Theremin Project

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Introduction

The theremin is an electronic musical instrument created by Russian physicist Leon Theremin in 1920. The instrument comprises of a box containing radio tubes that generate oscillations at two sound-wave frequencies beyond the audible range. When combined, these frequencies create a lower, audible beat frequency. A theremin typically has two antennas, one for controlling pitch and the other for controlling volume. The pitch is manipulated by moving a hand or a baton closer to or farther away from the pitch antenna. This motion alters the frequency of one of the two oscillators, changing the audible beat frequency. The harmonics, also known as component tones, can be selectively removed, enabling the creation of various tonal qualities across a span of six octaves. The other antenna controls the volume of the theremin by altering the frequency of a third, separate oscillator which controls the output gain of the pitch, amplifying the sound produced. A miniature theremin mimicking the features of a theremin was built using basic circuit components, excluding the volume antenna. The volume antenna was replaced with an amplifier of variable gain, allowing volume adjustment.

Theory

The built theremin consists of 6 major building blocks – the antenna, the oscillators, the envelope detector, the amplifier, the filter, and the speaker.

The pitch antenna is a metal rod connected to four inductors in series. Before being integrated, the antenna was characterized to have 110.4 Ω of resistance and 32.75 mH of inductance. The capacitance based on hand location to the Theremin was also recorded.

Two LM 311 comparators were configured with an RC circuit to work as oscillators. The constant charging and discharging of the capacitor at the input terminal generated a square wave whose frequency could be varied by adjusting the resistance or capacitance values, changing the time it takes the capacitor to charge or discharge. The two oscillator outputs were first delivered to unit gain amplifiers and then joined together to create a single beat frequency, which would be pitch of the theremin. A unit gain amplifier, also called a buffer, refers to an operational amplifier (op amp) configured to have unit gain, meaning the output would be equal to the input voltage. A unit gain amplifier is advantageous as while the voltage remains the same, there is no current flowing through the amplifier, isolating the output voltage from the previous circuit.

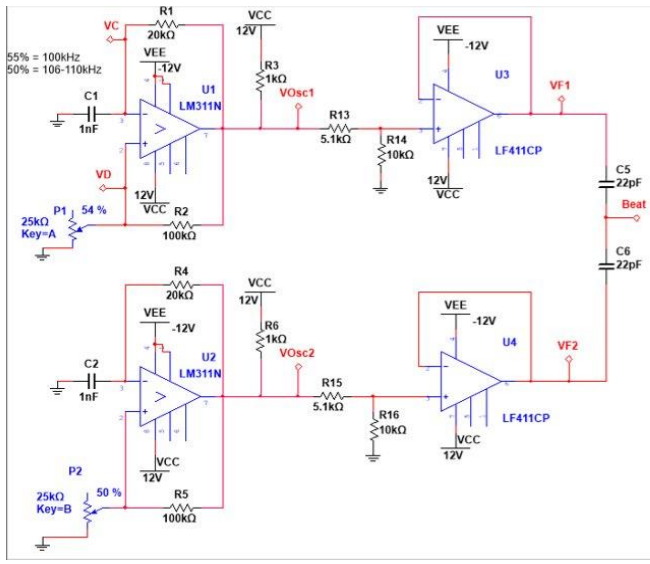

Figure 1 – Frequency Summing Circuit Diagram

With the pitch antenna connected in parallel to the capacitor of one of the two oscillators, the location of the hand alters the frequency of that oscillator. When no object is near the antenna, the two oscillators are in synchronization, generating identical wave frequencies. As a hand approaches the antenna, the capacitance between the antenna and the hand is added to C1 in Figure 1, shifting the frequency of the oscillator determined by the R1C1 time constant. With the measured capacitance of between a hand and the antenna being 14.3 pF when far away and 18 pF when close, the 1nF capacitor in parallel needed to be replaced for the moving of the hand to affect the frequency of the oscillator. The 1nF capacitor was replaced by a 101.0 pF capacitor and R1 was changed to a 238.9 kΩ resistor to maintain a similar frequency range with U2. The potentiometers P1 and P2 were further varied to completely synchronize the oscillators at rest.

The resulting summed output was once again passed through a buffer to minimize interference by the load resistance in the circuit. A diode detector, a form of an envelope detector, consisting of a diode followed by a capacitor and resistor in parallel, was implemented to modulate the amplitude of the signal. The properties of the diode convert the negative parts of the signal to positive signals, a process called rectification [2]. The envelope detector conducts when the output of the buffer exceeds the turn-on voltage, leading to the charging phase of the capacitor. When the converse is true, the diode remains non-conductive, marking the moment when the capacitor discharges. This results in the output signal following the peaks of the input signal, seemingly wrapping the signal like an envelope. The accompanying RC circuit acts as a passive low-pass filter, filtering high-frequency components, thereby minimizing high-frequency noise in the signal [2]. This is achieved since at high frequencies, the capacitor charge and discharge are unable to significantly occur due to the exponential charging/discharging characteristic of the capacitor.

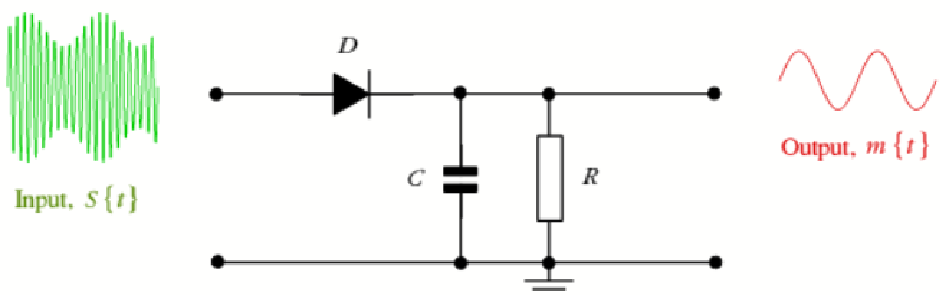

Figure 2 – Envelope Detector Circuit Diagram [2]

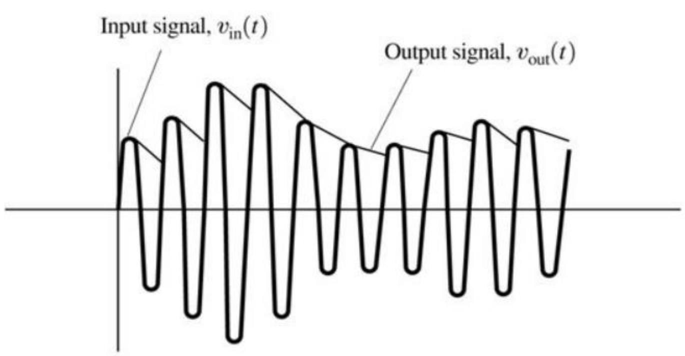

Figure 3 – Sample Output of an Envelope Detector [2]

Following the envelope detector, an op amp was configured with a potentiometer as a non-inverting amplifier with variable gain. The previously modulated signal's amplitude is amplified based on the potentiometer value (more specifically $1 + \frac{Potentiometer}{Resistor}$). The gain is saturated near the input (Vcc) voltage driving the op amp. This amplification determines the volume level of the theremin.

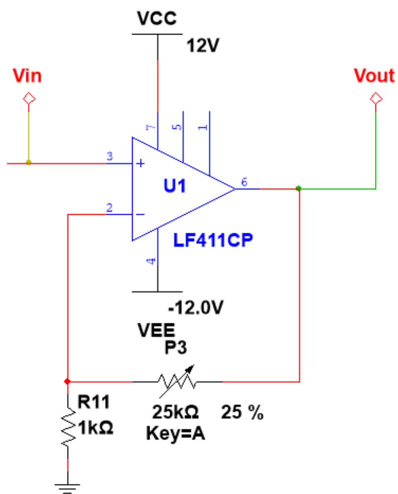

Figure 4 – Non-inverting Amplifier Circuit Diagram

The 25 kΩ potentiometer was replaced with a 10 kΩ potentiometer as Vcc is 10 V and even with a 25 kΩ potentiometer, the gain would saturate around 10 V. The 10 kΩ potentiometer ensures a more precise control of gain when playing the theremin.

Then, the signal is filtered through an active low-pass filter built with an op amp and an RC circuit. The active low-pass filter, more specifically the inverting amplifier filter circuit, attenuates frequencies above the cutoff frequency and passes frequencies below it [3].

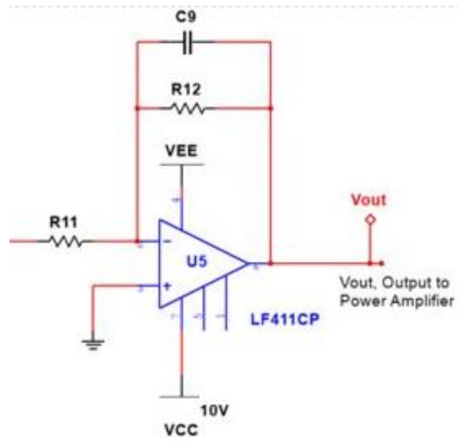

Figure 5 – Active Low-pass Filter Circuit Diagram

The cutoff frequency is simply the reciprocal of the capacitor value multiplied by the parallel resistor value ($\omega_0 = \frac{1}{R12\ C9}$). With a R12 being 2.164 kΩ and C9 being 9.78 nF, the cutoff frequency was 47k rad/s or 7.5 kHz. This indicates the built theremin could theoretically play sounds up to 7.5kHz or the 8th octave A#. This was not the actual playing range of the theremin as the change in frequency due to hand movement was not extreme. Unlike the passive low-pass filter previously mentioned, the active low-pass filter allows for gain in output and the load resistance does not affect its electrical characteristics [4]. The final low-pass filter allows for the setting of the frequency range of the output signal, or in other words, the playing range of the theremin.

The final component of the theremin is the speaker. Since the direct current from the theremin is not sufficient to directly drive a speaker even when amplified, a prebuilt audio amplifier was used to boost the current to play audio from the speaker. Unlike previous figures, the audio amplifier limits the theremin Vcc and Vee to 10 V and -10 V respectively due to limitations of the components used in the audio amplifier.

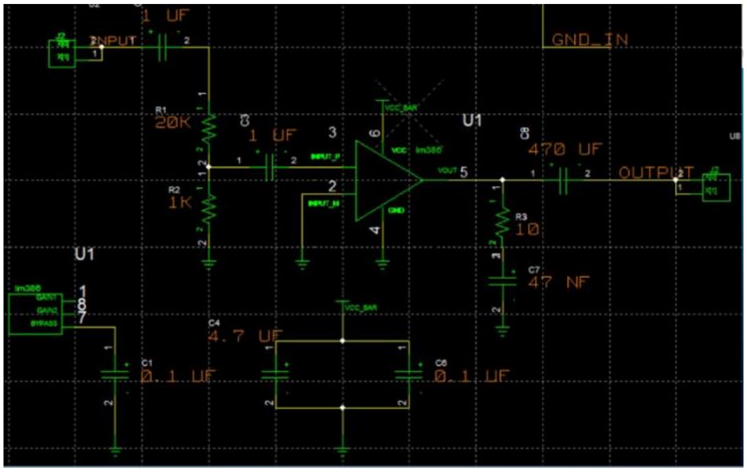

Figure 6 – Preliminary Audio Amplifier Circuit Diagram

Results

The completed theremin was as following.

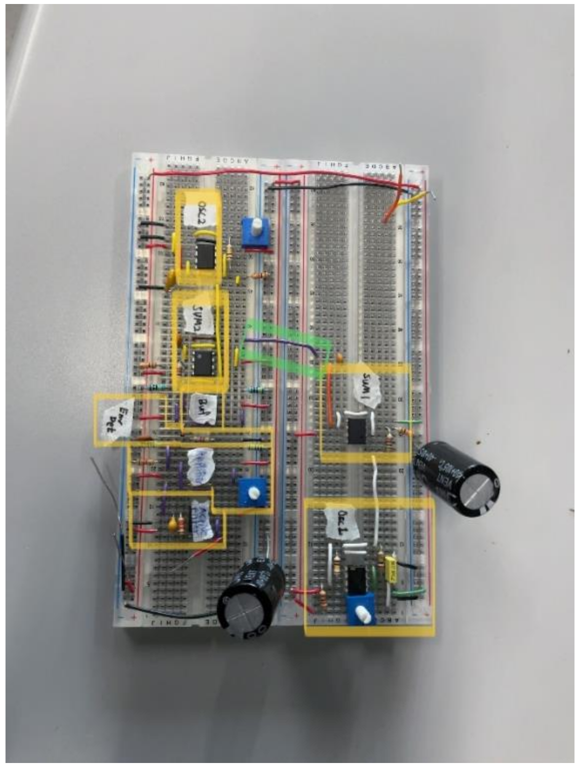

Figure 7 – Complete Theremin Circuit

The oscillators were all built according to the component values of Figure 1, with changes made to U1 as mentioned. The exact values of the components were R2 = 100.1 kΩ, R3 = 0.983 kΩ, R4 = 20.16 kΩ, R5 = 100.3 kΩ, R6 = 0.985 kΩ, C1 = 0.985 nF, P1 = 12.97 kΩ, and P2 = 7.52 kΩ for the results of this following test measurements. The potentiometers were varied to produce a frequency range that granted a better range of motion when playing the theremin. This frequency range varied every trial even with identical values and the theremin had to be “re-tuned” to ensure a wide range of motion, leading to an enhanced variety of notes played by the theremin.

In Figure 8, the oscillators generate identical frequency waves when at rest, resulting in a 0 Hz beat frequency. The beat frequency represents the difference between the frequencies of the oscillators.

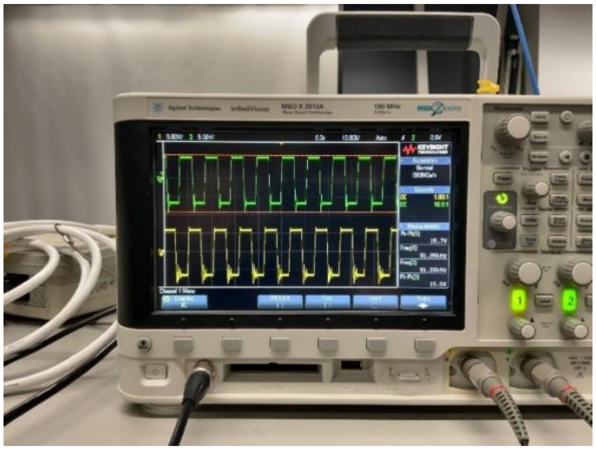

Figure 8 – Oscillators Oscilloscope Outputs

In Figure 9, the beat frequency formed by two different oscillators could be shown on the oscilloscope.

Figure 9 – Beat Frequency Oscilloscope Output

The buffer was also fully functional, the output directly following the input signal.

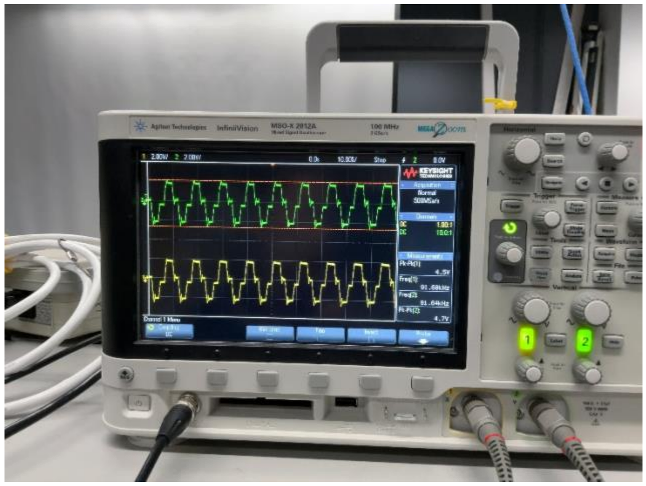

Figure 10 – Buffer Oscilloscope Input(yellow)/Output(green)

A smooth output signal following the peaks of the input beat frequency was obtained at the output of the envelope detector, demonstrating the diode and the passive low-pass filter worked as designed. As seen in Figure 11, the output voltage range of the envelope detector is only around 2 Vpp.

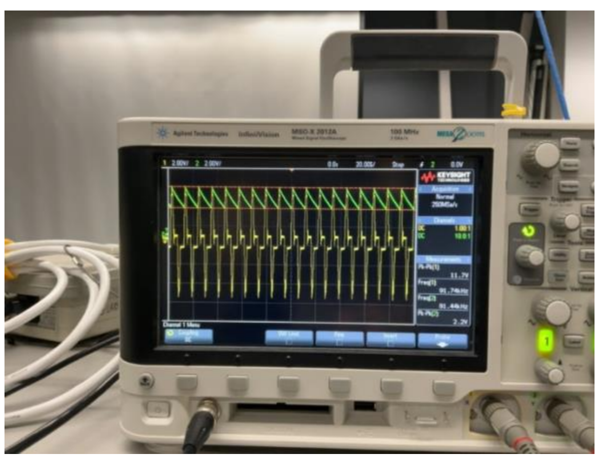

Figure 11 – Envelope Detector Oscilloscope Input(yellow)/Output(green)

The amplifier amplifies the output from the envelope detector depending on the value of P3 in Figure 4.

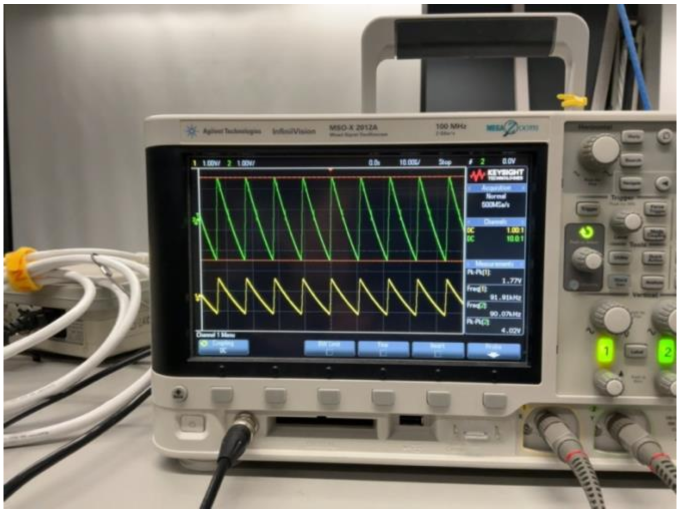

Figure 12 – Non-inverting Amplifier Input(yellow)/Output(green), Set to 2.27 Gain

With outputs taken when the theremin is at rest – when the oscillators are at the same frequency – the active low-pass filter filters the high frequency of the signal and outputs a signal less than 700 mVpp.

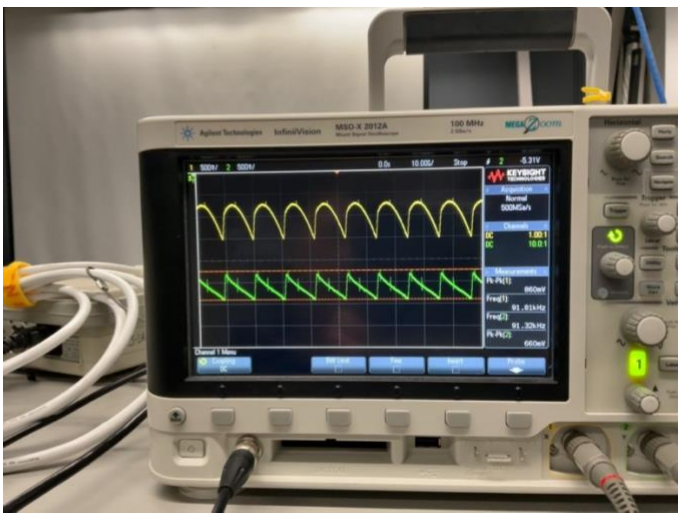

Figure 13 – Active Low-pass Filter Input(yellow)/Output(green)

Conclusions

In conclusion, the miniature theremin was built and played successfully. The key components of the built theremin functioned seamlessly, allowing an octave or more range of notes. The lab provided a hands-on experience of the intricate circuitry behind the theremin, offering valuable insights into how its electronic components are utilized to function as a musical instrument. The practical implementation of each building block contributed to a deep and meaningful experience, fostering a full understanding of the functionalities of the designed components.

References

[1] E. Bond, "How the Theremin Works," eMastered, [Online]. Available: https://emastered.com/ blog/ how-the-theremin-works (accessed Dec. 13, 2023).

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