Watt 5% Resistor
9-10	2 each	1k2, 12k	¼ Watt 5% Resistor
11-12	2 each	1k5, 15k	¼ Watt 5% Resistor
13-14	2 each	180r, 180k	¼ Watt 5% Resistor
15-19	2 each	220r, 2k2, 22k, 220k, 2M2	¼ Watt 5% Resistor
20-22	2 each	270r, 2k7, 27k	¼ Watt 5% Resistor
23-25	2 each	330r, 33k, 330k	¼ Watt 5% Resistor
26-27	2 each	390r, 3k9	¼ Watt 5% Resistor
28-30	2 each	470r, 4k7, 47k,	¼ Watt 5% Resistor
31-33	2 each	560r, 5k6, 56k	¼ Watt 5% Resistor
34	2	62k	¼ Watt 5% Resistor
35-37	2 each	680r, 6k8, 68k	¼ Watt 5% Resistor
38-39	2 each	820r, 820k	¼ Watt 5% Resistor
40-42	5 each	91r, 1k0, 3.3k	¼ Watt 5% Resistor
43-44	10 each	10k, 100k	¼ Watt 5% Resistor
45	2	0.022uF	Ceramic Capacitor 223
46	2	0.01uF	Ceramic Capacitor 103
47	6	0.1uF	Ceramic Capacitor 104
48	4	1.0uF	Ceramic Capacitor 105
49	2	100uF	35V Electrolytic Capacitor Radial
50	4	10uF	35V Electrolytic Capacitor Radial
51	4	1N4004	SI-Rectifier Diode
52	10	1N4148	Small Signal Diode
53	2	1N4729A	Zener Diode 3.6 Volt
54	2	1N4735	Zener Diode 6.2 Volt
55	2	2N3904	BJT Transistor NPN
56	2	2N3906	BJT Transistor PNP
57	1	1k Trim Pot	Mini Trim pot
58	2	10k Trim Pot	Mini Trim pot
59	10	Test Leads	Alligator Clip Test Leads
60	5	110-502	Red LED
61	2	110-505	Green LED