Toronto Metropolitan University

Department of Electrical & Computer Engineering
Faculty of Engineering & Architectural Science

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Instructor:	**Dr. Alice Rueda**

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Assignment/Lab Title:	**Major Project (Linear Voltage-Controlled Function Generator) Final Report**

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Student LAST Name	**Student FIRST Name**	**Student Number**	**Section**	**Signature***
Babar	**Umar**	**501116508**	**01**	
Rahman	**Muhammad Afnan**	**501024590**	**01**	A.R

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1. Abstract

For this project, we had to implement multiple circuits and record measurements through a series of weekly milestones to confirm and verify the calculated specifications from our pre-lab simulations and analysis. The project applied practical skills in circuit design, analysis, modeling, and testing to create a linear voltage-controlled multi-function waveform generator. The experimental procedure for this project involves simulating the calculated resistor values and other component parameters using Multisim, based on detailed handwritten calculations and circuit design considerations. These simulations are subsequently verified through in-lab experiments, where each circuit is tested and validated on a breadboard to ensure the correct placement of components and connections as we progress through the project.

The main components utilized at each milestone include resistors, capacitors, diodes, operational amplifiers, and voltage sources. For each milestone, we recorded data measurements using electrical and electronic measuring equipment such as oscilloscopes, waveform generators, power supplies, and digital multimeters. In the final project report, any discrepancies or deviations that may have altered the expected results are discussed. Additionally, the precision and accuracy of our measurements are analyzed, along with a comparison of pre-lab and post-lab results.

Throughout the project's duration, after completing each milestone, we slowly observed the creation of the linear voltage-controlled multi-function waveform generator, which began with testing each individual circuit (Integrator, Bistable Multivibrator, DC to DC converter, and a buffer) in the initial weeks and then combining them through recalculation of components in the latter half of this project. An example of this could be the incorporation of the Limiter for the Bistable Multivibrator and the DC to DC converter during milestones 2 and 3 as well as the addition of the potentiometer and the buffer circuit for gain control in milestone 4. Although we encountered some discrepancies along the way, such as obtaining incorrect output voltages for the square waveform in milestone 3 when integrating the waveform generator with a DC-to-DC converter, we ensured that these issues were resolved in the subsequent milestone.

In summary, for this project, we recommend that when implementing the circuit design from the pre-lab work and simulations, it is important to account for any potential distortion or short-circuiting issues that may arise during the in-lab phase. These issues should be addressed not only with strong theoretical knowledge but also by employing effective circuit-building techniques and careful breadboard implementation.

2. Objectives

The purpose of this project is to design, simulate, implement, and test a Linear Voltage-controlled Multi-function Waveform Generator that generates square and triangular waveforms with the specifications provided in the project manual through four separate milestone sub-projects. Each milestone focuses on gradually enhancing and fine-tuning the design to meet the required specifications. The first specification of the design project is the assigned output frequency of f_o = 3100 Hz, which was utilized to determine the two desired frequency ranges of approximately 100 Hz to 3100 Hz (range #1) and 20 Hz to 620 Hz (range #2). The second set of specifications consists of a user-selectable symmetrical triangular or square wave output waveform with 0 to 4 volts peak amplitude, with amplitude control implemented through the utilization of potentiometers. Along with this, the input DC voltage control range must be user-controlled from 0.1 to 5 volts. The last specification involves the mandatory use of a +/- 12 Volts power supply for the completed design.

3. Introduction

A Linear Voltage-Controlled Frequency Generator (LVCFG) is an electronic circuit that produces a waveform with a frequency that is directly proportional to an input control voltage. This means that as the input control voltage changes, the output frequency changes linearly in response. This is particularly useful in applications requiring frequency modulation or dynamic signal control, such as signal processing, communication systems, and audio synthesis. The LVCFG's operating principle revolves around adjusting the frequency of oscillation in response to a control voltage. The relationship is typically designed to be linear, meaning the output frequency increases or decreases in direct proportion to the voltage input. This linearity makes it a versatile and controllable source of waveforms across various frequencies.

The design process begins with an in-depth theoretical analysis through calculations and simulations during the prelab phase, where theoretical research on waveform generation methods is conducted through the lecture material, and initial circuit designs are created. The results of this analysis serve as a foundation for constructing the various subcircuits implemented to create the final waveform generator circuit design. Utilizing the appropriate op-amps and individual components is essential for meeting the desired performance targets. Circuit simulations, primarily conducted in Multisim, are employed to model the subcircuits and validate their performance against theoretical expectations.

During the in-lab experiment portions of the project, to ensure the correct implementation of the project based on the given requirements that need to be met, we developed and implemented our circuit design on breadboards to test and verify the simulations and handwritten calculations performed during the pre-lab. As the project progresses through various milestones, we validate the circuit by conducting measurements to confirm its alignment with the specifications derived from our pre-lab simulations and analysis. Although the main objective of this project is to design and build a multi-function waveform generator controlled by linear voltage, it also aims to enhance our practical skills in circuit design, analysis, modeling, and testing.

4. Theory & Design Analysis

Refer to Appendix A-D for more information on resources that were available/used in circuit design and implementation.

Product Overview:

From Major Project Lab Manual, Kassam 2022.

Figure 1.0 is the overall system overview of the objective:

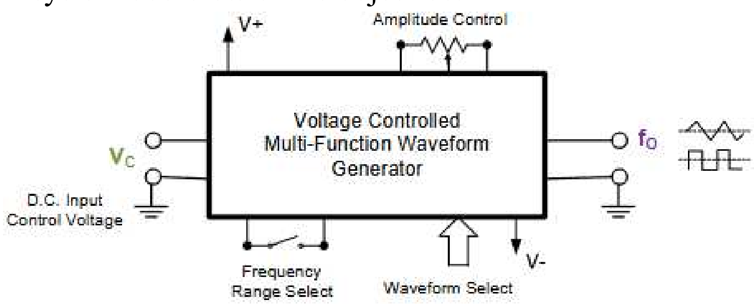


Figure 1.0

Figure 1.1 is the overall Linear VCFG transfer function of the objective where $f_x = 3100\ Hz$:

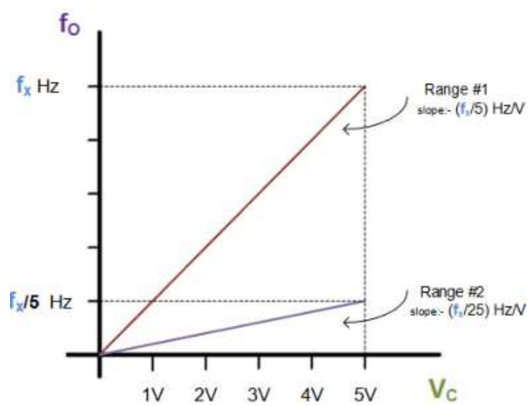


Figure 1.1

Figure 1.2 is the overall Block Diagram:

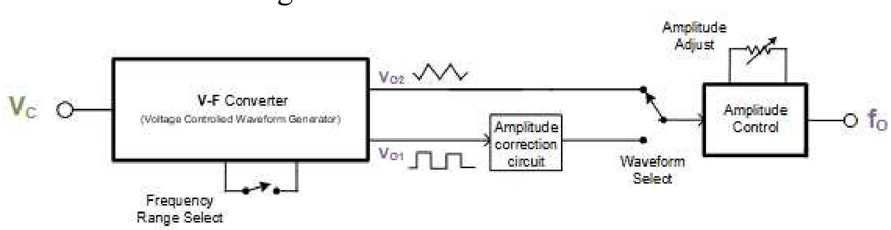


Figure 1.2

Figure 1.3 is the overall V-to-F Converter scheme:

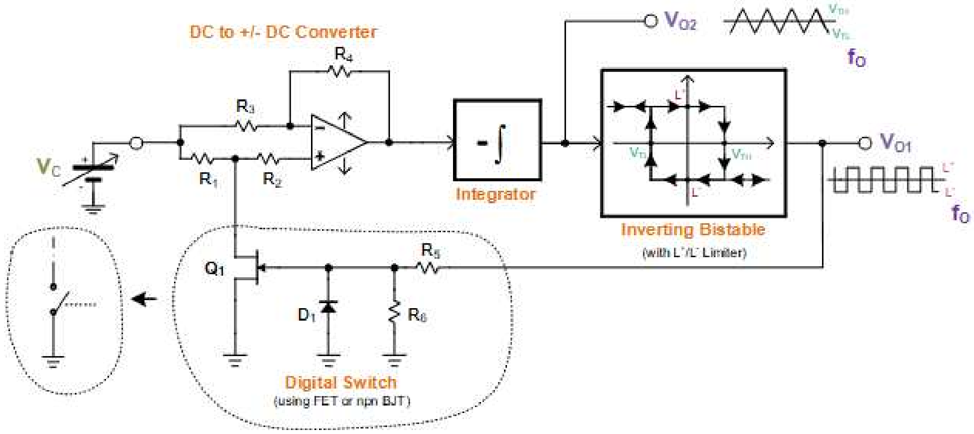


Figure 1.3

Milestone-1

- Create a fixed-frequency waveform generator.

Given:
Output voltage level: 4Vpeak
Power Supply: +/-12V d.c.
L+/L- : +10.5V/-10.5V
$C = 0.01\ \mu F,\ f_x = 3100\ Hz$

(E1.) is the transfer function of a Non-Inverting Bistable Multivibrator:

E1. $V^+ = V_o\left(\frac{R1}{R1+R2}\right) + V_I\left(\frac{R2}{R1+R2}\right)$

(E2.) and **(E3.)** are derived from the above equation, and represent threshold voltages that are tripped at $V^+ = 0$, as $V_I = (+\ /-\infty)$

E2. $V_{TL} = -L^+\left(\frac{R1}{R2}\right)$ Low Threshold Voltage

E3. $V_{TH} = -L^-\left(\frac{R1}{R2}\right)$ High Threshold Voltage

E4. $R = \frac{L^+}{2f_x(V_{TH}-V_{TL})C}$ where $f_x = f_o$ Outward Resistor

E5. $T = 2T_1,\ T_1 = \frac{(V_{TH}-V_{TL})RC}{L^+}$ Period

Given 8 Vpp, | L+/- | = 10.5 V applied to **(E2.)**, we have the option to choose R1 and R2 in a 4:10.5 ratio. R1:R2 can be 8 kΩ: 21 kΩ. To suit the restrictions of available lab resources, 22 kΩ can be substituted for R2, the 21 kΩ. Using given and calculated values subbed into **(E2.)** reveals as such:

$\therefore V_{TH} = 3.81\ V\ and\ V_{TL} = -V_{TH}$

Given $C = 0.01\ \mu F,\ f_x = 3100\ Hz$, R can be calculated as 22.22 kΩ from **(E4.)**. The value 22.22 kΩ can be substituted with 22 kΩ per the available resistors in the lab kit.
$\therefore R = 22\ k\Omega$

$\therefore T = 3.2 * 10^{-4} s$, after plugging in all the values given and calculating them into **(E5.)**.

This is enough to design the fixed-frequency wave generator. LM741CN and LM318 op-amps were used as per the configuration below. **Figure 1.4** is the accumulated design for part one of this project:

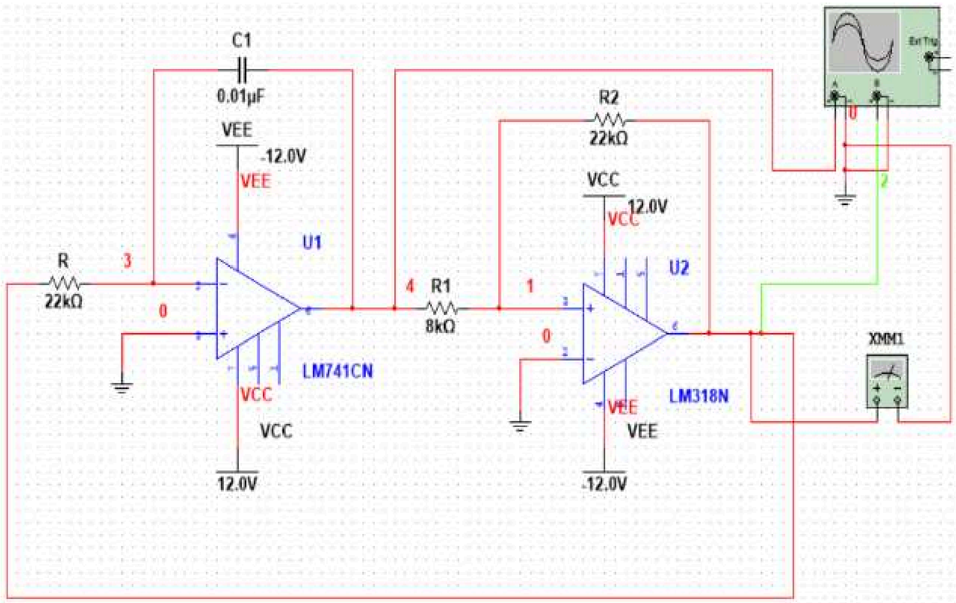


Figure 1.4

Milestone-2

- Create a fixed-frequency waveform generator with precise L+/L- voltage output value, and a DC-to+/-DC converter.

Given:

Output voltage level: 4Vpeak

Power Supply: +/-12V d.c.

L+/L- : +6.3V/-6.3V

Iz = 10 mA

$C = 0.01\ \mu F$

$f_x = 3100\ Hz$

E6. $R_3 = \frac{V_i - V_o}{I_z}$

E7. $i = \frac{V_c - 0}{R} = \frac{0 - V_o}{R}\ where\ R\ can\ be\ 1k\Omega$

<u>Integration of integrator and Bistable Multivibrator</u>
Using **(E3.)** and the newly given elements of L+/L- and output voltage, the new ratio of R1: R2 can be calculated as 4:6.3. To achieve this ratio approximately within the limits of lab kit resources, R1: R2 is chosen as 40 kΩ : 62 kΩ.Using given and calculated values subbed into **(E2.)** reveals as such:

Using **(E6.)** with given elements such as the Power Supply Voltage, |L+|, and Iz, R3 can be calculated as the following:

$$R_3 = \frac{V_i - V_o}{I_z} = \frac{12-6.3\,V}{10*10^{-3}A}$$

$$\therefore R_3 = 570\,\Omega$$

$$\therefore V_{TH} = 4.065\,V \; and \; V_{TL} = -V_{TH}$$

Given L+/L-: +6.3V/-6.3V, $C = 0.01\,\mu F$, $f_x = 3100\,Hz$, R can be calculated as 12.4986 kΩ from **(E4.)**. The value 12.4986 kΩ can be substituted with 12.47 kΩ as -per the available resistors in the lab kit.

$$\therefore R = 12.47\,k\Omega$$

$\therefore T = 3.22 * 10^{-4}\,s$, after plugging in all the values given and calculating them into **(E5.)**.

LM741CN and LM318 op-amps were used as per the configuration below. **Figure 2.0** is the accumulated fixed-frequency waveform generator with precise L+/L- voltage output value design for part two of this project:

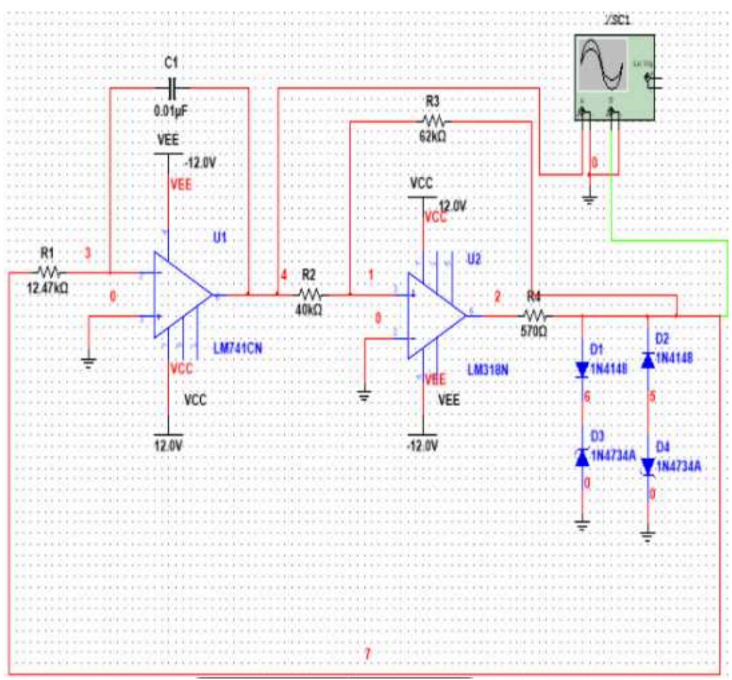


Figure 2.0

<u>DC-to+/-DC converter</u>
Using **(E7.)** $V\rho$ is set to 6.3 V . LM741CN op-amp was used as per the configuration below.
Figure 2.1 is the DC-to+/-DC converter for part two of this project:

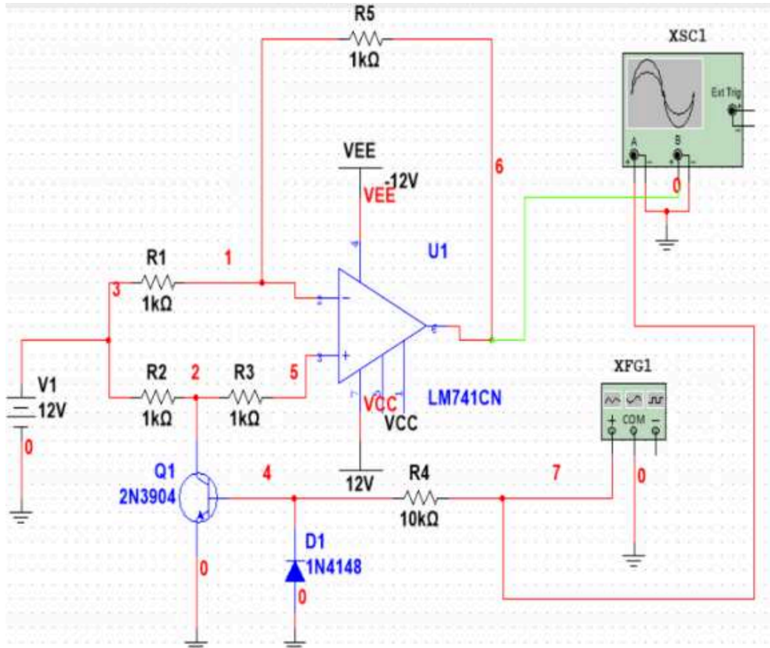


Figure 2.1

Milestone-3

- Integrated Linear Voltage Controlled Waveform Generator

Given:
Output voltage level: 4Vpeak
Power Supply: +/-12V d.c.
L+/L- : +6.3V/-6.3V
$|V_{TH}| = 4\,V$
Iz = 10 mA
$V_c = 5\,V$
$C = 0.01\,\mu F$
$f_x = 3100\,Hz$

E8. $V_{TL} = L^{-}\left(\frac{R1}{R1+R2}\right)$

E9. $V_{TH} = L^{+}\left(\frac{R1}{R1+R2}\right)$

E10. $V_{\rho} = 2f_x(V_{TH} - V_{TL})RC$

Integrator
Given $C = 0.01\,\mu F$, $f_x = 3100\,Hz$, $V_c = 5\,V$, R can be calculated as 10.8 kΩ from **(E4.)**. The value can be substituted with 10 kΩ per the available resistors in the lab kit.
$\therefore R = 10\,k\Omega$

Bistable Multivibrator
Using **(E8.)** and **(E9.)** along with the newly given elements V_{TH}, the new ratio of R1: R2 can be calculated as 4:6.3. To achieve this ratio approximately within the limits of lab kit resources, R1: R2 is chosen as 4 kΩ : 2.3 kΩ.

Using **(E10.)** with newly calculated R, dispenses $V_{\rho} = 4.96 \approx 5.0\,V$

R_3 will remain unchanged.

<u>DC-to+/-DC converter</u>
Using **(E7.)** $V\rho$ is set to 5V.

$\therefore T = 2.54 * 10^{-4} s$, after plugging in all the values given and calculating them into **(E5.)**.

LM741CN and LM318 op-amps were used as per the configuration below. **Figure 3.0** is the finalized circuit design of part three of the project:

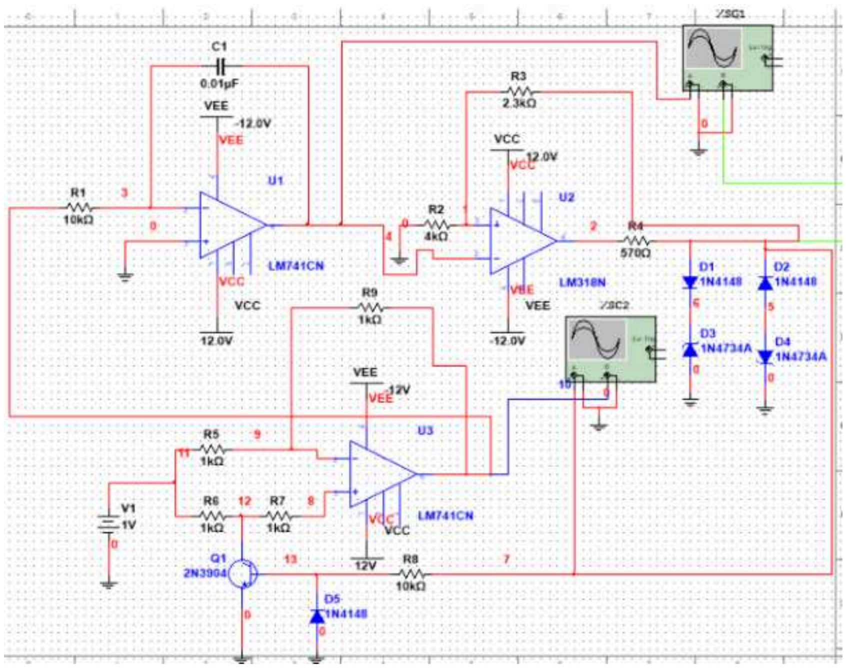


Figure 3.0

<u>Milestone-4</u>

- "Frequency Range control" and "Gain control" are integrated into the Linear Voltage Controlled Waveform Generator.

Given:
Output voltage level: 4Vpeak
Power Supply: +/-12V d.c.
L+/L- : +6.3V/-6.3V
$|V_{TH}| = 4\,V$
Iz = 10 mA
$V_c = 5\,V$
$C = 0.01\,\mu F$
$f_x = 3100\,Hz$ (Range #1)
$f_o = \frac{3100}{5} = 620\,Hz$ (Range #2)
10k potentiometer

E11. $A = \frac{V_o}{V_i} = -\frac{R_f}{R_i}$

Integrator
(Range #1)
It is analyzed as unchanged from part three.

(Range #2)
Given $V_{TH} = 4V$, $f_o = \frac{3100}{5} = 620\ Hz$, $C = 0.01\ \mu F$, R can be calculated as 50.403 kΩ from **(E4.)**.
The value 50.403 kΩ can be substituted with 50 kΩ as -per the available resistors in the lab kit.

Bistable Multivibrator
It is analyzed as unchanged from part three.
For both ranges $V_\rho = 4.96 \approx 5.0\ V$ the first range is unchanged from the previous part and the new range has a frequency difference of a fifth that is cancelled by the resistor difference of 5 times.
R3 will remain unchanged.

DC-to+/-DC converter
It is analyzed as unchanged from part three.

Unity Gain Buffer
Gain must be equal to 1. Negative feedback means the (-) terminal tracks the (+) terminal.
Using **(E11)**, the gain will invert.
$\therefore R_f = R_i = 10\ k\Omega$

(Range #1) - It is analyzed as unchanged from part three.
$\therefore T_{Range\ \#1}$ = 2.54 *10-4 s, after plugging in all the values given and calculating them into **(E5.)**.
(Range #2) - Where the 10 kΩ is replaced with a 50 kΩ in **(E5.)**.
$\therefore T_{Range\ \#2}$ = 2.54 *10-4 s.

LM741CN and LM318 op-amps were used as per the configuration below. **Figure 4.0** is the culminated circuit design of the project:

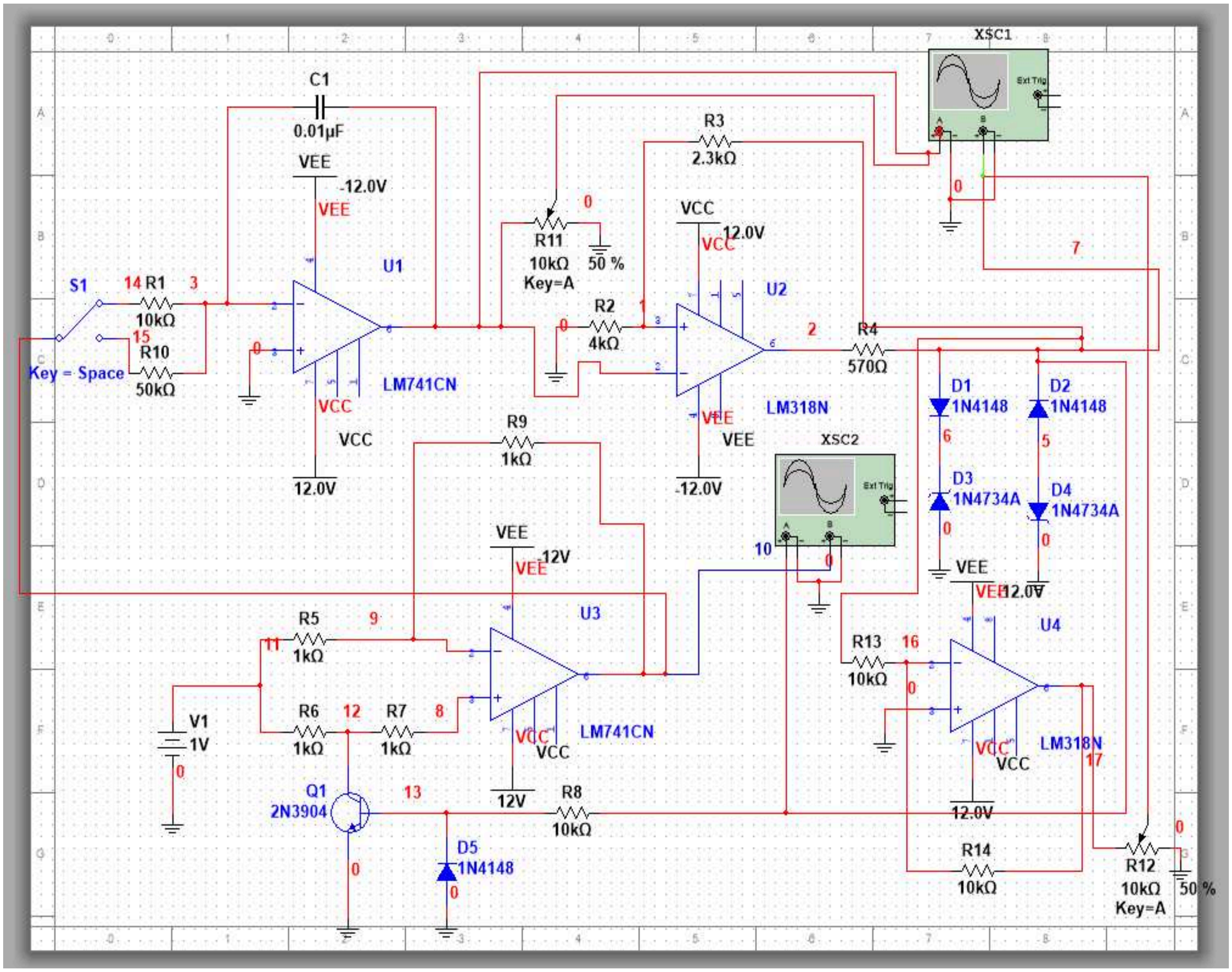

XSC1
C1
0.01µF
VEE
-12.0V
R3
2.3kΩ
VCC
12.0V
R11
10kΩ
50 %
Key=A
S1
R1
10kΩ
R10
50kΩ
Key = Space
U1
LM741CN
R2
4kΩ
U2
LM318N
R4
570Ω
D1
1N4148
D2
1N4148
D3
1N4734A
D4
1N4734A
XSC2
R9
1kΩ
VEE
-12V
U3
LM741CN
R5
1kΩ
R6
1kΩ
R7
1kΩ
V1
1V
Q1
2N3904
D5
1N4148
R8
10kΩ
12V
R13
10kΩ
U4
LM318N
R14
10kΩ
R12
10kΩ
50 %
Key=A

Figure 4.0

5. Experimental Procedure

The following procedure (scribed in present tense) was followed for each milestone:

Milestone-1

Prelab

1. Simulations are first-hand written, and values of resistors and other required components are calculated using the frequency value provided by our TA
2. Bistable multivibrator and integrator circuits are then designed by hand and integrated.
3. Handwritten design is assembled on multisim to simulate and capture the necessary waveforms for the design
4. Use the Oscilloscope tool in multisim to observe the output waveform. Measure and record:
    a. V_{TH}, V_{TL}, L+/- , f_x
5. Capture the waveform to observe/record the:
    a. Amplitude of the waveform
    b. Waveform shape (e.g., square, sine, or triangular)

In-Lab Verification

1. Assemble the integrated bistable multivibrator and integrator circuits onto a breadboard, following the design specifications from the Pre-Lab
1. Connect a ±12V power supply to the circuit.
2. Use an oscilloscope to observe the output waveform. Measure and record:
    a. V_{TH}, V_{TL}, L+/- , f_x
3. Capture the waveform to observe/record the:
    a. Amplitude of the waveform
    b. Waveform shape (e.g., square, sine, or triangular)
4. Compare observed waveform characteristics with expected values from the Pre-Lab design and simulations. Record any differences observed

Milestone-2

Prelab

1. Simulations are first-hand written, and values of resistors and other required components are calculated using the frequency value provided by our TA
2. Bistable multivibrator and integrator circuits are then designed by hand and integrated.
3. Handwritten design is assembled on multisim to simulate and capture the necessary waveforms for the design
4. Repeat the same process in step 2 but for the DC-to-+/-DC converter circuit.
5. Use the Oscilloscope tool in multisim to observe the output waveform. Measure and record:
    a. V_{TH}, V_{TL}, L+/- , f_x

6. Capture the waveform to observe/record the +Vo / -Vo per change Vc; {Vc = 1, 2 , 3, 4, 5 V}

    a. Amplitude of the waveform
    b. Waveform shape (e.g., square, sine, or triangular)

In-Lab Verification

1. Assemble the integrator and bistable multivibrator circuit onto a breadboard, following the design specifications from the Pre-Lab.
2. Connect a ±12V power supply to the circuit.
3. Use an oscilloscope to observe the output waveform. Measure and record:
    a. V_{TH}, V_{TL}, L+/- , f_x
4. Capture the waveform to observe/record the +Vo / -Vo per change Vc; {Vc = 1, 2 , 3, 4, 5 V}
    a. Amplitude of the waveform
    b. Waveform shape (e.g., square, sine, or triangular)
5. Assemble the DC-to-+/-DC converter circuit on a breadboard, following the design specifications from the Pre-Lab.
6. Repeat Step 4.
7. Compare observed waveform characteristics with expected values from the Pre-Lab design and simulations. Record any differences observed

Milestone-3

Prelab

1. Simulations are first-hand written, and values of resistors and other required components are calculated using the frequency value provided by our TA
2. The circuit for the integrator, bistable multivibrator, with the integration of the DC-to-+/-DC converter circuit is then designed by hand and integrated.
3. Handwritten design is assembled on multisim to simulate and capture the necessary waveforms for the design
4. Use the oscilloscope tool in multisim to observe the outputs at the bistable and the converter with varying Vc; {Vc = 1, 2, 3, 4, 5 V}. Measure, record, and capture the:
    a. |+Vtrig| (+) , |-Vtrig |(-), Vsquare +/-(Output) , f_x
    b. Amplitude of the waveforms
    c. Waveform shape (e.g., square, sine, or triangular)

In-Lab Verification

1. Assemble the integrator, bistable multivibrator, with the integration of the DC-to-+/-DC converter circuit onto a breadboard, following the design specifications from the Pre-Lab.
2. Connect a ±12V power supply to the circuit.
3. Use an oscilloscope to observe the outputs at the bistable and the converter with varying Vc; {Vc = 1, 2, 3, 4, 5 V}. Measure, record, and capture the:
    a. |+Vtrig| (+) , |-Vtrig |(-), Vsquare +/-(Output) , f_x
    b. Amplitude of the waveforms
    c. Waveform shape (e.g., square, sine, or triangular)

4. Compare observed waveform characteristics with expected values from the Pre-Lab design and simulations. Record any differences observed

Milestone-4

Prelab

1. Simulations are first-hand written, and values of resistors and other required components are calculated for both required frequency ranges using the frequency value provided by our TA
2. Based on the design specifications, our previous waveform generator schematic is redesigned by hand to meet the requirements for frequency Range #1 (fx = 3100 Hz)
3. The same process in step 2 is repeated, except for Range #2 (fx = 3100/5 = 620 Hz)
4. Handwritten design is assembled on multisim to simulate and capture the necessary waveforms for the design
5. Use the oscilloscope tool in multisim to observe the Range # 1 and #2 outputs and the inputs with varying Vc; {Vc = 1, 2, 3, 4, 5 V}. Measure, record, and capture the:
    a. |+Vtrig| (+) , |-Vtrig |(-), Vsquare +/-(Output) , f_x
    b. Amplitude of the waveforms
    c. Waveform shape (e.g., square, sine, or triangular)

In-Lab Verification

1. Assemble the Range #1 circuit, following the design specifications from the Pre-Lab.
2. Connect a ±12V power supply to the circuit.
3. Use an oscilloscope to observe the output and the input with varying Vc; {Vc = 1, 2, 3, 4, 5 V}. Measure, record, and capture the:
    d. |+Vtrig| (+) , |-Vtrig |(-), Vsquare +/-(Output) , f_x
    e. Amplitude of the waveforms
    f. Waveform shape (e.g., square, sine, or triangular)
4. Assemble the Range #2 circuit, following the design specifications from the Pre-Lab.
5. Repeat Step 3.
6. Compare observed waveform characteristics with expected values from the Pre-Lab design and simulations. Record any differences observed

6. **Results and Observations of All Milestones**

Milestone-1

This first portion of the project was aimed at designing a fixed-frequency waveform generator capable of producing square and triangular wave outputs. To accomplish this, we needed to construct an inverting integrator and a non-inverting bistable multivibrator. In the pre-lab, we were tasked with building and simulating these two circuits to observe their output waveforms. The actual circuits used in the lab consisted of one LM741CN and LM318CP op-amps, resistors, and a 0.01 µF capacitor, arranged according to specific design requirements. The results and observations from the in-lab measurements were then compared to the pre-lab simulation data.

Lab Prelab Parameters

- Output voltage level: 4Vpeak
- Power Supply: +/-12V d.c.
- Op-Amp output saturation level: +10.5V/-10.5V

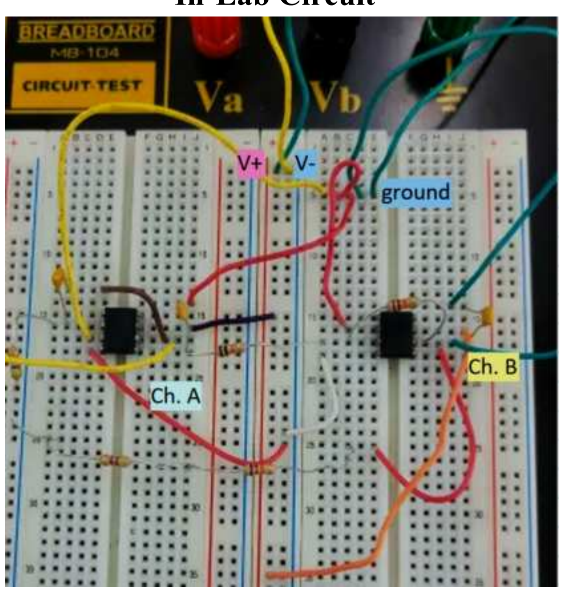
Given fX = 3100Hz
Calculated R = 21.169 kOhms
Calculated R1 = 10 kOhms
Calculated R2 = 26.25 kOhms
C0 = 0.01 uF

Lab Parameters

given fX = 3100Hz
R = 21.4 kOhms
R1 = 10 kOhms
R2 = 27 kOhms
C0 = C1 = C2 = 0.01 uF

Experimental Results and Observations

In-Lab Circuit



Fixed-Frequency Waveforms

The goal of milestone 1 was to design and implement a fixed frequency waveform generator and to verify the design through testing of the circuit via the oscilloscope to measure and observe the frequency and the peak-to-peak voltage values of the input and output waveforms (as shown above).

In-Lab Results Table 1.0

R	R1	R2	C	Measured VTH	Measured VTL	Measured L+-	Measured fx
21.4 kOhms	**10 kOhms**	**27 kOhms**	**0.01 uF**	+4.7 V	-4.7 V	+/- 11.85 V	3.0476 kHz

Percent Error WRT Designed Values Table 1.1

R	R2	R1	R	VTH / VTL	L+-	fx
ex. calculation |(21.169 - 21.4)/(21.169)|* 100 % = 1.09 %	2.86 %	0 %	1.09 %	17.5 %	12.86 %	1.72 %

Milestone-2

The objective of this portion of the project was to design and implement a fixed-frequency waveform generator with the addition of a diode limiter. Following the successful integration of the diode limiter, the output signal from the bistable multivibrator was observed to analyze the effects of the limiter on the waveform. Additionally, a DC to ±DC converter was constructed using a digital switch, with both the input and output signals measured using an oscilloscope. Before the lab, both circuit designs were simulated to obtain expected output waveforms, allowing for a comparison between simulated and practical results. Any deviations observed between the two can then be discussed and analyzed.

Prelab Parameters

- Output voltage level: 4Vpeak
- Power Supply: +/-12V d.c.
- L+/L- : +6.3V/-6.3V

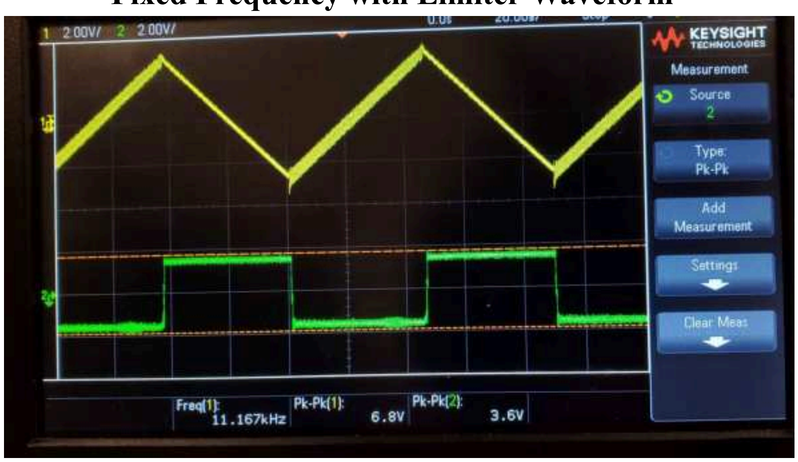
Given fX = 3100Hz
Calculated R = 12.47 kOhms
Calculated R1 = 40 kOhms
Calculated R2 = 62 kOhms
Calculated R3 = 570 Ohms
C0 = 0.01 uF

Lab Parameters

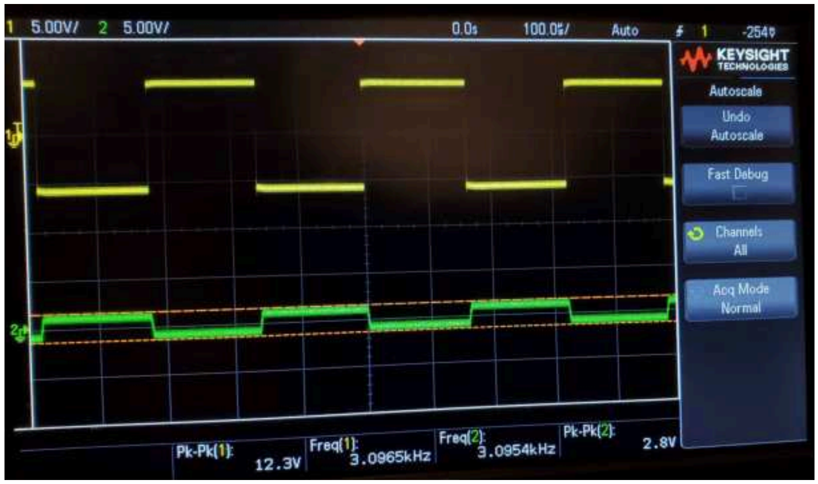
fX = 3100Hz
R = 12.47 kOhms
R1 = 40 kOhms
R2 = 62 kOhms
R3 = 570 Ohms
C0 = 0.01 uF

Experimental Results and Observations

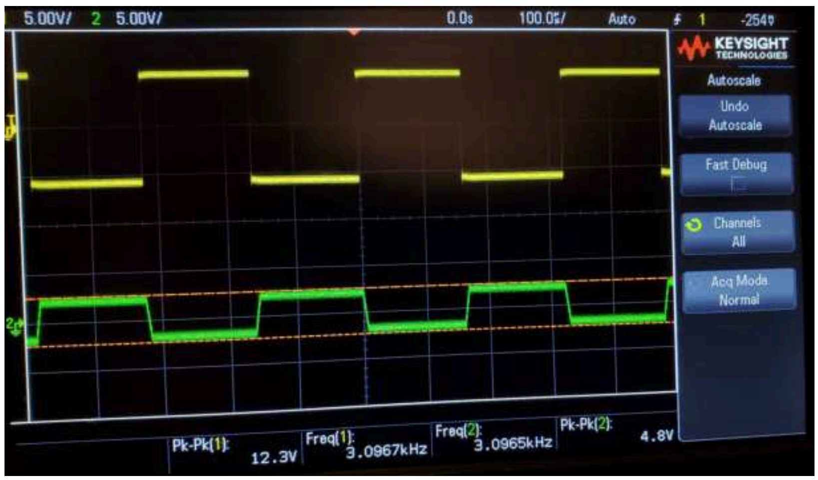
Fixed Frequency with Limiter Waveform



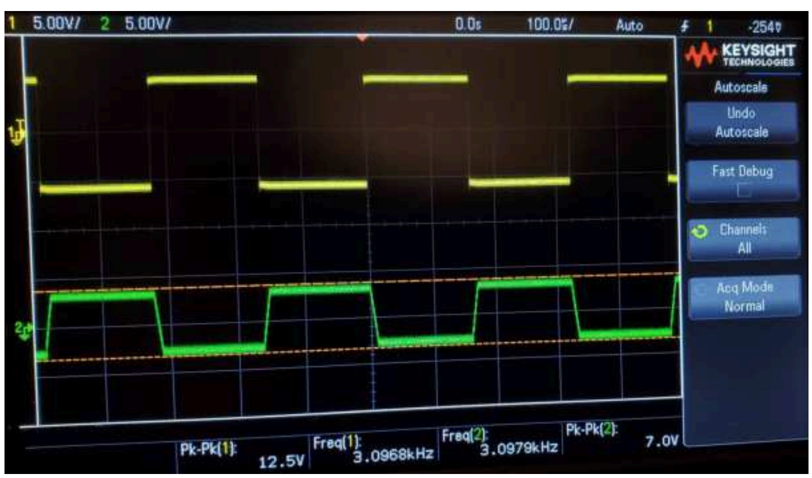
DC-to-+/-DC Converter Waveform - Vc = 1V



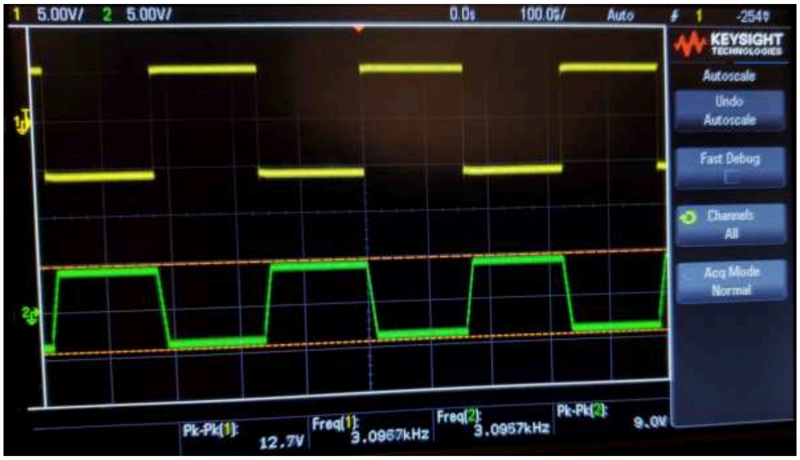
DC-to-+/-DC Converter Waveform - Vc = 2V



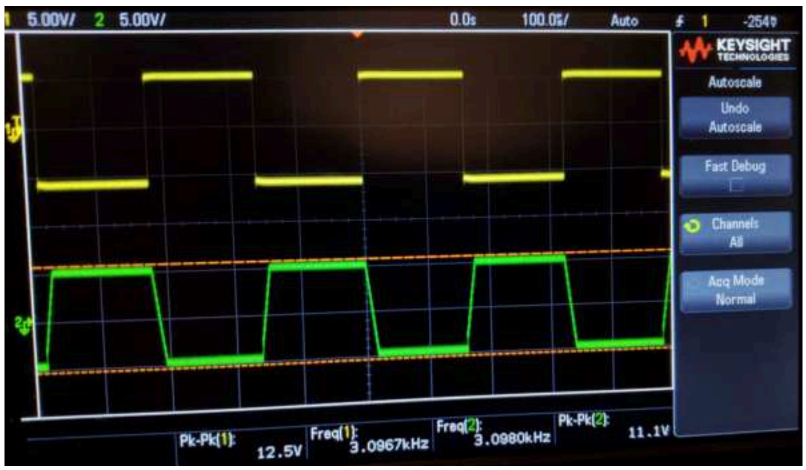
DC-to-+/-DC Converter Waveform - Vc = 3V



DC-to-+/-DC Converter Waveform - Vc = 4V



DC-to-+/-DC Converter Waveform - Vc = 5V



<u>In-Lab Results</u>

Table 2.1

Measured VTH/VTL	Measured L+-	Measured Fx
+-3.6V	+/- 3.4 V	11.167kHz

Table 2.2

Vc =*X*, R1-4 = 1 kOhm, R=10 kOhm, Vs = +-6.3, fx= 3.0967kHz	+Vo	-Vo
Vc = 1V	1.4V	-1.4V
Vc = 2V	2.4V	-2.4V
Vc = 3V	3.5V	-3.5V
Vc = 4V	4.5V	-4.5V
Vc = 5V	5.55V	-5.55V

Comparison of In-lab and Prelab Results

Table 3.1

	C	R	R1	R2	R3	Vth	Vtl	L +	L -	Fx
Prelab	0.01 uF	12.47 K Ohms	40 K Ohms	62 K Ohms	570 Ohms	4.065 V	-4.065 V	6.3	-6.3	3.1 kHz
Sim	0.01 uF	12.47 K Ohms	40 K Ohms	62 K Ohms	570 Ohms	3.677 V	3.677 V	6.207	-6.207	3.1 kHz
In Lab	0.01 uF	12.47 K Ohms	40 K Ohms	62 K Ohms	570 Ohms	3.4 V	3.4 V	1.8	-1.8	11.167 kHz

Table 3.2

	R1 - R4	R	+Vo	-Vo	Vs	Fx
PreLab	1 K ohms	10 K ohms	12 V	-12 V	+/- 6.3 V	3.1 kHz
Sim	1 K ohms	10 K ohms	10.615 V	-10.615 V	+/- 6.3 V	3.1 kHz
In Lab	Vc = 1 V	10 K ohms	1.4V	-1.4V	+/- 6.3 V	3.0967 kHz
	Vc = 2 V	10 K ohms	2.4V	-2.4V	+/- 6.3 V	3.0967 kHz
	Vc = 3 V	10 K ohms	3.5V	-3.5V	+/- 6.3 V	3.0967 kHz
	Vc = 4 V	10 K ohms	4.5V	-4.5V	+/- 6.3 V	3.0967 kHz
	Vc = 5 V	10 K ohms	5.55V	-5.55V	+/- 6.3 V	3.0967 kHz

<u>Percent Error WRT Designed Values (Part a)</u>

R	R	R1	R2	R3	VTH / VTL	L+-	fx
ex. calculation |(21.169 - 21.4)/(21.169)|* 100 % = 1.09 %	0 %	0 %	0 %	0 %	19.56 %	71.42 %	72.24 %

<u>Percent Error WRT Designed Values (Part b)</u>

R	R1 - R4	R	-Vo (using Vc = 1 V here for both in lab and pre lab)	+Vo (using Vc = 1 V here for both in lab and pre lab)	Vs	fx
ex. calculation |(21.169 - 21.4)/(21.169)|* 100 % = 1.09 %	0 %	0 %	28.43 %	28.43 %	0 %	0.107 %

Milestone-3

The objective of this part was to design and implement the linear voltage-controlled waveform generator developed in Milestone 2, with the addition of a DC to ±DC converter. Circuits were tested individually, where the DC converter received a signal from the function generator. Now both circuits are integrated to create a self-sustaining linear voltage-controlled waveform generator. Based on oscilloscope readings from the in-lab experiments, the results and observations are presented below.

Prelab Parameters

- Output voltage level: 4Vpeak
- Power Supply: +/-12V d.c.
- L+/L- : +6.3V/-6.3V

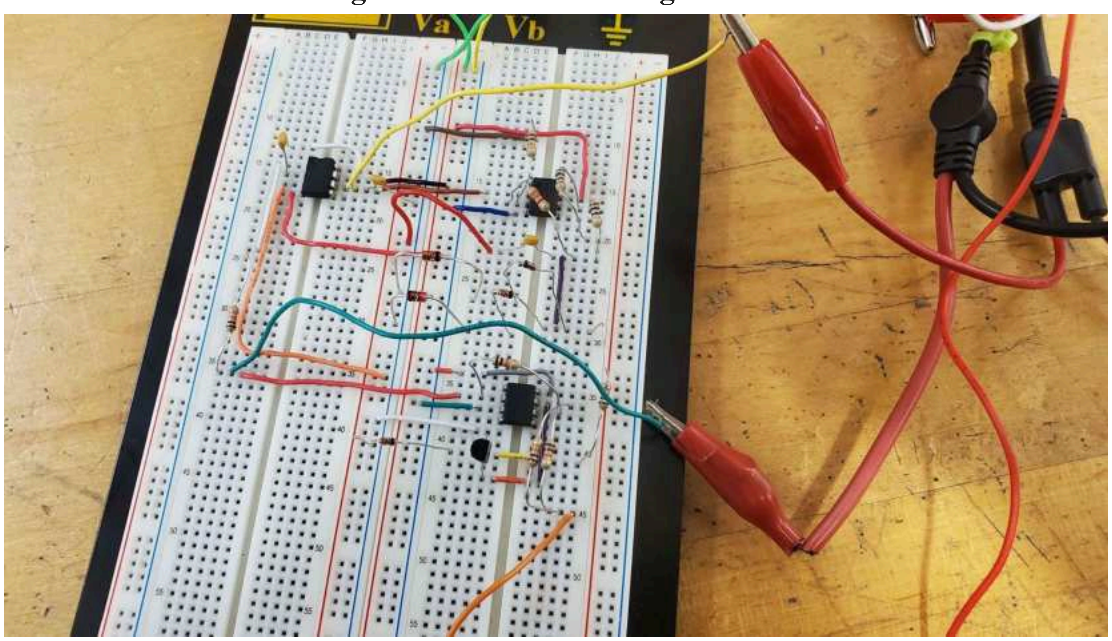
Given fX = 3100Hz
Calculated R = 10 kOhms
Calculated R1 = 4 kOhms
Calculated R2 = 2.3 kOhms
Calculated R3 = 570 Ohms
C0 = 0.01 uF

Lab Parameters

fX = 3100Hz
R = 10 kOhms
R1 = 40 kOhms
R2 = 23 kOhms
R3 = 570 Ohms
C0 = 0.01 uF

Experimental Results and Observations

In-lab Circuit of Linear voltage-controlled function generator with DC to ±DC converter



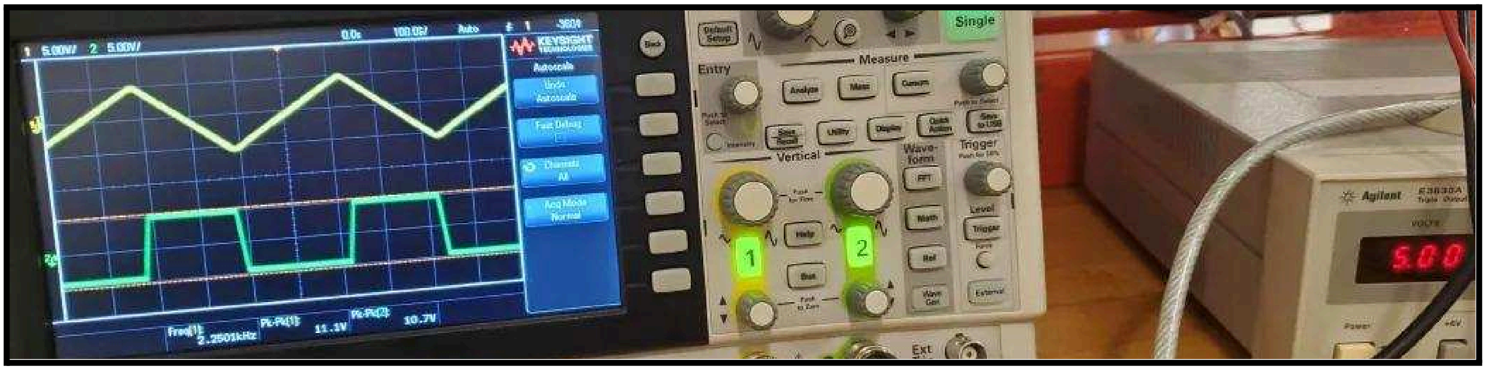
DC-to-+/-DC Converter Waveform - Vc = 1V

Figure 6.0DC-to-+/-DC Converter Waveform - Vc = 2V

DC-to-+/-DC Converter Waveform - Vc = 3V

DC-to-+/-DC Converter Waveform - Vc = 4V

DC-to-+/-DC Converter Waveform - Vc = 5V



<u>In-Lab Results</u>
Table 4.1

Vc =*X*, R1-4 = 10 kOhm, R=560 Ohm, Vs = +-6.3,	|+Vtrig| (+)	|-Vtrig |(-)	Vsquare +- (Output)	Measured Fx (KHz)
Vc = 1V	5.25	5.25	1.305	0.5096
Vc = 2V	5.45	5.45	2.35	1.0344
Vc = 3V	5.4	5.4	3.4	1.5185
Vc = 4V	5.55	5.55	4.4	1.9617
Vc = 5V	5.55	5.55	5.35	2.2501

Comparison of In-Lab and Prelab Results
Table 4.2

	C	R	R1	R2	R3
Prelab	0.01 uF	10 K Ohms	4 K Ohms	2.3 K Ohms	570 Ohms
Sim	0.01 uF	10 K Ohms	4 K Ohms	2.3 K Ohms	570 Ohms
In Lab	0.01 uF	10 K Ohms	40 K Ohms	23 K Ohms	570 Ohms
Percent error	0%	0%	900%	900%	0%

Percent Error WRT Designed Values (DC to Dc Converter)

R	R1 - R4	R	-Vo (Square)(using Vc = 5 V here for both in lab and pre lab)	+Vo (Square) (using Vc = 5 V here for both in lab and pre lab)	Vs (= +/- 6.3 V)	fx (using Vc = 5 V here for both in lab and pre lab)
ex. calculation |(21.169 - 21.4)/(21.169)|* 100 % = 1.09 %	900 %	0 %	6.214 %	6.214 %	0 %	27.416 %

Milestone-4

This final portion of the project implemented a Linear Voltage Controlled Waveform Generator (VCWG) circuit on a breadboard to produce triangular and square wave outputs, with adjustable frequency range and gain control features. Based on prior Pre-Lab analysis, the design is tested against the technical specifications detailed in Section 3.0, focusing on waveform accuracy and stability. To validate performance, the input control voltage (VC) is varied in 1-volt increments, with outputs captured and analyzed to verify alignment with expected waveforms.

Prelab Parameters

- Output voltage level: 4Vpeak
- Power Supply: +/-12V d.c.
- L+/L- : +6.3V/-6.3V

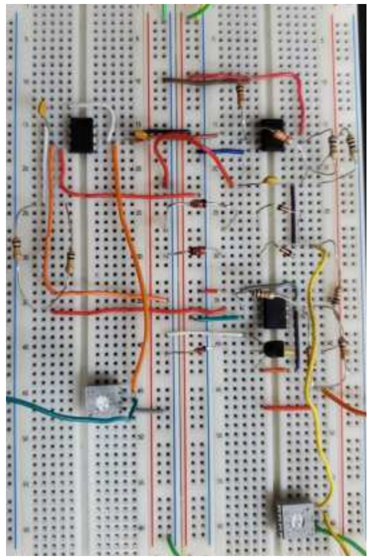
Given fX = 3100Hz
Calculated R = 10 kOhms
Calculated R1 = 4 kOhms
Calculated R2 = 2.3 kOhms
Calculated R3 = 570 Ohms
C0 = 0.01 uF
FRC & GC Circuit

Lab Parameters

fX = 3100Hz (Range #1)
fo = $\frac{3100\ Hz}{5}$ = 620 Hz (Range #2)
R = 10 kOhms (Range #1)
R = 50 kOhms (Range #2)
R1 = 40 kOhms
R2 = 23 kOhms
R3 = 570 Ohms
C0 = 0.01 uF
10k potentiometer

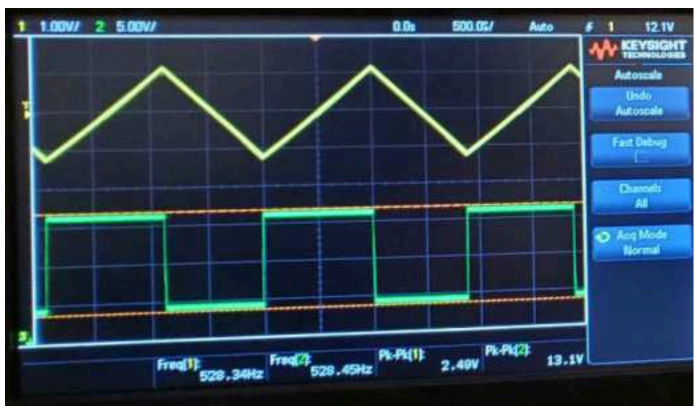
Experimental Results and Observations

In-lab Circuit with Potentiometer

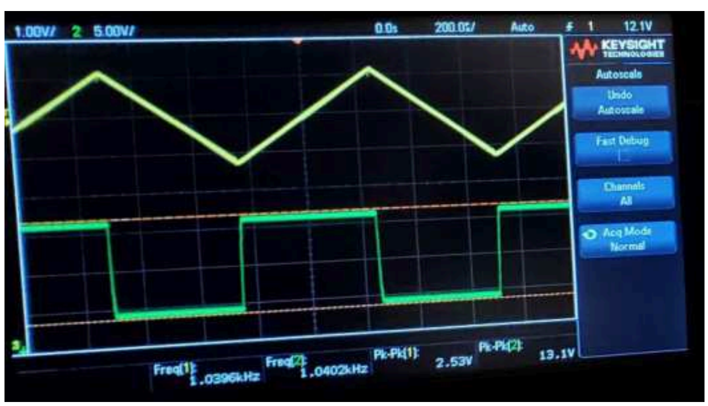


Range #1 waveforms (R = 10 kOhms)

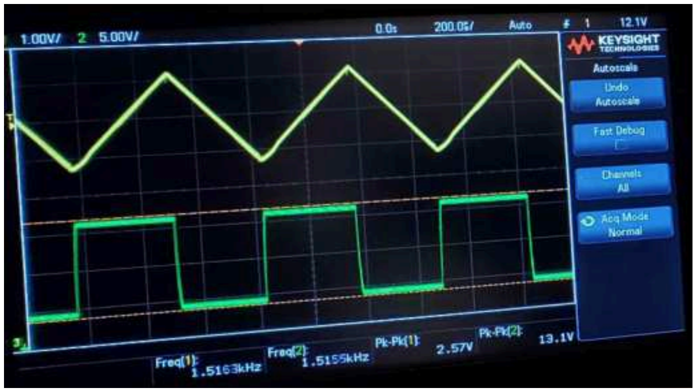
DC-to-+/-DC Converter Waveform - Vc = 1V



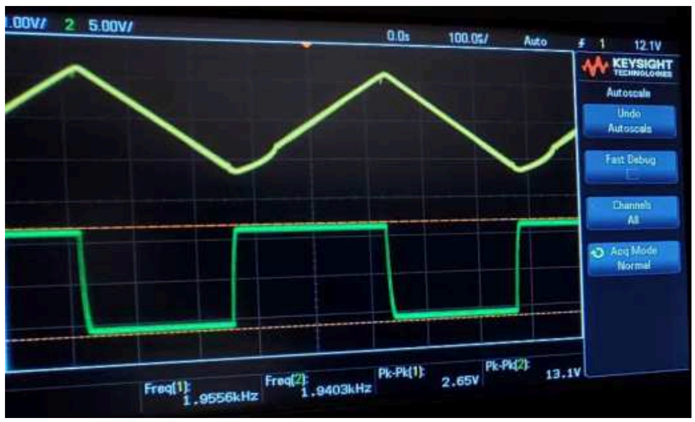
DC-to-+/-DC Converter Waveform - Vc = 2V



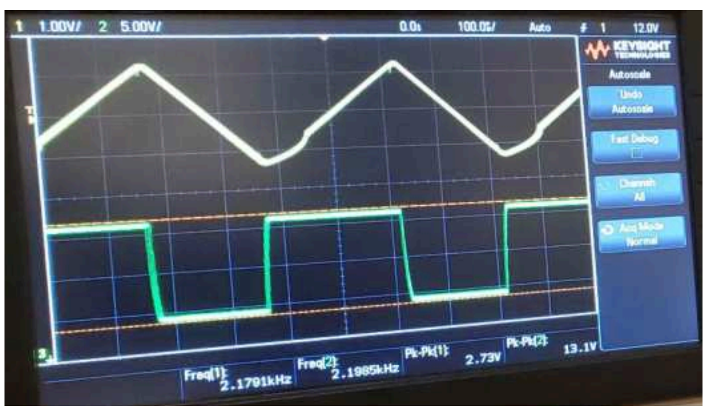
DC-to-+/-DC Converter Waveform - Vc = 3V



DC-to-+/-DC Converter Waveform - Vc = 4V

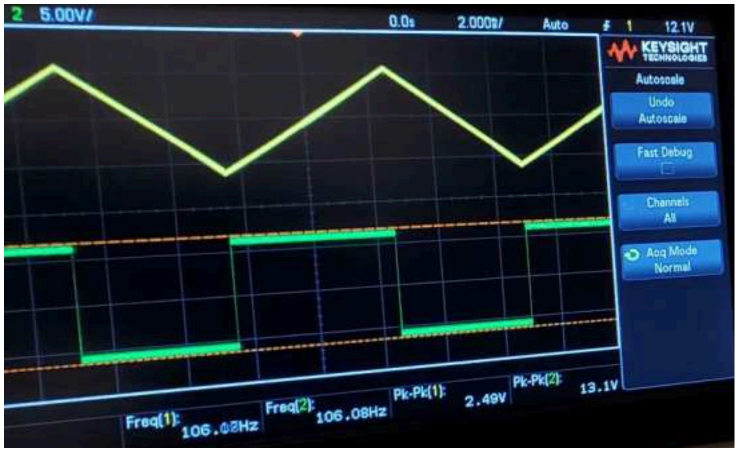


DC-to-+/-DC Converter Waveform - Vc = 5V

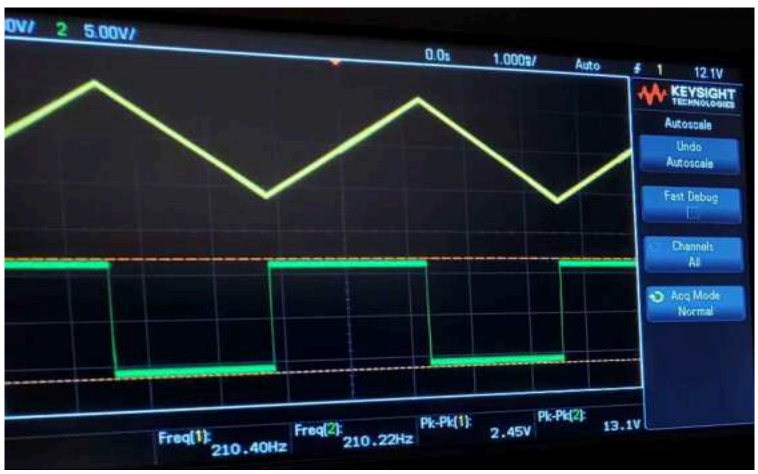


Range #2 waveforms (R = 50 kOhms)

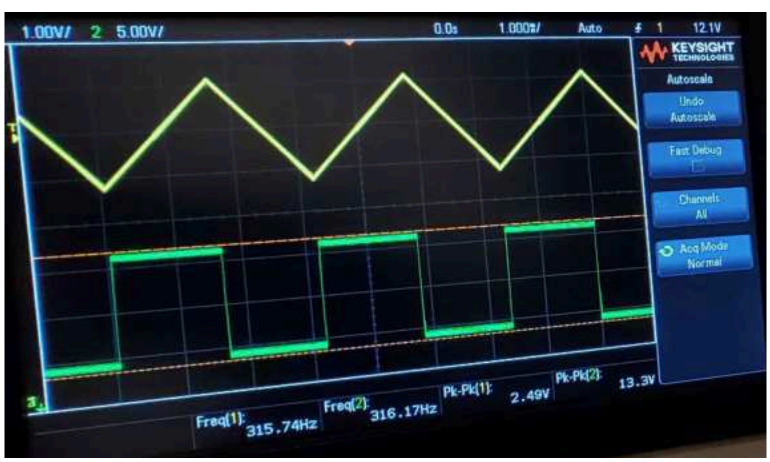
DC-to-+/-DC Converter Waveform - Vc = 1V



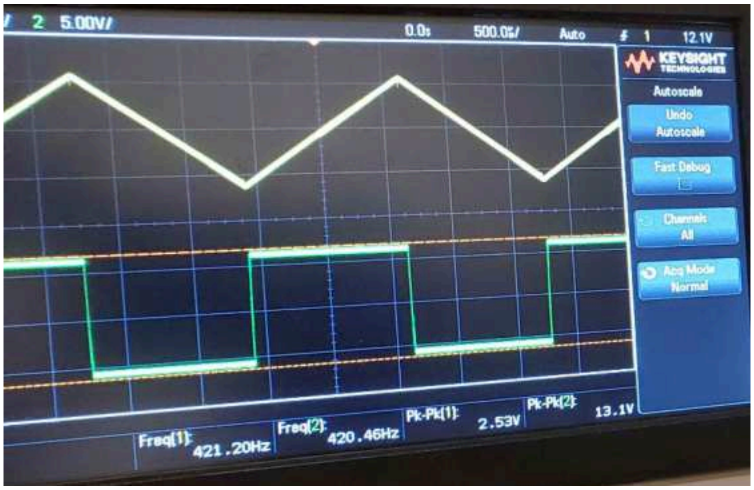
DC-to-+/-DC Converter Waveform - Vc = 2V



DC-to-+/-DC Converter Waveform - Vc = 3V



DC-to-+/-DC Converter Waveform - Vc = 4V



DC-to-+/-DC Converter Waveform - Vc = 5V

<u>In-Lab Results</u>

Table 1

Vc =*X*, R = 10 K ohms, Vs = +-6.3 V	|+Vtrig| (+)	|-Vtrig |(-)	Vsquare +- (Output)	Measured Fx (KHz)	Fx (KHz) (Prelab)
Vc = 1V	1.245	1.245	6.55	0.52834	3.1
Vc = 2V	1.265	1.265	6.55	1.0396	3.1
Vc = 3V	1.285	1.285	6.55	1.5163	3.1
Vc = 4V	1.325	1.325	6.55	1.9556	3.1
Vc = 5V	1.365	1.365	6.55	2.1791	3.1

Table 2

Vc =*X*, R = 50 K ohms, Vs = +-6.3 V	|+Vtrig| (+)	|-Vtrig |(-)	Vsquare +- (Output)	Measured Fx (KHz)	Fx/5 (KHz) (Prelab)
Vc = 1V	1.245	1.245	6.55	0.10608	0.620
Vc = 2V	1.225	1.225	6.55	0.21040	0.620
Vc = 3V	1.245	1.245	6.55	0.31574	0.620
Vc = 4V	1.265	1.265	6.55	0.42046	0.620
Vc = 5V	1.265	1.265	6.55	0.49127	0.620

Comparison of In-Lab and Prelab Results

Table 3

	C	R (S1)	R (S2)	R1	R2	R3
Prelab	0.01 uF	10 K Ohms	50 K Ohms	4 K Ohms	2.3 K Ohms	570 Ohms
Sim	0.01 uF	10 K Ohms	50 K Ohms	4 K Ohms	2.3 K Ohms	570 Ohms
In Lab	0.01 uF	10 K Ohms	50 K Ohms	40 K Ohms	23 K Ohms	570 Ohms
Percent error	0%	0%	0%	900%	900%	0%

Percent Error WRT Designed Values (DC to DC Converter)

R	R1 - R4	R	+/- Vo (Square, R = 10K ohms)	+/- Vo (Square, R = 50K ohms)	+/- Vi (Triangle, R = 10K ohms) (using Vc = 5 V here for both in lab and pre lab)	+/- Vi (Triangle, R = 50K ohms) (using Vc = 5 V here for both in lab and pre lab)	Vs (= +/- 6.3 V)	fx (10 K ohms) (using Vc = 5 V here for both in lab and pre lab)	fx/5 (50 K ohms) (using Vc = 5 V here for both in lab and pre lab)
ex. calculation |(21.169 - 21.4)/(21.169)|* 100 % = 1.09 %	900 %	0 %	6.99 %	6.61 %	210.63 %	216.52%	0 %	29.70 %	20.76%

Analysis of overall frequency control and transfer function

For the frequency control of the circuit design, we must test it for both ranges 1 and 2, but since range 2 is now fo/5, the R-value that is calculated based on the fo value will now change as well. Moreover, the R-value that was calculated is now 50k for range 2 compared to the 10k value that we found for range 1 in milestone 3. After finding both R values and since we have 2 of them, a switch design was created to switch between two resistors utilizing a physical switch. Furthermore, since the frequency values change at each Vc input value, we were able to find the frequency at each Vc through the period of the triangular wave and did f = 1/T and were able to analyze that the frequency increases linearly in comparison to Figure 1.0 in the Major Project Document. Overall, since our results were similar to the figure, we were able to conclude that this milestone was done correctly.

7. Conclusions and Recommendations

For Milestone # 1, all output distortions were solved with two additional 0.01uF capacitors grounded at the two outputs so both waveforms sought from the lab objectives were achieved in-lab. Using different resistor values (R, 1.9% difference WRT pre-lab; R2, 2.89% difference WRT pre-lab) due to equipment restrictions, the amplitude difference between pre-lab and in-lab was 17.5% with a saturation difference of 17.5%. This achieved the goal of maintaining a fixed-frequency design with only a 1.72% difference between in-lab and pre-lab values. Although the range of the observed value differences is acceptable, the changes in resistor values could be the reason behind the differences in the amplitude and frequency values.

For Milestone # 2, all output distortions were solved with the same circuit configurations utilized in the pre-lab, so both waveforms sought from the lab objectives were achieved in-lab. Starting with part a, although there were equipment restrictions, very similar resistor values (R, 0% difference WRT pre-lab; R1, 0% difference WRT pre-lab; R3, 0 % difference WRT pre-lab; R4, 0 % difference) were used between the in lab and pre-lab experiments so very low difference occurred. For the fixed frequency generator with the limiter, the amplitude difference between pre-lab and in-lab was 71.42% with a saturation difference of 71.42%. This did achieve the goal of maintaining a fixed-frequency design however we attained a large difference of 72.24 % difference between in-lab and pre-lab values.

As for the DC to DC converter, although there were equipment restrictions, very similar resistor values (R1 - R4, 0% difference WRT pre-lab; R, 0% difference) were used between the in-lab and pre-lab experiments so very low difference occurred. As for the acquired amplitudes for the pre-lab and in-lab simulations of the circuit, the amplitude difference between the experiments was 28.43% with a saturation difference of 28.43%. This achieved the goal of maintaining a fixed-frequency design with only a 0.107% difference between in-lab and pre-lab values. Overall, although the range of the observed resistor value differences is acceptable, the changes in frequency values could be the reason behind the differences in the amplitude.

By the end of Milestone # 3, the data proved to succeed the objective of designing and implementing the linear voltage-controlled waveform generator, integrating the DC to ±DC converter with the waveform generator. The circuits were successfully combined into a self-sustaining system, and the oscilloscope readings confirmed the functionality of the design. Although the lab results showed a 6.214% error in Vo+/- using a 27.42% frequency difference (for 1 V), this deviation is within an acceptable range for the given experimental conditions. The circuit's overall performance demonstrates the design's effectiveness, and the observed error provides an opportunity for further refinement and optimization.

In conclusion, by the end of Milestone #4, the project experiment analysis showed success in achieving the objective of designing and implementing the linear voltage-controlled waveform generator, integrating the potentiometer for frequency and gain control. The circuits were successfully combined into a self-sustaining system with frequency and voltage operating. The oscilloscope readings confirmed the functionality of the design. Although the lab results showed a 6.99% and 6.61% error in Vo+/- using a 29.70% and 20.76% frequency difference (for 5 V) when R equals 10 and 50 K ohms, this deviation is within an acceptable range for the given experimental conditions. The circuit's overall performance demonstrates the design's effectiveness, and the observed error provides an opportunity for further refinement and optimization. A few steps forward that can be taken for further efficiency are more accurate resistor values to be used in-lab, along with better measuring apparatus, and op-amps with higher slew rates.

Using more accurate resistor values, better measurement tools, and op-amps with higher slew rates would improve the Linear Voltage-Controlled Frequency Generator (LVCFG) circuit's performance in several ways:

- Accurate Resistor Values: Precision resistors with tighter tolerances would minimize variability in resistance, which is crucial in a frequency control circuit where resistance directly influences the output frequency. This would lead to a more predictable frequency output, reducing the likelihood of frequency drift or error, particularly important for circuits that rely on stable and consistent frequency generation.

- Improved Measuring Apparatus: Enhanced measurement tools with finer resolution and reduced noise would allow for more accurate readings of the output voltage and frequency. This would improve the reliability of the data collected, reducing measurement errors that could mask the true performance of the circuit.

- Op-Amps with Higher Slew Rates: A higher slew rate op-amp responds more quickly to changes in input voltage, which can improve waveform fidelity, especially at higher frequencies. This means that the output waveform would more closely match the intended design, with fewer distortions or delays in response time. For a waveform generator, this is particularly beneficial in maintaining signal clarity and stability, as well as reducing response time to voltage changes controlled by the potentiometer.

Together, these improvements would refine the circuit's accuracy, responsiveness, and overall reliability, leading to a more efficient LVCFG that operates with minimal error and enhanced signal quality.

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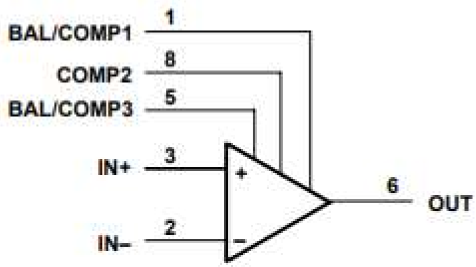
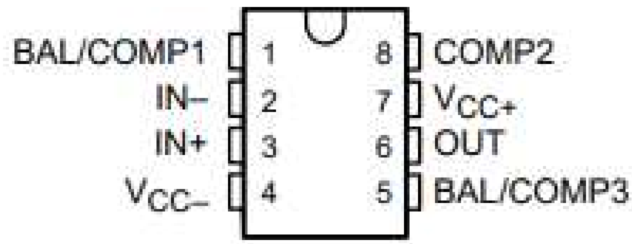
9. Appendix

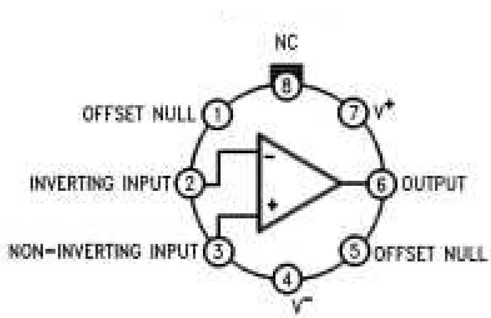
Appendix A - LM318 Operational Amplifier Pinout - Texas Instruments, SLOS063B datasheet



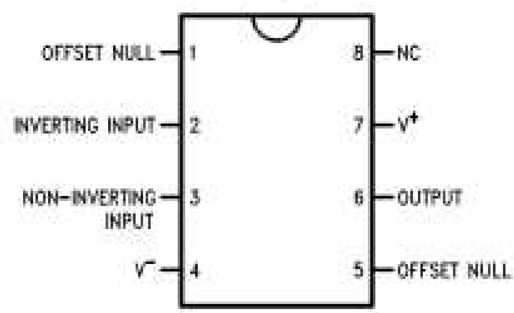


Slew Rate	$T_A = 25°C$, $V_S = ±15V$, $A_V = 1$ (2)	50	70		50	70		V/µs

Appendix B - LM741 Operational Amplifier Pinout - Texas Instruments, SNOSC25D datasheet



LM741H is available per JM38510/10101



Slew Rate	$T_A = 25°C$, Unity Gain	0.3	0.7			0.5			0.5	V/µs

Appendix C - 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

Appendix D - 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