ELE 504 Final Report

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Abstract

The end goal of this project was to construct and implement a "Linear Voltage-controlled Multi-function Waveform Generator" with certain voltage and frequency specifications. This was executed by carefully constructing and testing the different parts of the circuit separately and then finally putting the pieces together to make the final product. These parts included an integrator, bistable multivibrator, DC to +/- DC converter, a digital switch, and potentiometer voltage dividers. The bistable and integrator were both successful in producing square and triangular waveforms with the desired frequency and voltage. The circuit was observed to work as expected until the DC converter was added to the circuit. This is when linearity was observed to not exist as the amplitude and frequency of the output was not accurate when the DC converter input voltage was decreased. The final circuit was successful in producing the desired square waveform amplitude, however failed to produce the expected triangular wave amplitude and frequency for both waveforms. Unfortunately, the specific error for these results was not found however having a testing phase involving just the integrator and DC converter may have helped in getting results.

Objectives

The objective of this project is to design, simulate, construct and test a Voltage-Controlled Oscillator circuit with operational amplifiers, where the output frequency is linearly proportional to the control signal voltage. A symmetrical square wave will be used for the output, there will also be a symmetrical triangular wave output generated within an intermediate step of the circuit. A maximum frequency will be obtained at an input voltage of 5V and should linearly decrease when the voltage decreases by a factor of 'K'. The output voltages of both the triangular and square wave are controlled by a potentiometer with the maximum value being 8V peak-to-peak. All power supplies for operational amplifiers are set to +12V and -12V.

Introduction

The problem to be solved is the need to control an output frequency with an external control signal. There are many programs and uses for this type of circuit; some include a music synthesizer, data encoding and automatic control and measurement. A sound synthesizer is able to create sounds that a conventional instrument can not, allowing a wider range and more versatility to modem music. Data encoding is an important topic that sometimes needs to be performed at a faster pace than the typical or base speed and so by increasing the external signal (the voltage), we can increase the speed at which data is encoded and therefore transmitted.

The approach used for this study is a divide and conquer method. The Voltage-Controlled Oscillator is made up of 4 smaller circuits; them being the DC to +/- DC Converter, the Integrator, the Inverting Bistable and the Digital Switch. Each of these components can and will be analyzed separately ensuring that each of them work independently of each other and produce the correct values. Once each individual circuit works as expected, then we start to combine them and test values to make sure that together they perform as expected and produce the correct outputs.

Theory

First off, the ability to produce a square waveform and a triangular waveform was implemented using a bistable multivibrator (for square wave) and an integrator.

In an inverting integrator, a resistor in the negative terminal and a capacitor in the negative feedback loop is used to create threshold voltages that prevent the output from going past the set threshold limit. The threshold voltages, along with the input voltage amplitude, capacitor value, resistor value, and output frequency are related with the following equation:

$$Fo = L+ / 2(Vth-Vtl)RC$$

where Fo is the fundamental frequency at a value of 4100 Hz and the L+ value is different for each part, Vth is +4V and Vtl is -4V, the capacitor is 0.01uF and the resistance value is calculated based on the given frequency.

In an inverting bistable, the output voltage would saturate to either +Vcc or -Vcc as a positive feedback loop is used. However, a resistor in the positive terminal and the feedback loop can be used to create certain limits that makes sure the output voltage does not change unless the input voltage reaches certain values. In this project, those certain values are the same threshold voltages of the integrator, since the output of the integrator is used as the input of the bistable. This results in a relationship between the integrator's threshold voltages, the saturation voltages of the bistable, and the two resistor values of the bistable as follows:

$$Vth = -R2/R1 * L-$$
$$Vtl = -R2/R1 * L+$$

where L+ and L- are expected output voltage values and Vth and Vtl are +4V and -4V respectively. Given these values, the ratio of resistors is calculated and from this, the individual resistance values are calculated.

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. The voltage between the collector and emitter terminals is approximately 0.2V and

$$ib = (Vb-Vbe)/Rb$$

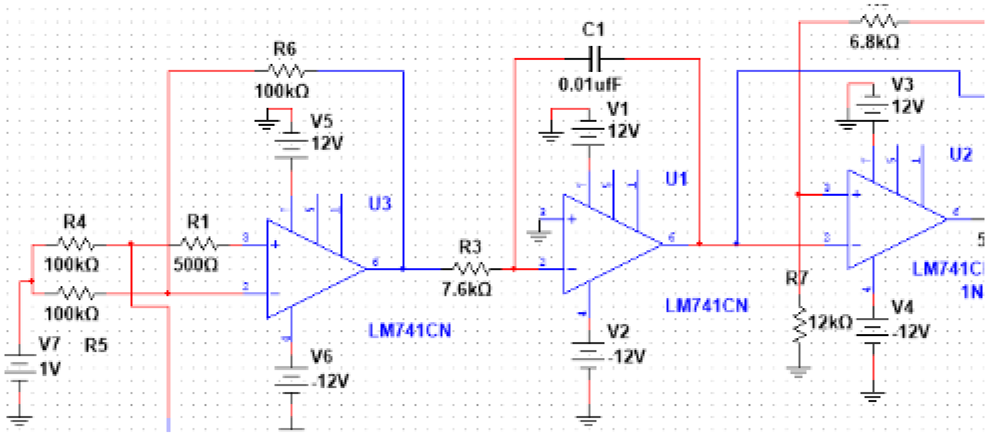
where ib is the base current, Vb is the base voltage, Vbe is the voltage from the base terminal to the emitter terminal and Rb is the base resistance.

During the cutoff mode, the transistor acts as an open circuit. Assuming there is a negative input voltage applied, it is equivalent to a zero-input signal. This occurs when the base voltage is 0 and the BJT is therefore open. There will also be a diode added to the base terminal of the transistor to minimize the voltage. From the datasheet, we know that the maximum voltage between the emitter and base is 6V, the maximum current at the collector is 200 mA and the gain is 100. The voltage entering the BJT base terminal is the output voltage peak values of +6.3V and -6.3V.

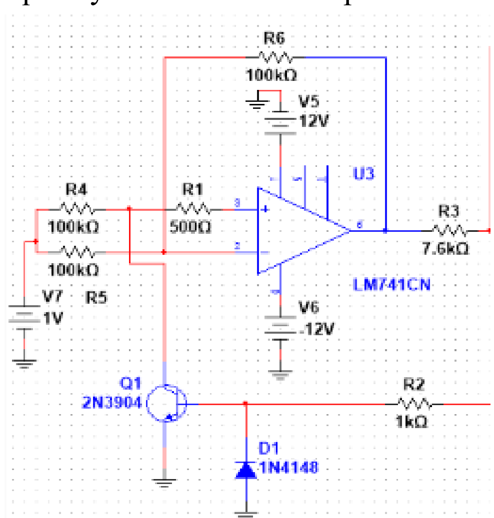
Design Analysis

In order to construct the waveform generator, the different components of the circuit were connected in a specific way.

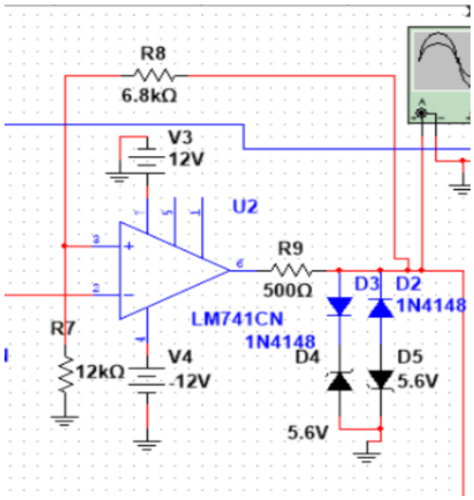
Firstly, the integrator, bistable, and DC converter were all inverting, meaning the inputs were connected to the negative terminal. The output of the DC converter was fed into the negative terminal of the integrator and the output of the integrator was fed into the negative terminal of the bistable. V(c) was the DC input voltage connected to the DC converter and this was essentially the input of the integrator.



In order to create a waveform at the output of the DC converter, a digital switch was connected to the positive terminal. This switch was controlled by the output of the bistable which meant that the frequency of the bistable output was the frequency at which the switch was turned on and off and this helped create a square wave at the output of the DC converter that had the same frequency as the bistable output.



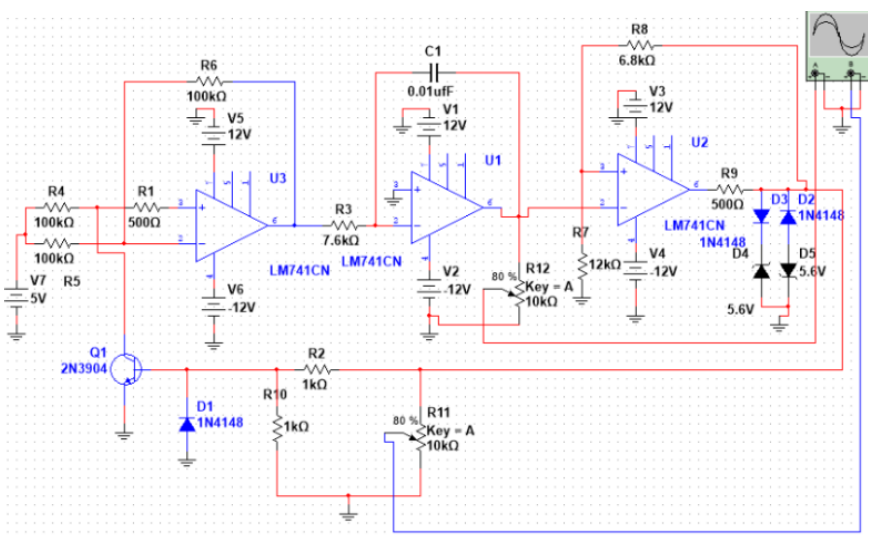
In order to eliminate variation in Vcc from affecting the output of the bistable, two zener diodes and two regular diodes were carefully placed at the output of the bistable to limit the output to 6.3V.



The integrator was used to provide a triangular waveform, while the bistable was used to provide the square waveform. The value of the resistor in the integrator input was determined using the relationship for the frequency discussed in the Theory section where the capacitance was set the 0.01uF, the threshold voltages were set to +/-4V, the frequency was set to the requirement (4100 Hz), and L was replaced with the output of the DC converter (5V). Next the value of the resistors for the bistable were calculated using the second relationship discussed in the Theory section, where L+/L- was replaced with +/-6.3V and Vth/Vtl were set to +/-4V(peak to peak max of 8V requirement).

Finally, the voltage control requirement was met by implementing potentiometer voltage division at both the integrator and bistable outputs. Varying the resistance of the potentiometers would result in triangular and square waveforms where the amplitude can be changed to any value between 0 and 4V(peak). However, it was important that the modified outputs of the integrator and bistable were not fed back into the circuit.

The circuit below is a schematic of the wrestling final circuit design.



Experimental Procedure

The procedure for conducting the experiment is a 4 stage process. The first step is to design the circuit and attain the correct component values to obtain the desired output. The second step is to simulate the circuit using MultiSim and visualize the behavior of the circuit. The third step is to construct the circuit on a breadboard. The fourth step is to test the circuit connecting a power supply and an oscilloscope to measure and visualize the outputs. If the circuit is not performing as expected, the process of troubleshooting starts.

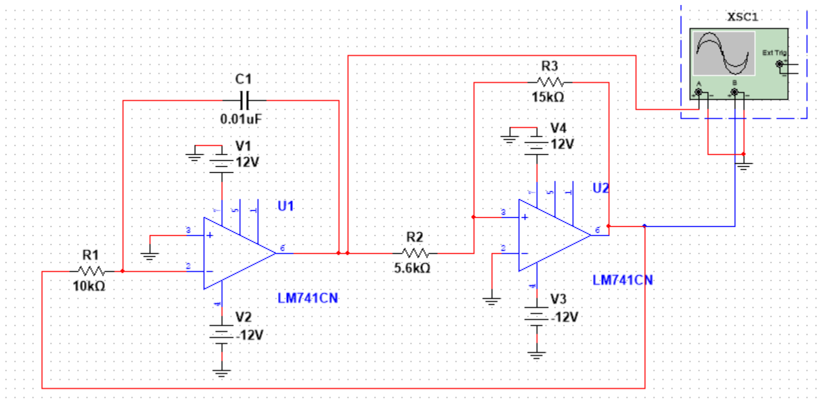
Troubleshooting starts at the simulation phase. The simulation allows the chance to correct any serious errors without harm to circuitry components. For example, if a capacitor is polarized in the wrong direction, it could potentially blow up. The simulation also allows testing for the correct output frequency and voltage and making sure that under ideal conditions, the circuit operates correctly. Once the circuit functions perfectly under simulated conditions, the troubleshooting of the breadboard can begin.

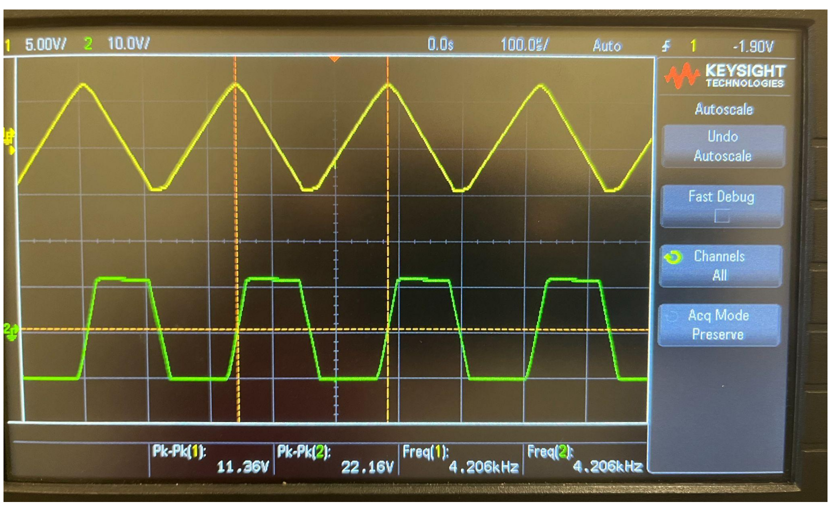
Many problems can arise when using a breadboard. The most common problem is a faulty connection which can occur when the pin of a component or a wire is not making contact with the internal plates or conductors of a bus on the breadboard. Another problem is shorting the circuit by having two components touching each other. For example, two resistors can be connected to a singular voltage source on one side, but have different connections on the other side; if the resistors are touching each other on the opposite side of the voltage source then the connection between them becomes the same, shorting the circuit and causing the circuit to behave incorrectly. Furthermore, a component may simply be broken such as an Op-Amp. The best way to troubleshoot all of these problems is to use a multimeter. With the use of a multimeter, the voltages all throughout the circuit can be tested and compared to the expected values and where they do not match, we can start to troubleshoot that specific part of the circuit.

Results & Observations

The experiment is split up into its constituent components to provide the ability to test and understand the faults in smaller parts. The results are therefore split into the components of the final product.

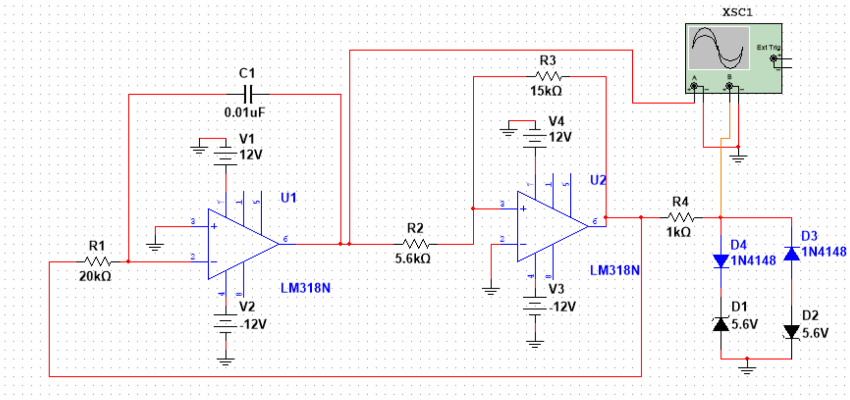
This first circuit and corresponding outputs of the integrator and bistable shows the frequency generator developed in the very first stage of this experiment from an integrator and a bistable. The desired frequency was 4100 Hz.

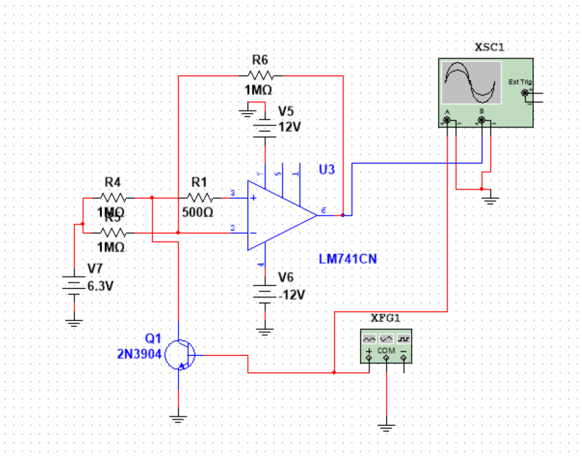




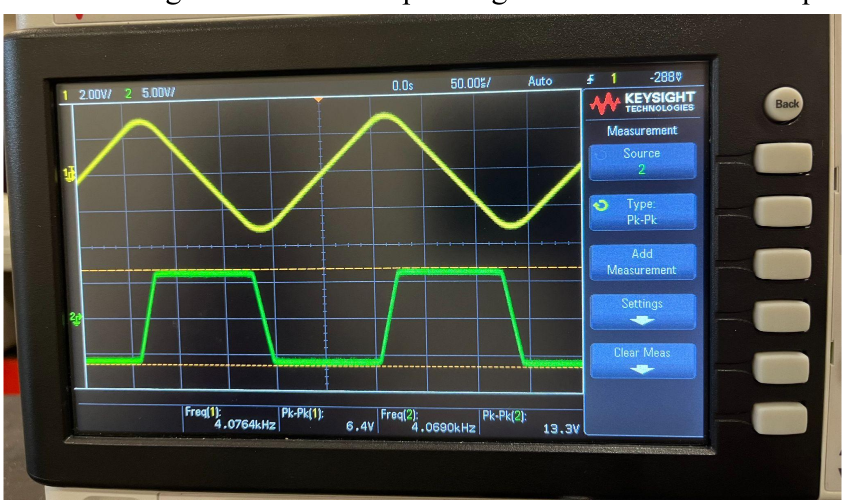
The conclusion of this experiment is by using the Vth and Vtl equations, we can control the peak to peak values of the triangular waveform. The desired output of 4100 Hz was not attainable due to the required resistance not existing in real-life practice.

The second part of the experiment consisted of a continuation circuit of part 1 and a new DC to +/- DC converter circuit. The continuation circuit of the previous part includes adding diodes and zener diodes to the output producing an output voltage with precise peaks of +6.3V and -6.3V but maintaining the required frequency of 4100 Hz. The DC to +/- DC converter circuit consists of an input DC voltage that is variable and a switch built with a transistor.

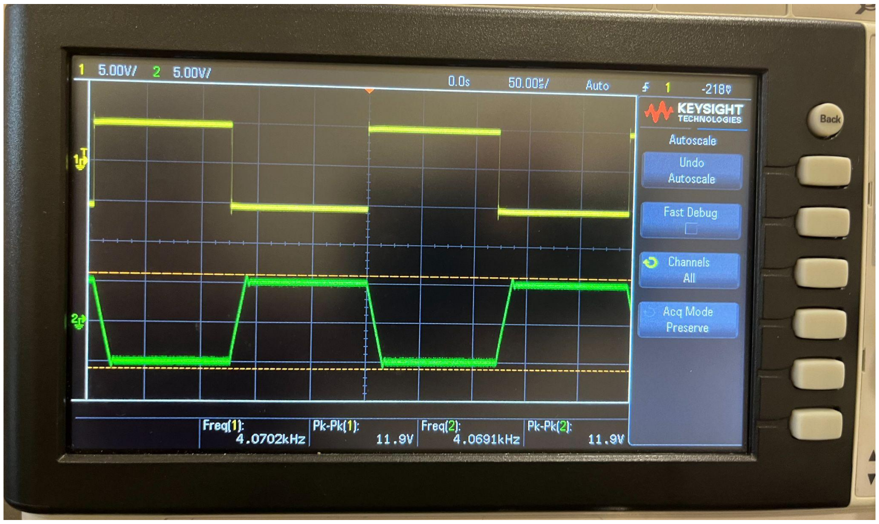




The following shows the corresponding waveforms for the frequency waveform generator.

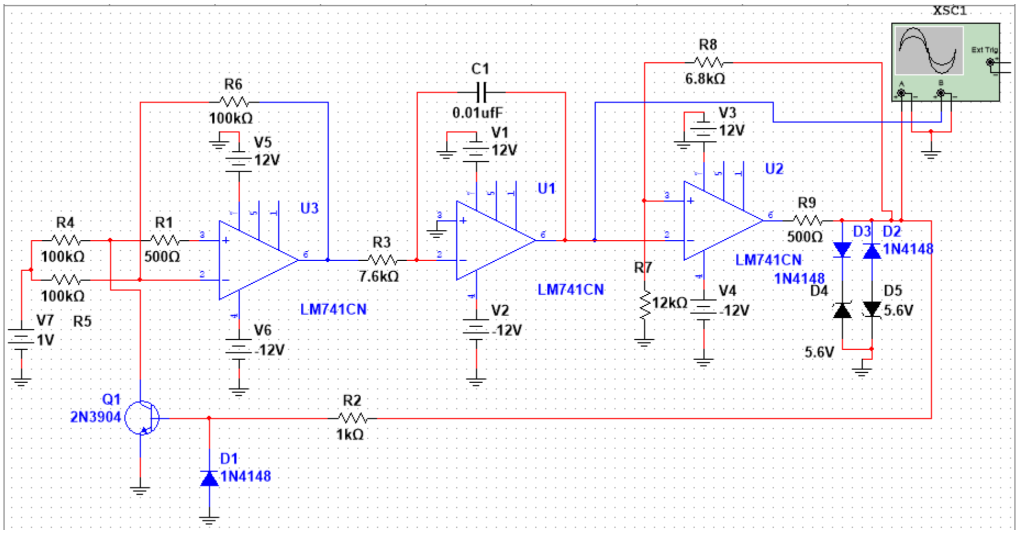


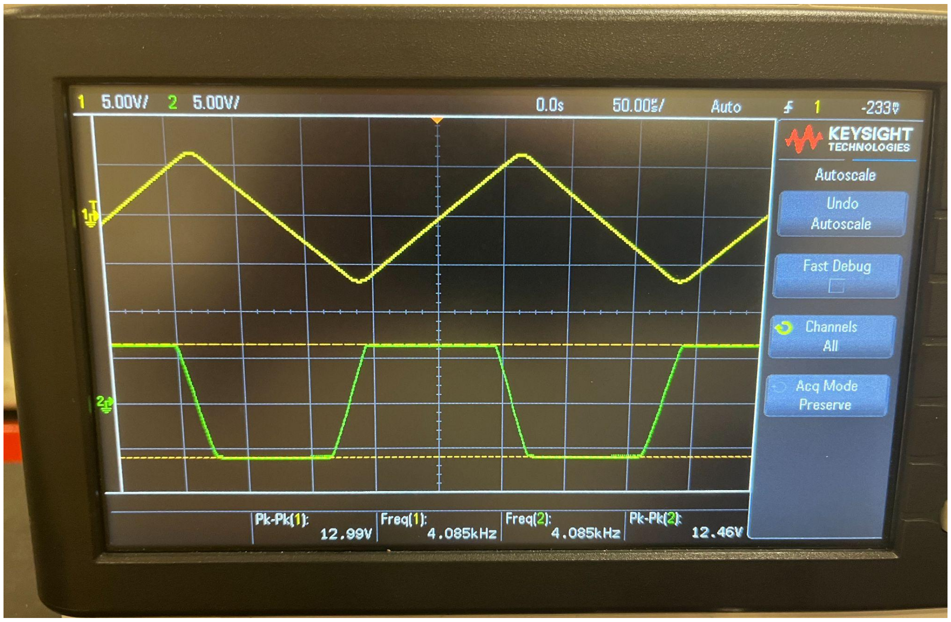
This oscilloscope reading shows the waveforms for the DC converter at an input voltage of 5V.



The conclusion of this experiment is that the frequency generator circuits output peak to peak voltage can be varied with the addition of diodes and zener diodes. The other conclusion would be that the DC converter's output voltage is directly proportional to the input voltage where a decrease in the input voltage will result in a decrease of the output waveform peak value until the input voltage reaches a value of 0V where the output voltage will also have a value of 0V.

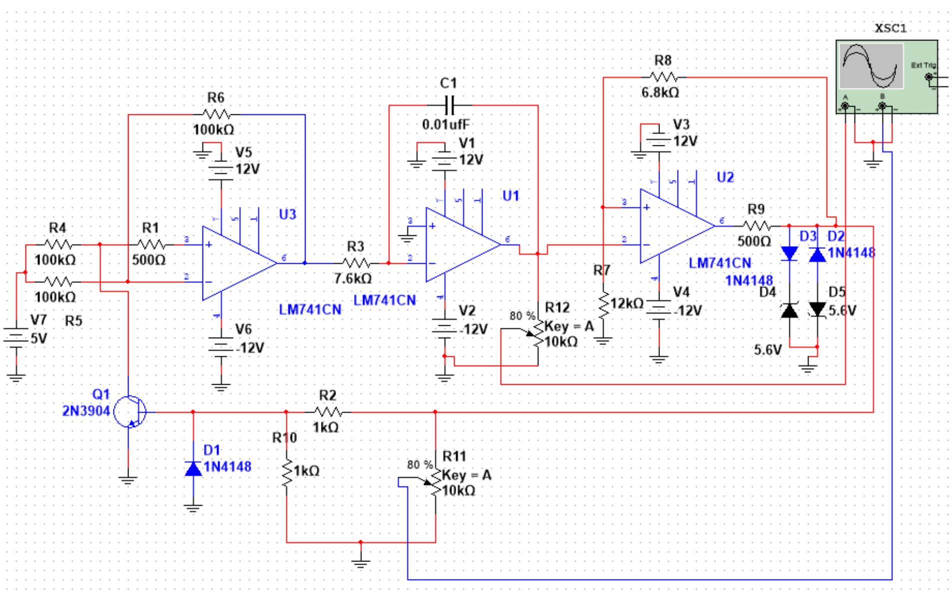
The third part of this experiment is the combination of the DC converter and the frequency generator circuit to create a linear voltage controlled waveform generator that can create a linear relationship between the input voltage and the frequency.



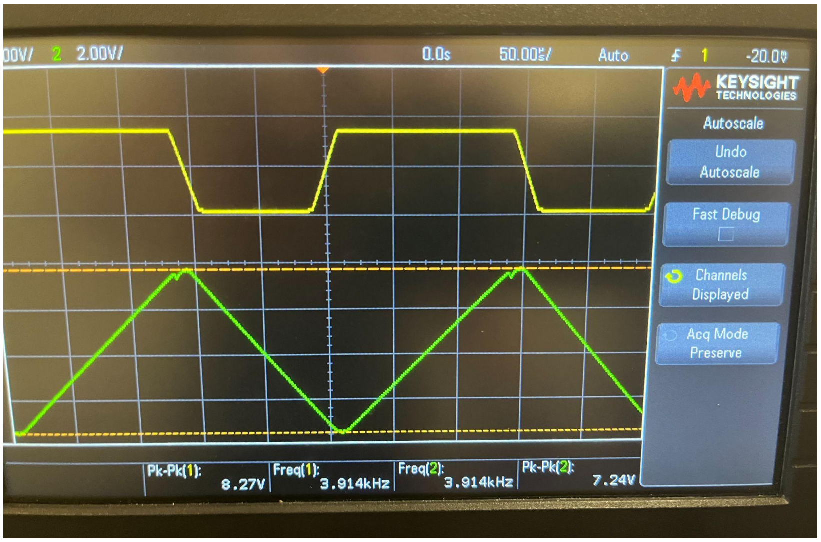


The conclusion of this part of the experiment is that there was an unwanted relationship between the input voltage and output voltage where a decrease in the input voltage would result in a decrease of the output peak-to-peak voltage. After many different tests and changing of components this problem was not solved and is still unresolved. Due to this unforeseen circumstance, the frequency also decreased in a non-linear fashion with a decrease in the input voltage which is also undesirable.

The fourth part of this experiment is the final part where the circuit from step 3 is altered very slightly with the addition of potentiometers at the outputs of the integrator and bistable. This allows us to control the voltages without affecting the frequencies obtained in part 3.



The following oscilloscope screenshots show an input voltage of 5V with a 100% potentiometer value and a 50% potentiometer value.



The conclusions to be drawn from this step is that the circuit exhibited the correct behavior where the potentiometers affected the output voltages in the correct way where the value at 100% is 8V peak-to-peak. Since the problem from part 3 was not resolved, the voltage of the triangular waveform decreases with a decrease in the input voltage and the frequency does not decrease linearly with the decrease in the input voltage.

Conclusions & Recommendations

After conducting the major project and completing the milestones that led up to the final product, some requirements were met while some were not. Firstly, both triangle and square waveforms were produced with a maximum voltage of 4V(peak). Secondly, the initial frequency of 4100 Hz was produced with correct waveforms at the output. The potentiometers also allowed for the output voltage amplitudes to be controlled. The diodes at the bistable also worked in setting the output voltage of the bistable to 6.3V which would prevent variations of Vcc from affecting the output. However, one requirement that was not met was the linearity of the system. As the input of the DC converter (Vc) was decreased, the desired outcome was that the frequency would decrease linearly with Vc. However, the frequency did not decrease linearly after Vc was decreased past 4V. Instead, the circuit ended up decreasing the amplitude of the triangular waveform which was not supposed to happen. Therefore, the frequency control feature did not work properly and the triangular waveform was also incorrect. In the end the root cause for this error was unknown, however it was likely due to miscalculation in digital switch values or component values in the integrator or DC converter. In general, 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 input of the DC converter (Vc) as expected.

References & Bibliography

The reference texts and books used are:

Microelectronics Circuits, by Sedra & Smith, Oxford Press

ELE 504 and ELE 404 Lecture Materials

Datasheets for the different components

Applications of Analog Integrated Circuits, by Sidney Soclof, Prentice Hall

Appendix

- LM741CN Operational Amplifier
- LM318CM Operational Amplifier
- 2N3904 BJT
- 1N4148 Diode
- 5.6V Zener Diode
- DC Power Supplies
- Data Sheets can be accessed at : https://courses.ryerson.ca/d2l/le/content/655773/viewContent/4493001/View
- Multisim files can be accessed at: https://courses.ryerson.ca/d2l/lms/dropbox/user/folders_list.d2l?ou=655773&isprv=0