Theremin Lab Report

ECE 291 - Sophomore Projects

Kengbo Lu, Nicholas Storniolo, Ridwan Hussain

Dec 15 2022

Table of Contents

Introduction

The theremin is a musical instrument created in 1954 during the Cold War. The instrument was named after its inventor, Leon Theremin, who was a spy for the USSR. The instrument's original use was to send different radio frequencies to measure certain properties of gas. However, Theremin noticed that the audio output changed based on where his body was positioned, making it a unique instrument that can be played without human touch. Although not related to the instrument directly, Theremin had an impact outside of just inventing the theremin. Theremin was able to impress Vladimir Lenin with his instrument and toured Europe and America. However, while touring America, Theremin gained access to factories and patent offices, which helped him as a spy for the USSR [1].

The theremin is a unique instrument because it can be played without direct human contact. To play a theremin, one must move their hands near the vertical bar to adjust the pitch and the horizontal bar to adjust the volume [2]. The purpose of the project was to recreate a theremin with a variable pitch using the knowledge of analog circuits.

[1] "How the Theremin Works," emastered.com, https://emastered.com/blog/how-the-theremin-works, Accessed December 14, 2022.
[2] "60.17 The Electric Guitar," University of California, Santa Barbara, https://web.physics.ucsb.edu/~lecturedemonstrations/Composer/Pages/60.17.html, Accessed December 14, 2022.

Theory

Implementing the functionality of a theremin was done systematically in blocks. Each block of the theremin had a unique purpose and were combined sequentially.

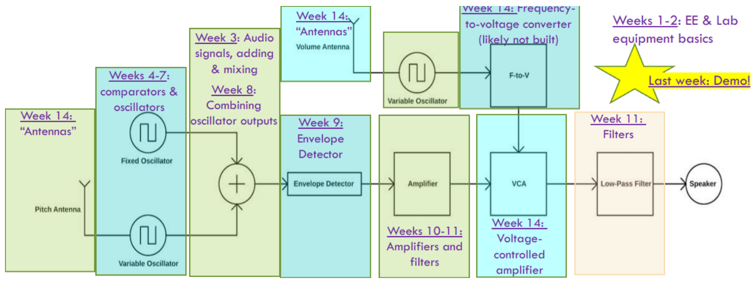

Figure 1: Block diagram of the Theremin. [3]

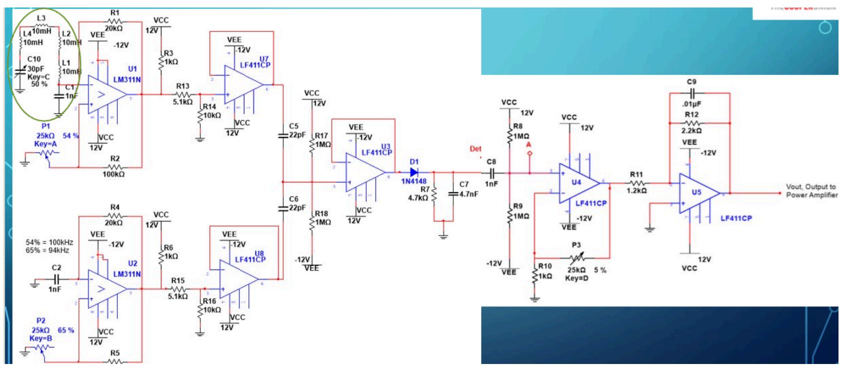
Figure 2: Full diagram of the Theremin built with the pinouts. [3]

These were the final theremin circuit schematics, provided to us by Dean Shay [3]. The circuit mostly consisted of comparators (LM311), amplifiers (LF411), as well as various resistors, capacitors, and potentiometers. In addition, theremin had a pitch antenna (with inductors connected in series) to it. The V_{out} signal was connected to a PCB board that allowed the connection between our audio signal output and the speaker to produce the noise. These PCB boards were provided to us by Dean Shay as well.

The first segment of the system is the antenna, seen in the upper left. The antenna was made purely from inductors and a copper pipe, acting as an extremely small variable capacitor. Despite this model, the antenna also contains an insignificant parasitic resistance, but was still accommodated. This antenna's variable capacitance feeds into an oscillator, causing a change in its frequency. Another, identical oscillator sits opposite to it with a fixed frequency. The frequency is set up so as to match the frequency of the variable oscillator when the antenna is not picking up any capacitance. These two oscillators have their signals sent through voltage buffers (i.e. an amplifier with a gain of unity). These buffers prevent loading, acting to inhibit any feedback. Following the buffers the two oscillators are summed into one signal. From the

[3] L. Shay, "ECE291 - Week 14" presented at the Cooper Union New Academic Building, New York City, NY, November 2022.

properties of waves we can determine the resulting beat frequency:

$$f_1 - f_2 = |f_{Beat}|$$

The theremin signal now comprises only one oscillating signal. Passing through an envelope detector, a circuit consisting of an operational amplifier (op-amp) buffer, a diode, and passive low pass filter to ground. The combination functions as such; while the op-amp's output signal is high the diode conducts, but when the opamp output signal drops low, the diode prevents current flow over it and the capacitor in the filter begins to discharge providing a continued high voltage. This signal passes through an op-amp set up as a non-inverting amplifier. This amplifier controlled the volume of the output signal, with its gain determined by a potentiometer (R_{Pot}) ip to 25k Ω in the following:

$$Gain\ =\ \frac{1 + R_{pot}}{1000}$$

As a last step for the signal, any higher frequency (and unwanted) components to the signal must be removed through a first order op-amp low pass filter. This last major component has a transfer function of the following:

$$H(\omega)\ =-\ \frac{R_{12}}{R_{11}}\ *\ \frac{1}{1+j\omega C_9 R_{12}}$$

Finally, the signal passes off the breadboard section of the theremin. This signal passes through a provided PCB variable amplifier, intended and designed for use with audio signals before passing on an output speaker.

Results

The following figures are pictures of the oscilloscope output for certain blocks of the theremin.

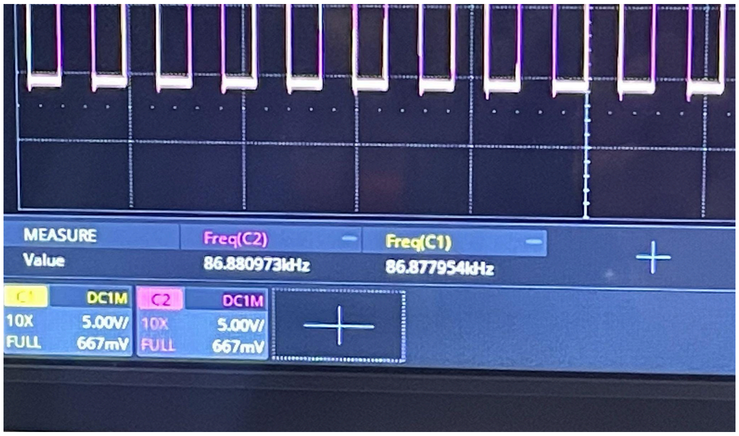

Figure 3: The frequencies when there is no object near the antenna.

When there is no hand around the antenna, the two oscillators produce nearly identical frequencies. The fixed oscillator is Channel 2 (the purple), and the variable oscillator is channel 1 (the yellow). It can be seen that the fixed oscillator has a frequency of 86.880973 kHz and the variable oscillator has a frequency of 86.877954 kHz. Since the frequencies are really close to each other, there is no significant beat frequency, so the theremin makes no noise.

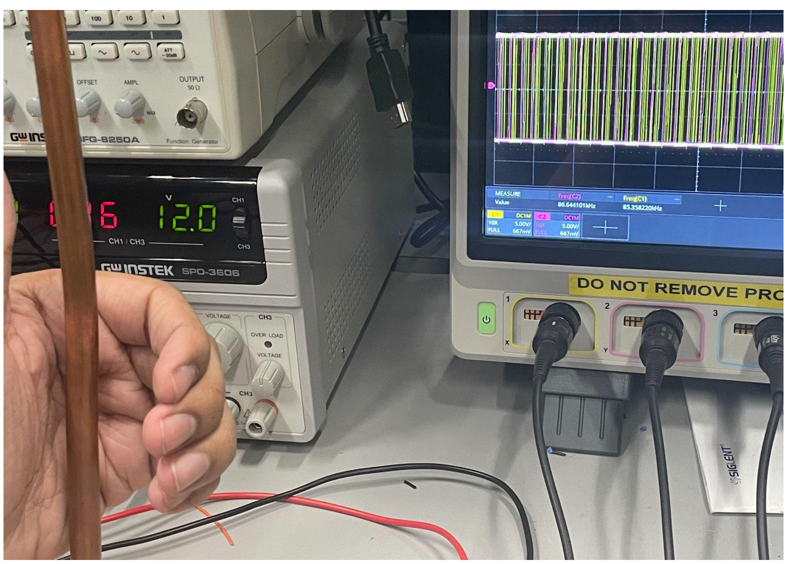

Figure 4: This is the output of the oscillators when a hand is next to the antenna.

The frequency of the variable oscillator (the yellow lines) visibly decreased to 85.358220 kHz while the frequency of the fixed oscillator remained unchanged. The reason why it seems the number of yellow lines increase is because the trigger was set to the fixed oscillator so it became out of sync with the fixed oscillator. Due to the change in frequencies, the beat frequency of the circuit is significant and noise can be heard from the theremin through the speakers.

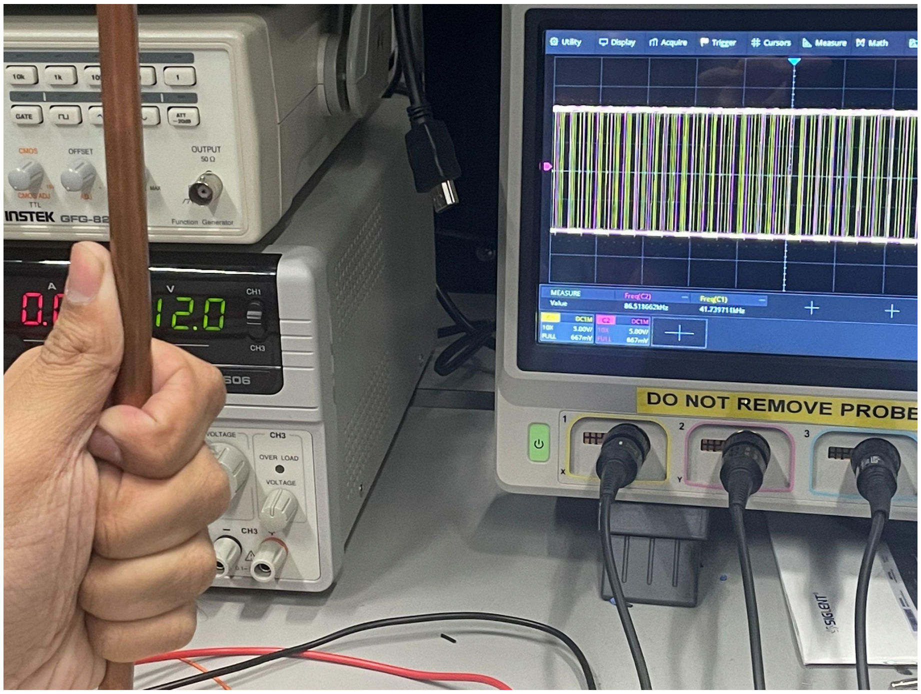

Figure 5: When the hand is in contact with the antenna, there is a more drastic change in capacitance, causing an even higher pitch and greater difference in frequency.

The frequency in this case went as low as 41.73971 kHz. This increased the beat frequency to a maximum and made the pitch the lowest it can go.

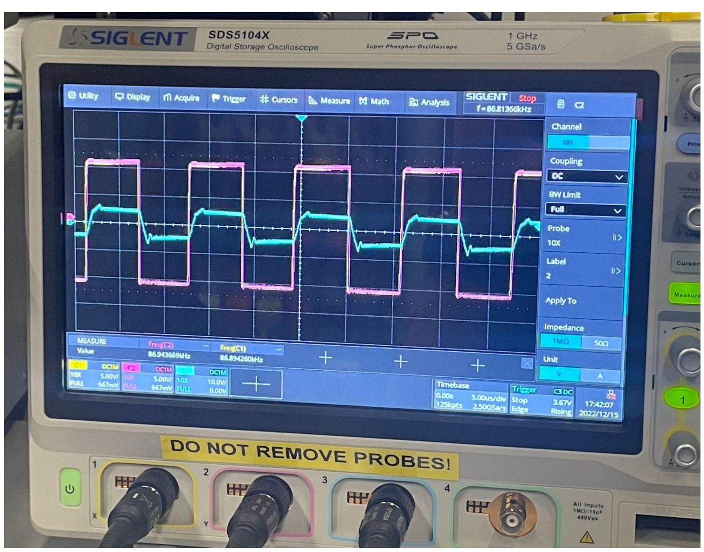

Figure 6: The blue wave represents the summing circuit of the two frequencies.

The oscilloscope shows the output of the summing circuit (the blue wave) of the two frequencies from the oscillators. The reason why the summing circuit looks lower than the two frequencies is because the voltage per division for the summing circuit was larger than the voltage per division for the two frequencies (10V/div vs. 5V/div). It can be seen that, after a short delay, when the two frequencies are at a peak, the summing circuit outputs a high peak and when the two frequencies are at a trough, the summing circuit outputs a low trough. This signal was put through a voltage follower then followed by a passive low-pass filter.

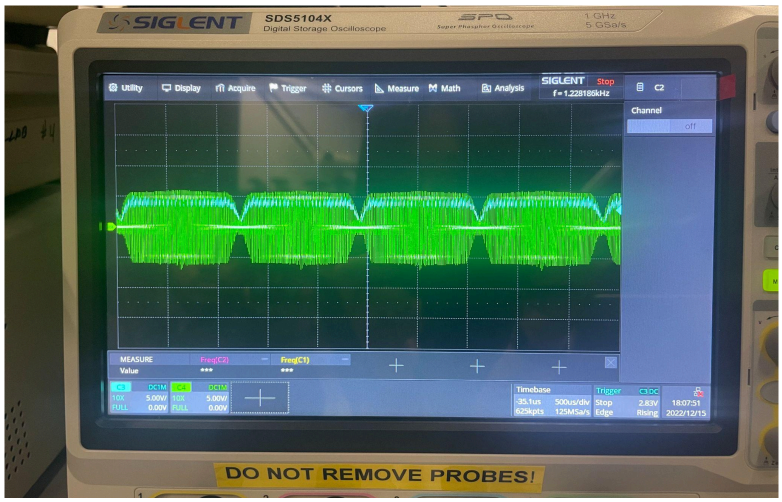

Figure 7: Beat Frequency & summing circuit (green), diode output (blue).

The output of the oscilloscope is the beat frequency and the diode that follows right after it. It can be seeen that the diode never has a negative voltage, which is expected of the diode since it only lets current flow in one direction.

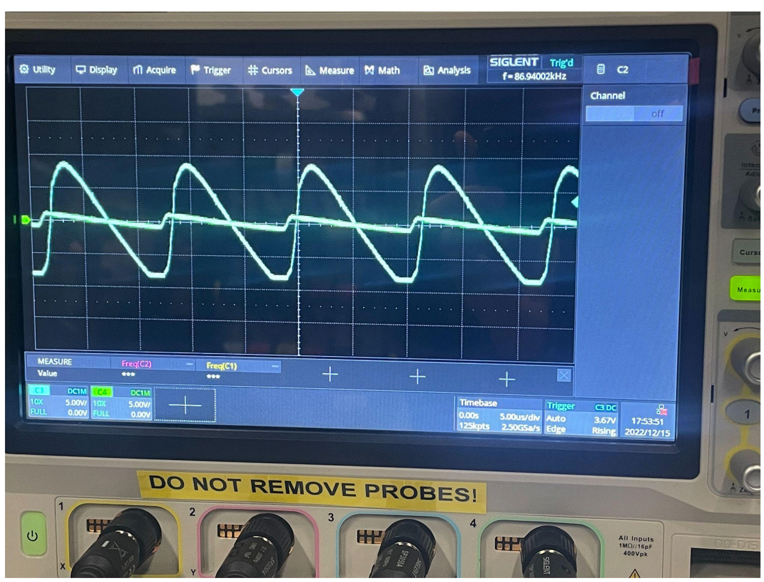

Figure 8: Comparison of signal before and after the amplifier (green is input signal, blue is amplified signal).

This is the output of the non-inverting amplifier. It can be seen that the input signal becomes greatly amplified after going through the operation amplifier, which is good because the audio signal becomes much more clear.

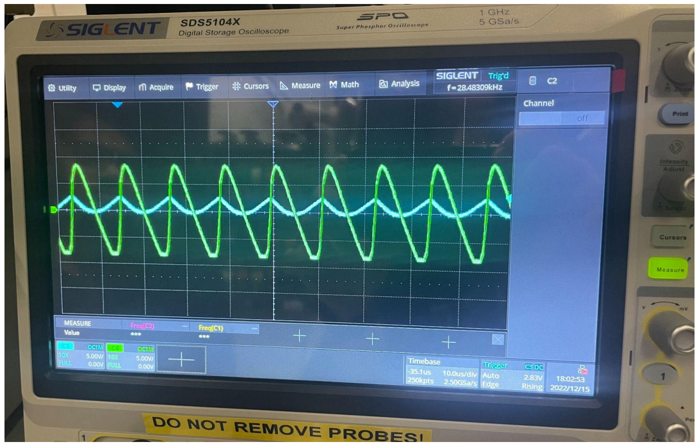

Figure 9: Low pass filter (green is input, blue is output), no hand is nearby.(10us / div)

This is the input and the output of the low-pass filter at the very end of the theremin. The output of this op-amp is what is sent to the PCB board. When there is no hand nearby, the audio output only becomes high when the input signal is low. However, the peak of the audio signal is not high enough to produce audible noise from the theremin (which is what should happen).

Figure 10: Low pass filter when hand is around the antenna (green is input, blue is output), (500us /div).

This is the input and output of the low-pass filter when there is a hand around the antenna. The output has visible peaks when the input has a longer trough, and as a result, when it gets sent to the PCB board and into the speaker, noise is made from the theremin.

Resistor #	Value (Ω)	Potentiometer #	Value (Ω)	Capacitor #	Value (F)
R1	19.80k	P1	13.98k	C1	1.11n
R2	99.75k	P2	14.90k	C2	1.03n
R3	0.99k	P3	12.80k	C6	24.82p
R4	20.21k			C5	23.97p
R5	98.52k			C7	5.09n
R6	0.98k			C8	9.60n
R7	4.69k			C9	9.85n
R8	0.998M			Decap b/w +VCC & GND	1.75m
R9	0.994M				
R10	0.998k			Decap b/w -VCC & GND	1.76m
R11	1.184k				
R12	2.16k				
R13	5.05k		Antenna (#1)		
R14	9.89k		Resistance(Ω)	Capacitance (F)	Inductance(H)
R15	5.06k		108	Distant: 1.5p	31.825m
R16	9.91k			Close: 6.7p	
R17	0.999k			Contact: 19n	
R18	1.000M				

Table 1: List of measured values (labeling is based on the labels on Figure 2).

Something to note from the table is that the value of C8 is different from the expected value on the diagram and the large decoupling capacitor values. The reason for this is that when testing out the theremin, we had trouble keeping the circuit working for more than a few seconds and we decided to change the value of certain capacitors and found that our theremin was working after these changes were made (and it sounded much clearer as well). As a result, the changes to the capacitors were left in the circuit. This capacitor is part of a high pass filter for AC coupling. A larger capacitance leads to a lower cutoff frequency, resulting in a fuller sound.

Conclusion

Overall, the theremin was a good project for sophomore projects. The main chips used for the project were the LM311 comparators and LM411op-amp. In addition, various resistors, potentiometers, and capacitors were used to provide different functions for the circuit such as a low pass filter or to provide a gain to the circuit. Thus, the circuit was an analog circuit and with that, some parts of the circuit were very sensitive, requiring careful adjustment. It was also interesting to play an instrument that does not require touching.

References

[1] "How the Theremin Works," emastered.com, https://emastered.com/blog/how-the-theremin-works, Accessed December 14, 2022.
[2] "60.17 The Electric Guitar," University of California, Santa Barbara, https://web.physics.ucsb.edu/~lecturedemonstrations/Composer/Pages/60.17.html, Accessed December 14, 2022.
[3] L. Shay, "ECE291 - Week 14" presented at the Cooper Union New Academic Building, New York City, NY, November 2022.

We'd like to acknowledge the Cooper Union for providing the materials and tools needed to build and test the circuit. We'd also like to thank Dean Shay, Evan Murphy, and our classmates for the various help they provided when we were building the theremin.