Theremin Project

ECE291 Sophomore Project

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Fall 2021

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Section 1 – Introduction to The Theremin

Introduction

The Theremin is a unique musical instrument that operates without the use of touch. It typically incorporates two antennas that change the tone and pitch based on the capacitances present on each of the antennas. Thus, the Theremin is played simply by changing the capacitance of the antennas usually by how close the user's hands are to each of the antennas, allowing for smooth, analog transitions between different frequencies and amplitudes.

Originally, the Theremin was invented by a Russian physicist Lev Sergeyevich Termen in 1920 under Soviet government-sponsored research for the development of proximity sensors. His invention was accidental as his research attempted to use sound waves to sense approaching objects, but he found he could manipulate and combine the sound waves to create ominous and intriguing sounds. He began sharing his discovery to pack houses throughout Europe, stunning his audience by creating music seemingly from the thin air, conducting it using slight hand movements in a way that many thought was magical. Eventually he brought his invention to the USA and patented it in 1928 as "The Theremin", after his westernized name, León Theremin. Although the Theremin was not a commercial success, it fascinated audiences throughout the world and continues to do so to this day; it continues to be celebrated by musicians, inventors and musicology enthusiasts alike despite it being a difficult instrument to master, equal to that of its complex electrical construction.

The Theremin that we will be building is much simpler to that of the modern commercial standard. For one, we will only be using a single antenna to change the pitch, whereas the standard Theremin employs two for both tone and pitch modulation. Furthermore, our oscillators will be square waves instead of the preferable sinusoidal waves; the consequence being that there will be sharper bends in the waveforms generated and greater need to filter out the resulting high frequencies. Furthermore, the filters we will be using are quite basic, but will be effective in their purpose to remove unwanted frequencies at the expense of partially degrading desirable frequencies. In terms of audio output, the processed waveform will need to be sent to a basic, pre-built amplifier circuit that can output the sound though a 12v basic speaker.

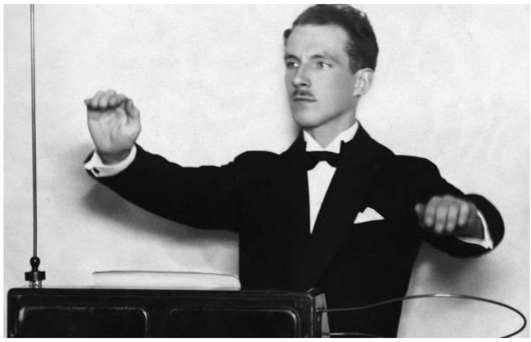


Figure A: León Theremin playing his Theremin

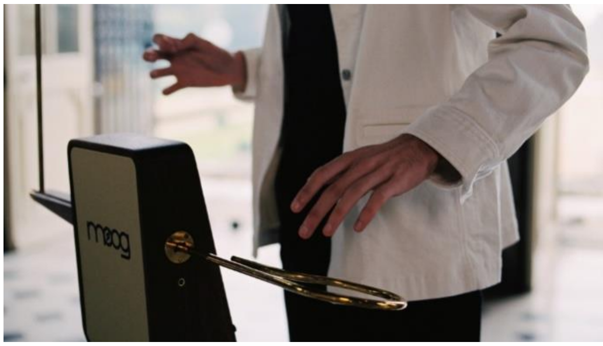


Figure B: A Modern Theremin

Section 2 –Theory

Theremin Block Diagram Overview

The general block diagram of the Theremin will be shown below. The Theremin for this semester's projects will **NOT** include the following components: the volume antenna, its variable oscillator, the frequency to voltage converter, and the voltage-controlled amplifier.

The Theremin will consist of two oscillators, one stationary, one variable, an envelope detector to extract the envelope of the beat frequency, an amplifier to amplify the envelope, and an active low-pass filter to attenuate high frequency noise.

Each block of the Theremin will be more thoroughly examined, with its circuit diagram and any relevant equations shown in the following sections below.

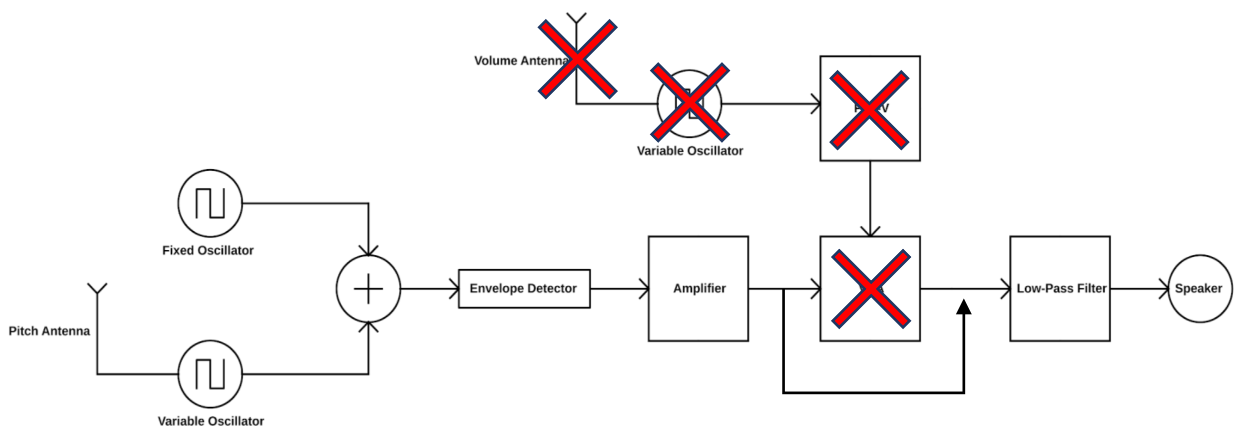


Figure 1: Block diagram of the Theremin (Courtesy of Dean Shay's block diagram)

Theremin Block 1 – Oscillators

Theremin Block 1 consists of a fixed frequency oscillator and a variable frequency oscillator; both implemented using the LM311 Differential Comparator IC. The LM311 outputs an approximate square wave will be directed towards a LF411 JFET Operational Amplifier IC operating as a voltage buffer.

The frequency of the variable frequency oscillator is controlled by the Theremin antenna, which acts as one plate of a capacitor. By moving the Theremin controller's hand closer or farther from the antenna results in a change in capacitance. This change in capacitance is what allows the variable frequency oscillator to change its frequency.

Due to the LF411 encountering operating problems when given an input voltage swing similar to its power supply, the LM311 approximate square wave will first be sent through a voltage divider which will reduce the Vpp of the input signal to voltage swings the LF411 can accommodate.

In addition, due to the observation of LF411N variant's low slew rate,LF411CP was used in replacement of the LF411N due to its higher slew rate and response times to changes in input signals.

The relationship between V_osc2 and V_osc2raw can be quickly derived because the 51k and 100k resistor forms a voltage divider. By using the voltage divider equation, we obtain the following equation shown below. Since the LF411 is operating in voltage buffer mode, it has a unity voltage gain. This means that V_osc2F will have the same value as V_osc2.

$$V_{osc2} = \frac{R_8}{R_7 + R_8} V_{osc2raw}$$

The circuit diagram for this block will be shown on the next page.

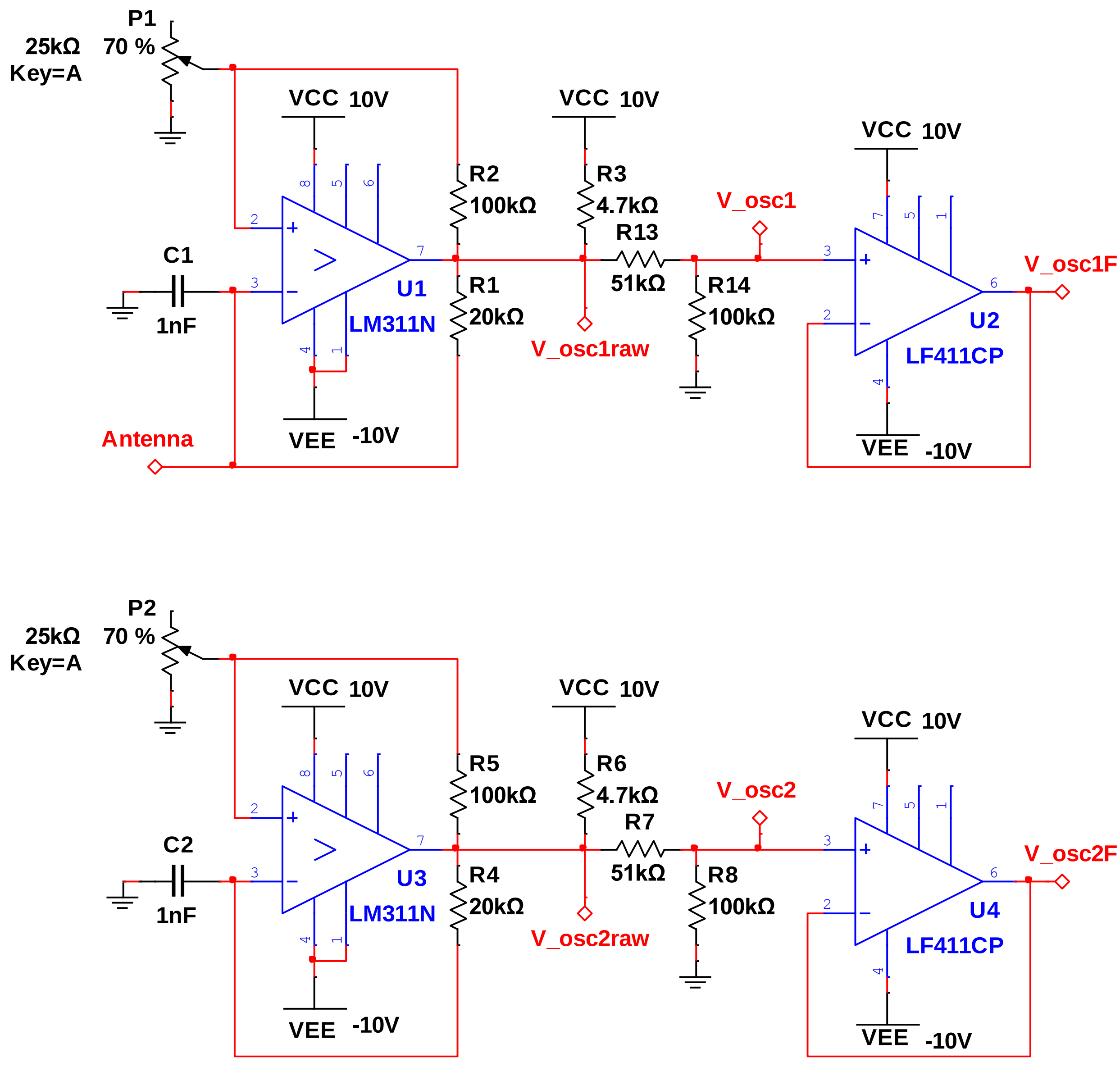


Figure 2: Circuit diagram forstationary and variably frequency oscillators

Theremin Block 1.1 – AC Signal Coupling

Theremin Block 1.1 consists of two AC coupling capacitors connected to the outputs of the voltage buffers from the first block to generate a beat frequency based on the difference in frequency between the fixed and variable frequency oscillator. The beat frequency is then directed towards another LF411 operating as a voltage buffer.

The circuit diagram for this sub-block will be shown below.

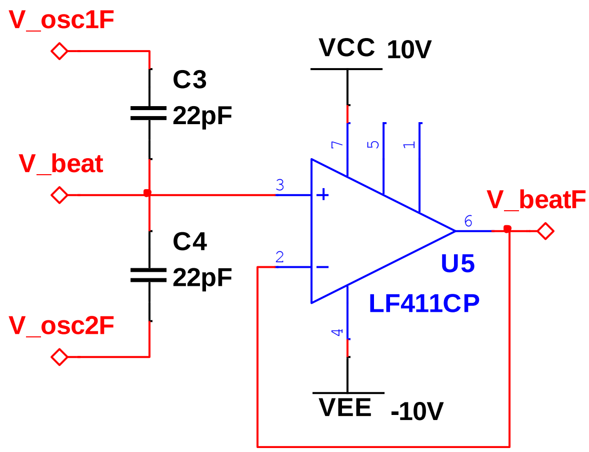


Figure 3: Circuit diagram for AC coupling two oscillator signals

Theremin Block 2 –Envelope Detector

Theremin Block 2 consists of a diode and a RC power dissipation circuit (passive lowpass filter) which serves as the envelope detector for the incoming beat frequency. The envelope detector will attempt to track the envelope of the incoming signal.

The circuit diagram for this block will be shown below.

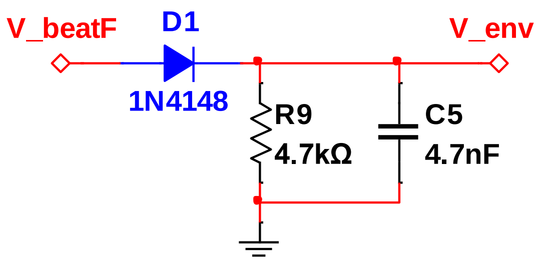


Figure 4: Circuit diagram for envelope detector

Theremin Block 2.1 –AC Coupling and Floating Input Nullification

Theremin Block 2.1 consists of an AC coupling capacitor, a pull-up and pull-down resistor. While the capacitor removes any DC offset from the input signal, the pull-up and pull-down resistors ensure that any floating input will be tied to GND, thereby eliminating any possibility of floating noise being propagated through the rest of the circuit.

The circuit diagram for this block will be shown below.

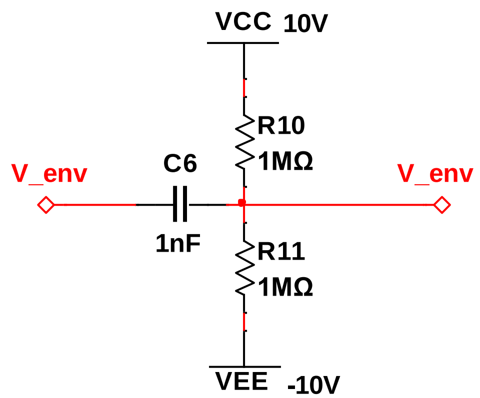


Figure 5: Circuit diagram of AC coupling capacitor, and pullup/pulldown resistor voltage divider

Theremin Block 3 –Non-inverting Amplifier

Theremin Block 3 consists of a LF411 operating as a non-inverting amplifier. This block takes the envelope detector's output and amplifies it.

The circuit diagram for this block will be shown below.

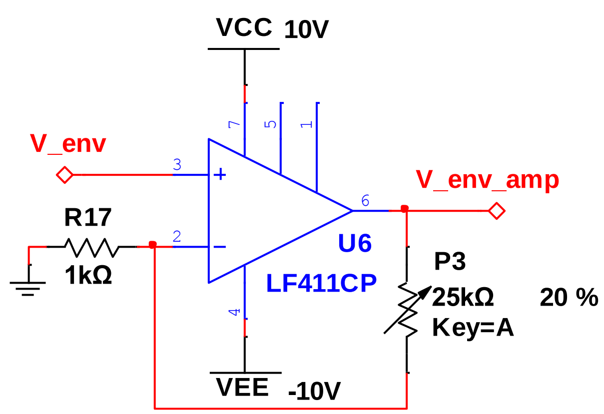


Figure 6: Circuit diagram for non-inverting amplifier

The relationship between $V_{env,amp}$ and V_{env} can be found by using the non-inverting amplifier equation.

$$V_{env,amp} = (1 + \frac{P_3}{R_{17}})V_{env}$$

Theremin Block 4 –Active Low Pass Filter

Theremin Block 4 consists of a LF411 operating as an active low-pass filter. This block takes the amplified envelope detector output and attenuates high frequency noise above a certain cutoff frequency.The circuit diagram for this block will be shown below.

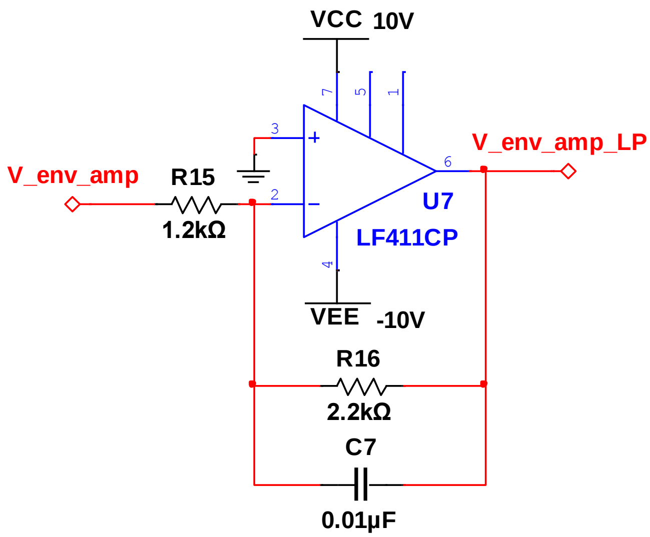


Figure 7: Circuit diagram for active low-pass filter

The transfer function for the active low-pass filter above can be derived by noticing that the OPAMP is set up as an inverting amplifier. The transfer function of an inverting amplifier is shown below.

$$H(s) = \frac{-Z_f}{Z_i}$$

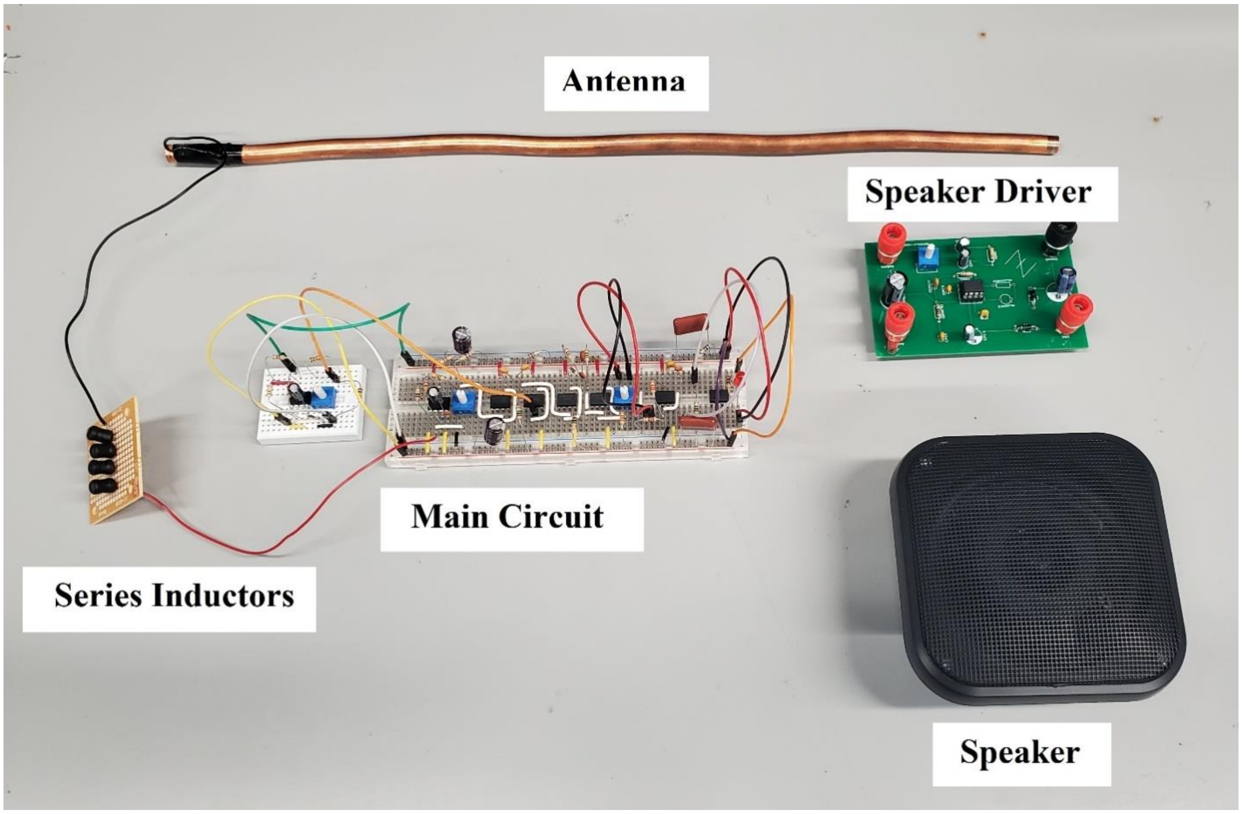
By rewriting the 2.2k resistor and 0.01uF capacitor as a single complex impedance Z_f, and the 1.2k resistor as a single complex impedance Z_i, the transfer function can be simplified to the equation below.

$$H(j\omega) = -\frac{R_{16}}{R_{15}} \frac{1}{1 + j\omega C_7 R_{16}}$$

When analyzing the transfer function, the cutoff frequency can be determined by determining the pole of the transfer function. Because this transfer function only has a magnitude gain and a pole, it can be deduced that this is a low pass filter with a pass-band gain magnitude of 1.83 [V/V] or 5.26 [dB] and a cutoff frequency at 45.45 [krad/sec] or 7.23 [kHz].

Section 3 – Results

Final ComponentLayout



The image above shows the final completed Theremin circuit built on a large and mini sized breadboard. The reason why two separate breadboards were used for the "Main Circuit" was because the two oscillators would have interfered and resonated with each other if they were built on the same breadboard; isolating each oscillator on separate breadboards eliminates this. Further, we decided to add a few larger capacitors on the power rails to smoothen and clean the waveforms generated by the ICs.

Attached to the leg of the potentiometer of one of the oscillators is the wire that feeds to a series of four 10mH inductors which had a total measured inductance of approximately 32mH. These inductors were then coupled in series to the antenna which had a measured capacitance of around 1.33pF.

Finally, the provided "Speaker Driver" was used so that the low power output signal from the final stage of the Theremin (Active Low pass Filter output) can be amplified sufficiently to drive an audio output device. The Audio output device that we used was a standard 12v Speaker.

Theremin Block 1 – Oscillator Results

The images below show the waveforms generated by the LM311 comparators and their corresponding voltage-followers which utilize the LF411.The output frequencies of the comparators were calibrated to 87.50 kHz and 106.02 kHz. The corresponding voltage-follower frequencies were expectedly close to their respective comparators, 88.29 kHz and106.84kHz. We arbitrarily label one set of comparator and voltage-follower as “Fixed Oscillator” and the other set of comparator and voltage-follower as “Variable Oscillator” to demonstrate how the Theremin reacts when the oscillators don’t operate at the same frequency.

Fixed Oscillator:

Variable Oscillator:

Figure 8: LM311comparatorsetup to 87.50kHz

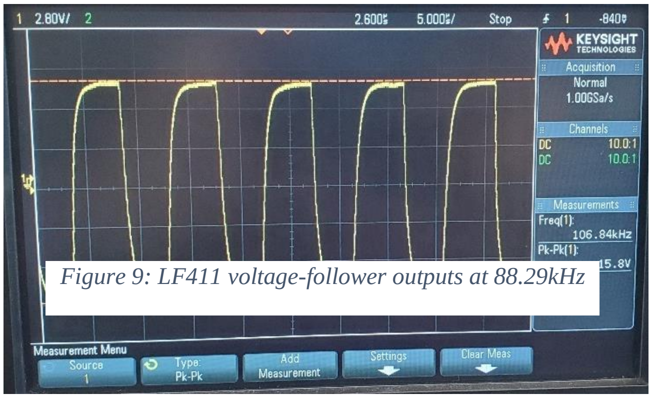


Figure 9: LF411 voltage-follower outputs at 88.29kHz

Theremin Block 1.1 – AC Signal Coupling Results

The picture below shows the resulting beat frequency that is generated due to the adding of the two oscillator outputs. The resulting frequency of the envelope is approximately 17.67 kHz as determined by an Oscilloscope. The beat frequency can also be determined by taking the absolute value of the difference of the two oscillator frequencies. This method calculates a beat frequency of 18.55 kHz based on the output frequencies of the two oscillator outputs on the previous page.

Figure 12: Beat frequency resulting from the combining of the two oscillator outputs

Theremin Block 2 – Envelope Detector Results

The picture below shows the extracted envelope of the beat frequency in the section above.

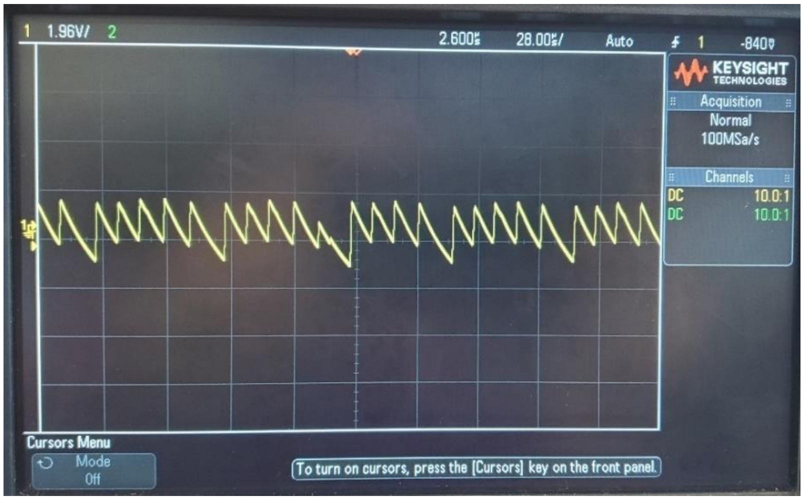


Figure 13: Output of envelope detector from beat frequency

Theremin Block 3 – Non-inverting Amplifier Results

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The picture shows the amplified version of the envelope detector's output.

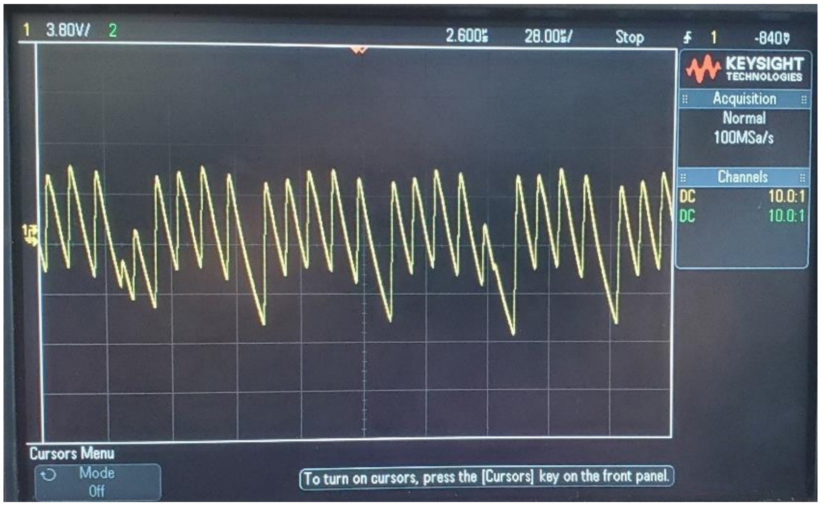

Figure 14: Amplified output of envelope detector

Theremin Block 4 – Active Low Pass Filter Results

The picture shows the amplified signal in the section above being passed through inactive low-pass filter. This signal is used as the audio input signal to drive the Theremin speaker.

Figure 15: Active low-pass filter output

Distance vs. Theremin Output FrequencyTable

Distance from Antenna (cm)	Frequency (Hertz)
4.5	196
3.5	288
2.5	432
1.5	715
0.5	1021

Figure 16: The table above shows how the frequency changes as a person's hand is moved progressively closer to the Theremin. The data shows a strong correlation between the distance the persons hand is and the resulting output frequency. The general trend is such that the frequency output of the Theremin is inversely proportional to the distance at which the operator is from the Antenna.

Section 4 – Conclusion

Project Conclusions

With the conclusion of Sophomore Projects, the process of building the Theremin was a very interesting and involved process that encompassed several important concepts in the EE field including but not limited to, learning to interpret a schematic, understanding and obtaining experience with standard troubleshooting of analog circuits by using oscilloscopes, the process of finding a workaround with various limitations of hardware, and the strategic placement of IC chips on the breadboard. An example of the strategic placement of IC chips, was how we manipulated the basic comparator logic to function as an oscillator output, or how we used amplifiers to build relatively effective filters; both of these examples illustrate the capabilities of an IC are not limited to by its definition, but by the user who can go beyond basic implementations of the IC to build much more complicated circuitry.

Something we found challenging was trying to improve the sound quality of the Theremin which was initially quite unpleasant. We found that setting the oscillator frequencies to be exactly the same, allowed the Theremin to attenuate its output when the user's hands were far away. Another improvement we made was ensuring that the non-inverting amplifier was not becoming overly saturated over time, which would result in a loss of wave definition and ultimately, static-like sound quality. Because we noticed that some of the oscillator outputs were not clean, we decided to add large capacitors on the power rails to compensate for the noise the ICs would generate, ensure clean wave outputs. All of these changes helped to improve the sound quality of our Theremin.

Section 6 – References

References Materials

[1]Magazine, S. (2020, December 3). *The Soviet Spy Who Invented the First Major Electronic Instrument*. Smithsonian Magazine. https://www.smithsonianmag.com/smart news/theremin-100-years-anniversary-instrument-music-history-180976437/

[2]Wikipedia contributors. (2021, December 5). *Theremin*. Wikipedia. https://en.wikipedia.org/wiki/Theremin

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[1] "JFET-Input Operational Amplifier datasheet (Rev. C)," *Texas Instruments*, Oct-1997. [Online]. Available:https://www.ti.com/lit/ds/symlink/lf411.pdf. [Accessed: Dec-2021].

[2] "LM111, LM211, LM311 Differential Comparators datasheet (Rev. K)," *Texas Instruments*, Mar-2017. [Online]. Available:https://www.ti.com/lit/ds/symlink/lm311.pdf. [Accessed: Dec-2021].