ECE291 – Theremin

Victor Zhang, Jonathan Lam

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1 Introduction

The goal of ECE291 is to produce a theremin (instrument), which uses the basic concepts of circuit analysis (ECE240) and operational amplifier circuits. The theremin is composed of two comparator-based square wave generators, whose outputs are low-pass filtered and combined to form a beat frequency. One wave generator uses a copper rod antenna for a variable frequency. The beat is collected by an envelope detector (an op-amp, diode, and RC circuit), and passively low-pass filtered. The resulting signal is then passed through a power amplifier into a speaker to produce music.

2 Theory

The schematic provided in lecture (see Fig. 1) did not provide a clean output signal. Much of the circuit is the same, however, and any deviations are discussed in detail in this section. For comparison, the schematic for the final design described in this report is displayed in Fig. 6.

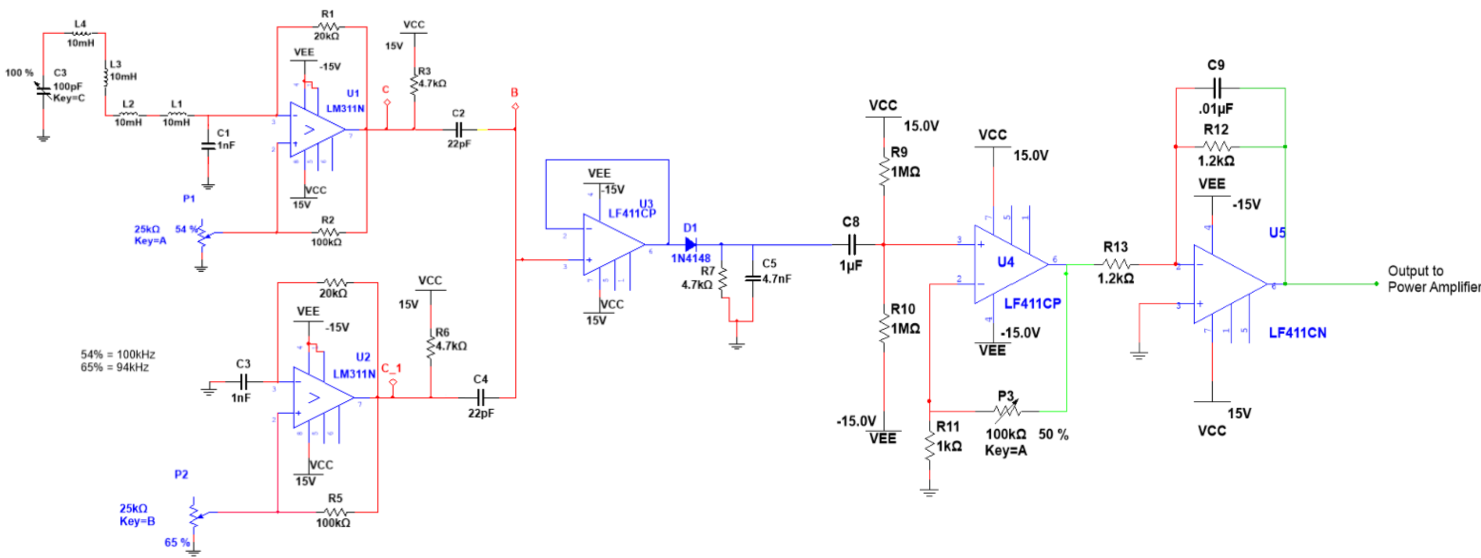


Figure 1: Overall provided block diagram of the Theremin. (Not accurate to the actualized project.)

2.1 Oscillator circuits

There are two square-wave oscillator circuits. Both use the LM311 comparator IC. This comparator is used to perform high-speed switching and desirable high-slew rate/low saturated power consumption (as opposed to the generic LF411 op-amp used for many of the other components in this project.) The variable oscillator circuit is shown in Fig 2, and a very schematic is used for the fixed oscillator circuit (namely, the lack of antenna and the replacement of the 470pF capacitor with a 1nF capacitor). This oscillator provides the desired square wave. However, we aimed to achieve a more symmetric, and larger-amplitude square wave output by replacing the 4.7kΩ pull-up resistor with a 1kΩ resistor. This reduces the changing time from roughly 400ns to 100ns, and increases the square wave's p-p amplitude from roughly 16V to roughly 19V (when VCC=10V, VEE= −10V); this is useful because filtering the square wave (discussed in the next section) greatly decreases the amplitude of the re-

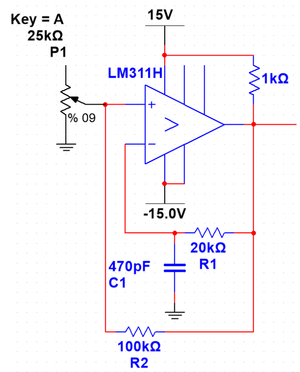


Figure 2: Square-wave (variable) oscillator circuit close-up

sulting wave. However, this did increase power consumption by each oscillator from roughly 0.01A to 0.02A.

Variable oscillator C_1 (pF)	470
Fixed oscillator C_1 (pF)	1000
R_1 (kΩ)	20
R_2 (kΩ)	100
R (kΩ)	1
P_1 (kΩ)	25
Emp. wave amp. (V p-p)	7.2
Emp. wave freq. (Hz)	100.40

Table 1: Square-wave oscillator values

2.1.1 Smoothing the oscillator output

Square waves do not produce desirable beats, but a sinusoid does. (See the Misc. Figures section.) "Smoothing" the square wave into a sinusoid was achieved by applying multiple low-pass filters in series to each oscillator output. The low-pass filters are tuned to have a cutoff frequency of roughly 100kHz, the target oscillator frequency. The chosen RC values are displayed in Table 2.

R (kΩ)	1.5
C (nF)	1

Table 2: Low-pass RC values

The cutoff frequency is calculated as follows.

$$f_c = \frac{1}{2\pi \text{RC}} = \frac{1}{2\pi(1.5 \times 10^3\Omega)(1 \times 10^{-9}\text{F})} = 106\text{kHz} \tag{1}$$

which is close to the desired 100kHz oscillation frequency. Four low-pass filters are used directly after the square wave oscillator to approximate a sinusoidal wave. This was then followed by an amplifier (Fig. 3), as each low-pass filter attenuated the oscillation's amplitude.

R_3 (kΩ)	1
R_F (kΩ)	15

Table 3: Inverting amplifier results

The amplification for the (inverting) amplifier is the known result shown below.

$$A_V = -\frac{R_F}{R_3} = -\frac{15\Omega}{1\Omega} = 15 \tag{2}$$

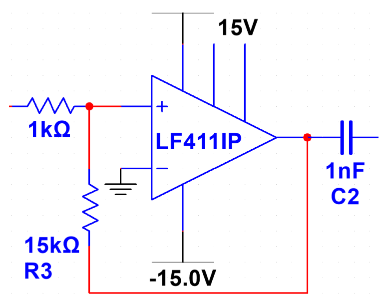


Figure 3: Inverted amplifier schematic close-up

2.1.2 Variable oscillator (with antenna)

A copper pipe, attached in series with four inductors, acted as a one-terminal capacitor, in series with the capacitor for one of the square wave oscillators. Its capacitance varies as the distance between the rod and other objects varies.

2.1.3 Other attempts to improve signal quality

We attempted to increase the carrier frequency to roughly 200kHz according to Prof. Frost's [2] advice in order to get a higher-quality envelope. However, this caused strange and unpredictable results with the LF411 op-amp circuits. Changing the higher carrier frequency back to 100kHz appeared to fix the anomalies.

We had multiple attempts to generate a sinusoidal wave in order to get a more defined beat frequency. One possibility we attempted was the Wien bridge oscillator [3], which is an op-amp circuit that uses a notch filter (high- and low-pass filter) on the positive feedback to force a self-reinforcing sinusoidal wave at its natural frequency. This design worked very well to generate a stable sinusoidal wave, but it could not be used for the variable oscillator because it requires two capacitors with the same capacitance (one for each the high- and low-pass filter). Another sinusoidal oscillator we tested was a notch filter circuit. While this also produced nice sine waves, there was a very large amplitude modulation with a change in frequency. This amplitude modulation caused by the changes in frequency is still present in the current circuit design, but to lesser degrees as the low-pass and high-pass filters are better-tuned to the desired frequencies.

In another attempt to obtain a clearer beat frequency from two mixed square wave generators, a summing amplifier was prototyped and tested under the presumption that this might allow for truer beats by summing the two waves. However, this produced an output insignificantly different from the simple decoupling capacitor "mixer," so we stuck to the simpler capacitor design.

Another attempt to improve the symmetry of the square wave was to use a 555 timer chip. However, this did not perform well in the 100-200kHz frequency range, producing very triangular wave and contradicting our purpose for using them.

2.2 Oscillator mixer

The two oscillator circuits are joined using an capacitor "mixer." The inputs are driven with buffers, so we can expect the output to act like two capacitors driven by two sinusoidal ideal voltage sources. This output should have a beat frequency, according to the well-known result for beat frequencies, shown in Equation 3:

$$\cos \omega_1 t + \cos \omega_2 t = 2 \cos \left(\frac{\omega_1 + \omega_2}{2} t \right) \cos \left(\frac{\omega_1 - \omega_2}{2} t \right) \tag{3}$$

which has the "fast" carrier modulation of $\frac{1}{2}(\omega_1 + \omega_2)$ and "beat frequency" of $\frac{1}{2}(\omega_1 - \omega_2)$. The values for the mixer are shown in Table 4.

C_2 (nF)	1

Table 4: Capacitor "mixer" values

2.3 Envelope Detector

The output of the oscillator mixer (with the beats) is fed into a voltage follower and then an AM (envelope) detector. This involves a diode (D_1) and a capacitor and resistor in parallel to ground, with the recommended values (Fig. 4).

2.4 Passive filtering and amplifier

The final low-pass filter (Fig. 5) is used to attenuate any high frequencies left behind by the carrier signal. Since we only wish to hear noises in the human

R_4 (kΩ)	4.7
C_3 (nF)	4.7

Table 5: Envelope detector values

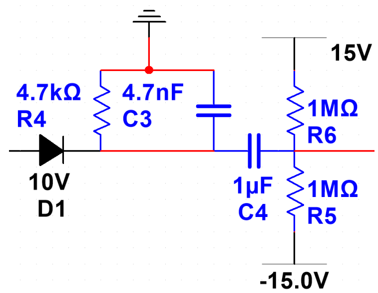


Figure 4: Envelope detector schematic close-up

hearing range (i.e., frequencies above 20kHz are squeaky, annoying, and may cause damage to the ear), the low-pass filter is tuned with a cutoff frequency of 20kHz. Additionally, we (as with many other project groups) noticed an ambient, small 60Hz overall modulation that appears after the diode, so there is also one high-pass filter with an identical cutoff frequency, and resistor/capacitor values (due to the similar nature of high- and low-pass RC filters). This creates a small "frequency notch"; i.e., the amplitude of the output frequency is most strongly transmitted at 20kHz, strongly attenuated at higher frequencies, and weakly attenuated at lower frequencies.

R (kΩ)	8.2
C (nF)	10

Table 6: Final high- and low-pass RC filter values

The cutoff frequency is calculated as follows.

$$f_c = \frac{1}{2\pi \mathrm{RC}} = \frac{1}{2\pi(8.2 \times 10^3 \mathrm{k}\Omega)(10 \times 10^{-9}\mathrm{F})} = 19.4\mathrm{kHz} \tag{4}$$

Six passive low-pass filter circuits are connected in series to attempt to smooth the envelope to approach a sinusoidal wave, similar to the filtering on the square wave oscillator. This replaces the final amplifier and active low-pass filter from the original recommended schematic. The (inverting) amplifier uses a variable resistor to amplify and vary the output amplitude. As with the other inverting amplifiers, the gain is given by:

$$A_V = -\frac{P_2}{R_3} \Rightarrow 1 \leq |A_V| \leq 10 \tag{5}$$

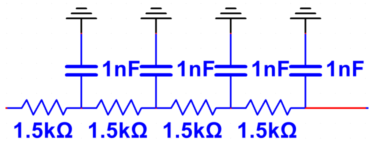


Figure 5: Post-AM detector passive low-pass filter close-up. Note that the first filter is a high-pass filter designed to filter out the 60Hz noise

R_7 (kΩ)	1
P_2 (kΩ)	10

Table 7: Final inverting amplifier values

This amplitude modulation serves as a tunable audio amplitude (i.e., volume) control.

3 Schematic and setup

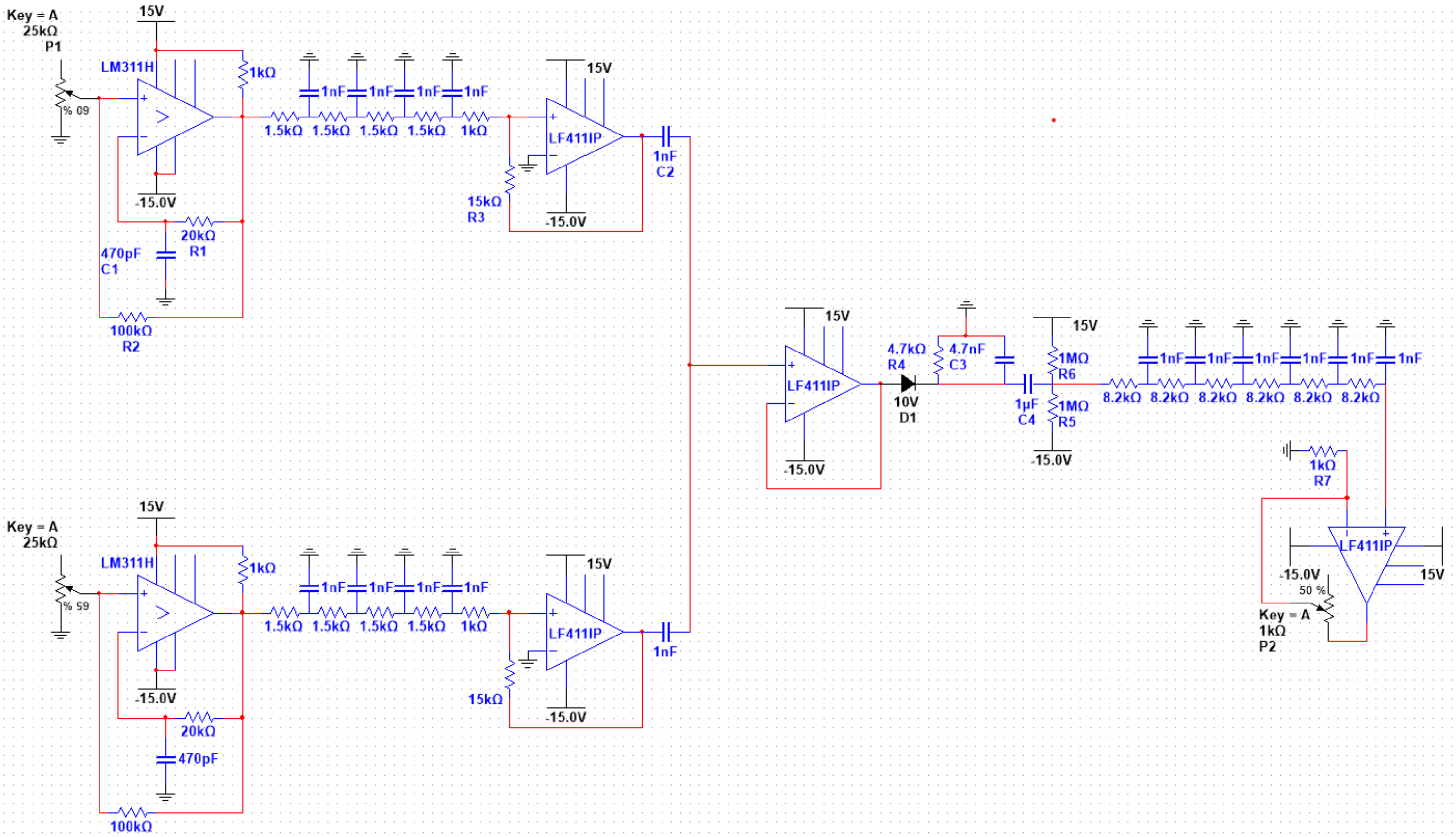


Figure 6: Main schematic

There are a few clearly visually distinguishing factors from Fig. 1, the originally recommended schematic. The low-pass filters between the square-wave oscillators and the capacitor mixer, and the low-pass filters between the envelope detector and the final amplifier are the most pronounced and the major deviation in our circuit design from the original.

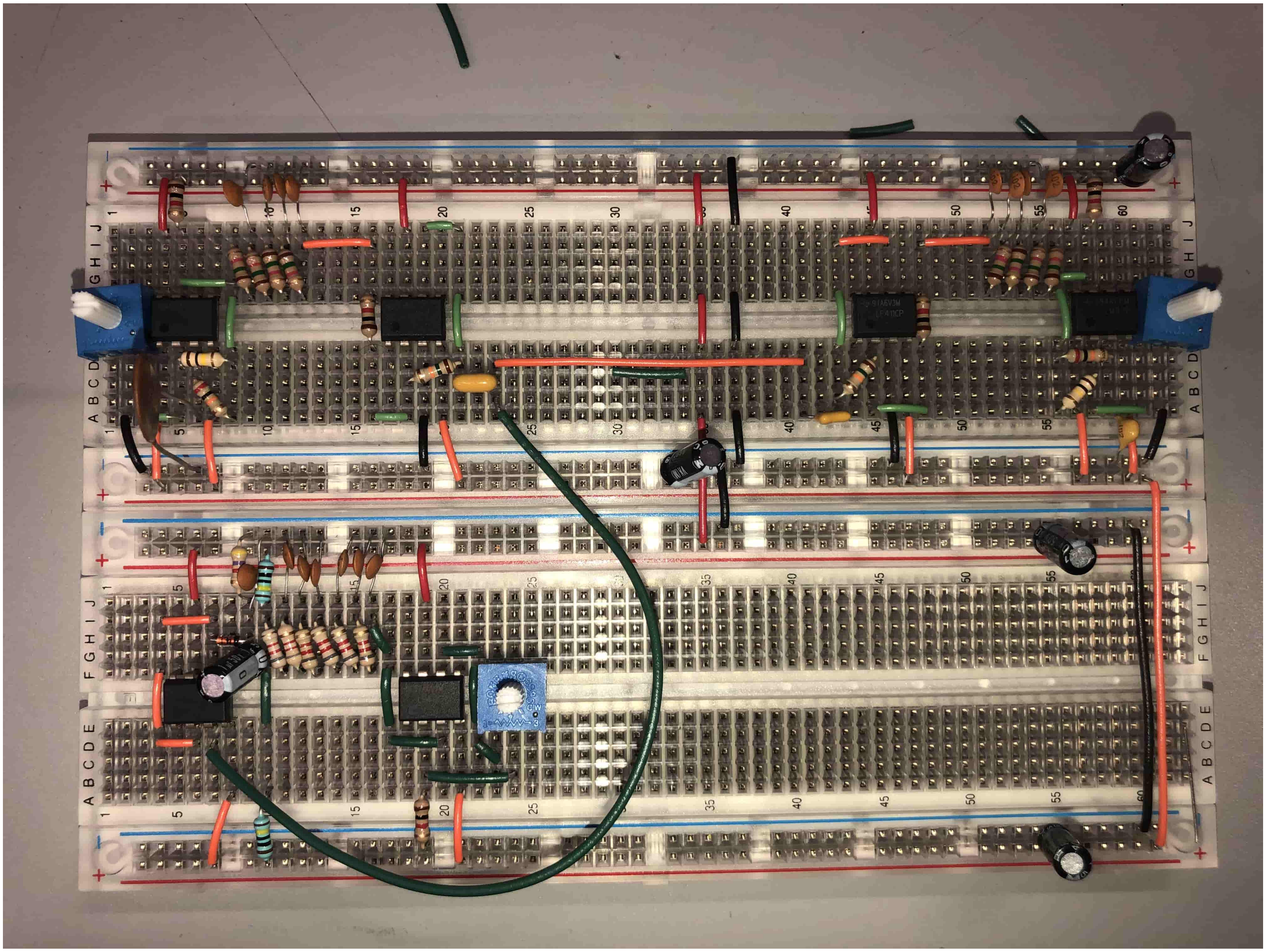
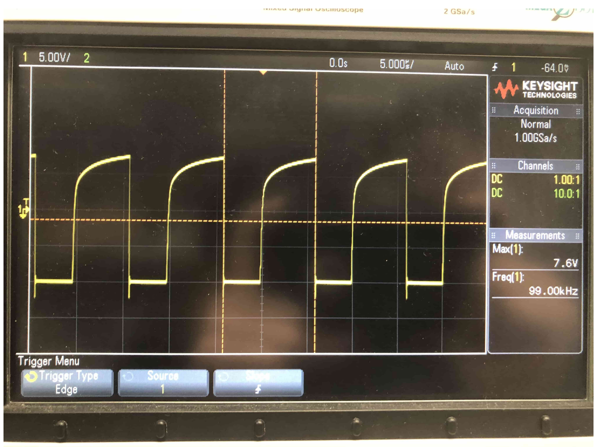


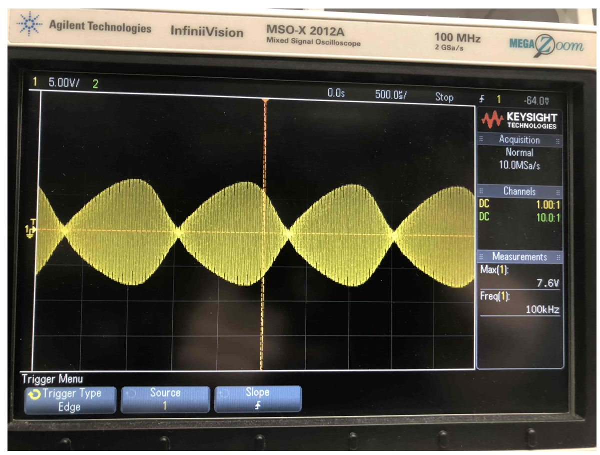
Figure 7: Experimental setup

4 Results

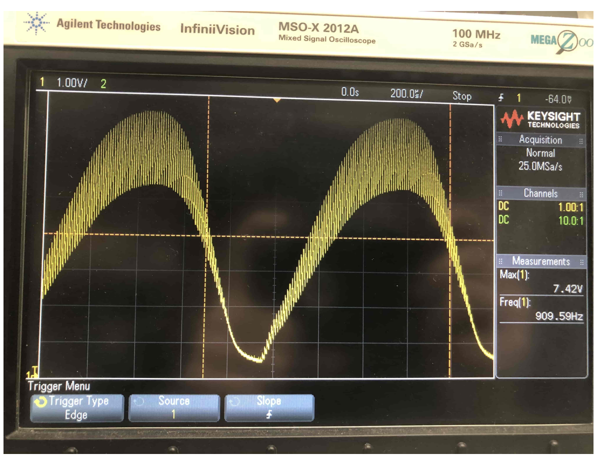
The evolution of the signal through the circuit is very pronounced. The square wave generators produce nearly 100kHz, nearly-square waves (Fig. 8.a). The oscillator inputs are mixed to produce beats (Fig. 8.b). (Not shown is the low-pass filtering of the square waves before mixing.) The AM detector picks up the signal (Fig. 8.c), which is filtered sinusoid (Fig. 8.d). The carrier signal used was 100kHz, and the beat frequencies were roughly on the scale of 1-20kHz.



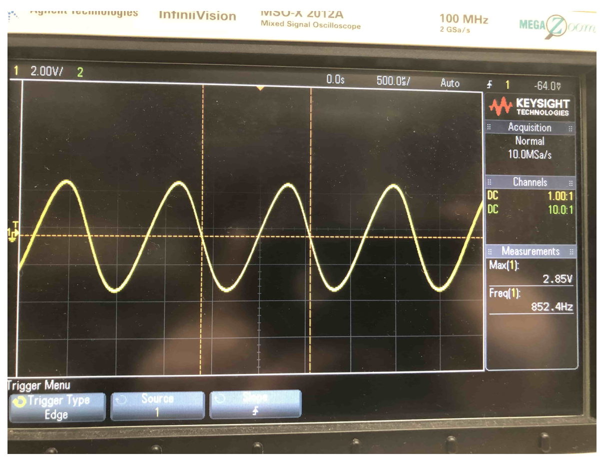
(a) Square wave oscillator input



(b) Oscillator beats



(c) Detected envelope



(d) Audio output

Figure 8: Signal evolution through circuit

4.1 Subjective description of theremin instrument

This iteration of the theremin tended to produce clean sinusoidal audio signals. The beat (and output) frequency tended to be stable in a range of roughly 300Hz to 20kHz. Subjectively, the most pleasing tones were in the 800-5000Hz range, where higher frequencies tended to be squeaky and aggravating. As mentioned in the Theory section, there tended to be some amplitude modulation that accompanied the frequency modulation, which we postulate to be due to the low-pass filters' frequency-dependent attenuation. The capacitor was fairly responsive to changes in distance, and was able to noticeably change pitch as people moved as much as a meter away from the antenna.

We were unsuccessful in playing the Cooper Union theme song on this instrument =(.

5 Conclusions

The theremin project introduces the use of the op-amp and comparator, and provides an opportunity to work with AC signal which magnifies the common modeling error in circuit analysis. Students learnt to reduce or avoid unwanted circuit behavior which is critical for implementing electrical engineering in real world. The theremin works as expected and produces relatively clean sound wave. Multiple prototyping iterations were gone through to optimize the circuit. The design process used can be significantly improved by doing more thorough modelling and testing. The students who conducted this experiment learnt how to generate high-frequency signals, filter (high and low frequencies), amplify, voltage-forward, invert, DC-block, and detect AM using various op-amp implementations. There was also useful learning in practical circuit-building and debugging skills, as well as learning how to deal with noisy, high-frequency, and audio signals.

References

[1] Shay, Lisa.

[2] Frost, Brian.

[3] "Wien Bridge Oscillator Tutorial and Theory." *Basic Electronics Tutorials*, Aspencore, 21 Feb. 2018, https://electronics-tutorials.ws/oscillator/wien_bridge.html.