Theremin, a Contactless Musical Instrument
ECE 394A - Junior Projects II

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Abstract

This project aims to build a musical instrument, theremin, that is able to produce sound in an audible range of frequencies with simple hand motions around the two antennas, each designated for pitch and volume. By moving hands around the antenna, an interference in the electromagnetic field varies the capacitance between the antenna and the hand. This change in capacitance in conjunction with LC tank then allows for detecting varying pitch and volume based on hand distance from the antenna. By mixing with another signal of high enough amplitude and constant frequency, the variance is detected and amplified for the user to hear the sound.

Introduction

This muscial instrument, patented in 1928 by Soviet inventor Leon Theremin functions by detecting varying capacitance due to the location of the players hands relative to the antenna, and produces a signal of varying frequency at the output oscillator. Instead of relying on some mechanical operations and contact to generate the sound and it creates audio by generating electromagnetic fields around two antennae, each dedicated to control pitch and volume - a straight and vertical, and a horizontal and looped, respectively. The shapes of the antenna surely provide distinct differences; while straight forms will work for both provided that variable capacitance can be detected, for the loop antenna, the angle at which the hand approaches serves as a factor in change in capacitance–the change in the field may be detected slower on the sides while at the center a more rapid change can be sensed. This allows for more careful adjustment in volume level; in addition, this distinction in the shape allows for the user to distinguish which is used for which functionality instantly. Thus, precise coordination of finger and hand gestures in the fields is an important criteria in working with this device, as each acts to deliver precise pitch and melodies, while also controlling the level of volume attenuation. There exist various applications of theremin mechanism where a theremin could use light sensors or an infrared field in place of electromagnetic field, a solar theremin could utilize solar energy to create tones, and other video theremins could employ synthesize tones from coordinating body movement variations.

The system is divided into several modular circuits, which are discussed in detail for implementation sections that follow. Although inconsistent input at the antenna prevented from sending a clean signal of high enough voltage through each oscillator, each circuit by itself served its purpose. The integration of all circuits in entirety posed some difficulties as the required voltage for each stage and phase shifts, in addition to noise and non-linearity from amplification interfered with properly biasing each stage.

Project Description

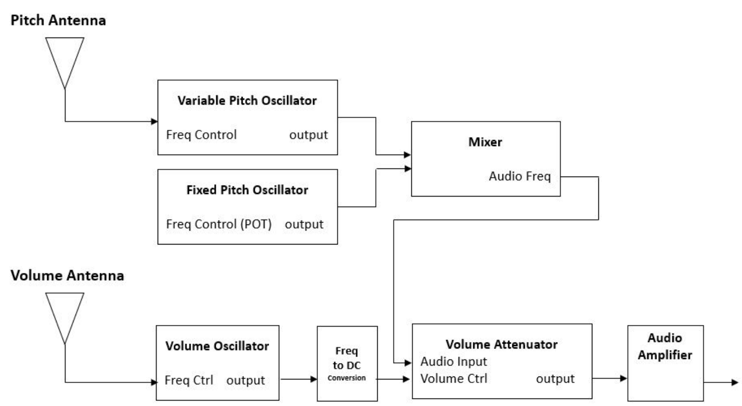

Figure 1: High-Level Block Diagram

The system is divided into subcircuits as described in Figure 1. The oscillators that have antenna as inputs use LC tank in parallel to keep the input signal match the specified resonant frequency at times when hand is placed far from the antenna. The output of the variable pitch oscillator is fed into a mixer circuit, which also takes the fixed oscillator as another input to take difference of those two signals. The output of the volume oscillator in AC is converted to DC signal in order to act as a control for attenuation. These two signals are the inputs to the attenuator circuit, whose output is then amplified so that the speaker can output an audible volume of generated signal.

Variable and Fixed Pitch Oscillators
The variable pitch oscillator takes in changing capacitance from the antenna, which is caused by the varied hand distance between the antenna and the hand acting as the ground plate, and this capacitance is connected to inductors in series to provide some linearity in the signal. This is then matched to an LC tank in such a way that there is maximum power transfer from antenna to LC circuit. This allows for obtaining a signal of varying frequency when the capacitance is changed, thereby producing an audible tone, which typically ranges from 65 Hz to 3 kHz.

In order to determine the specific values for inductance and capacitance in the LC tank that is connected in parallel to give a resonant frequency, we need to consider the range of frequencies in which we want the output to fall. Since the audible musical tone ranges up to around 3 kHz, we would like the range to match some frequency around 3 kHz, with the antenna's capacitance taken into account. We were not able to calculate the capacitance of the antenna directly, but through some experimental attempts at RC network with the antenna inputs, the its capacitance is found to fall some where around 10 pF. The maximum change in capacitance due to hand motion was somewhat difficult to measure, given the inconsistency in the antenna input measurement. The approximate value of 3 pF between far and near distances from the reference [4] is taken as the criteria for determining the values for inductance and capacitance.

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

$$\frac{df}{dC} = \frac{1}{4\pi\sqrt{LC^3}} = -\sqrt{\frac{L}{2C}} f_{resonant} \tag{2}$$

With approximate change in capacitance by hand distance considered, differential change in frequency per capacitance is calculated for a certain set of inductance and capacitance values. After several attempts, inductance of 3.3 mH and capacitance of 120 pF are chosen to produce a resonant frequency of 253 kHz, also giving $\frac{df}{dC} = 1.05\frac{kHz}{pF}$ and a range of $C_{max,antenna-hand} * \frac{df}{dC} = 3.15kHz$.

This experimentally determined resonant frequency allows for use of lower inductance and capacitance values, which were rather easily available in the lab inventory. However, because the resulting resonant frequency is set to one that is out of audible scope, an additional circuit for heterodyning these two signals is employed thoruogh a separate mixer circuit. The output of the mixer circuit is designed to take the difference and lower the frequency to the desired audible frequency range.

In order to mix, a reference frequency needs to be fed in to the mixer. This is generated separately from the variable oscillator, by an RC oscillator. The circuit for heterodyning two signals of pitch frequencies allows for converting a small perturbations in the capacitance from the antenna to audible pitch signal. This purpose requires that the fixed pitch oscillator circuit be highly stable since minor variations in the frequency (drifts) could change the reference frequency and thus affect the audio frequency, tunable for possible variance in capacitance and frequency drift in the oscillator affecting the resonant frequency, and adaptable to producing sine or square waveform.

This RC oscillator circuit is similar to a Schmitt Trigger, but with a negative feedback loop with a capacitor. The presence of the capacitor at the negative input causes the output to vary with the effect of capacitor charge/discharge varying states. In the steady state, the capacitor is simply an open-circuit, so it is V_{cc} (+12V). In the transient state, the output oscillates due to the capacitor charging towards V_{cc} (+12V) and discharging towards -V_{ee} (-12V) for $|V_{-}| < V_{TH}$. Setting two thresholds for + and - allows for a square wave output. The frequency of this fixed oscillator is set equal to the resonant frequency of the LC tank in the variable, so that any difference could be extracted.

$$f_{osc} = \frac{1}{T} = \frac{1}{2RC\ln(1.19)} \approx f_{resonant} \tag{3}$$

With C = 0.01 uF and R = 1.1 kΩ (using 2 kΩ POT), the base frequency is matched. This then becomes an input to the mixer, where the difference in frequencies due to antenna's varying capacitance is extracted. At the last stage of the fixed oscillator is a voltage divider, used to adjust the voltage (attenuate by a factor of 0.08).

Volume Oscillators

Volume oscillator acts similarly to the variable pitch oscillator in general. Since the antenna's shape is in loop instead and there are parts where capacitance change may not be detected as much as other parts, we would like greater $\frac{df}{dC}$ for this particular LC tank. Thus, we initially experimented with L = 1 mH, C = 120 pF, which would give 459 kHz and differential frequency of 1.87 $\frac{kHz}{pF}$ theoretically. This ratio is higher than that for the pitch so that smaller change could yield greater volume output change. The tuning, where for the fixed oscillator it was handled by an additional fixed oscillator, for volume was to be managed by a variable capacitor, in order to adjust for ambient change in capacitance in the LC tank–it would be connected in parallel in the LC tank originally. However, the particular variable capacitor purchased (GMB30300) did not perform at its maximum capability, and made thus it difficult to work with. The general topology is similar to variable pitch oscillator (feedback, unity gain buffers to scale down voltage), but instead a potentiometer is used to allow for output swing to be adjusted.

Frequency to DC Converter

The purpose of this stage is to generate a signal to control the level of attenuation in the attenuator stage. This is achieved by first passing through a LPF to attenuate the signal, and through a peak-detector circuit. As the hand distance changes, the frequency of input varies inversely, and the magnitude of the amplitude is decreased accordingly, and then the peak magnitude determines the DC voltage at the output.

Volume Attenuator
This attenuator circuit takes the output of the mixer and DC converted signal as inputs to drain and gate, respectively, and controls the amount of attenuation by the resistance of JFET at the drain. Depending on the resistance at the drain from JFET, the level of attenuation of the mixer output is determined as follows.

$$V_{audio} = \frac{R_{JFET}}{R_{JFET} + R_3} V_{mixer.output}$$

This exploits the property of JFET (source grounded) voltage across gate-source:
$V_{control} = 0$ V: smallest resistance at drain, most attenuation
$V_{control} \approx$-10 V: largest resistance at drain, bare attenuation

Voltage-Controlled Audio Amplifier
The final stage is a 2nd order active LPF, which is designed to remove frequencies higher than audible range of frequency (chosen to be $\approx$ 15 kHz), while also giving enough gain to be audible ($\approx$ 3.5.

$$f_{cutoff} = \frac{1}{2\pi RC} = \frac{1}{2\pi(10k\Omega)(0.001uF)} \approx 15kHz$$

$$Gain_{max} = 1 + \frac{R4_{POT}}{R4} \approx 3.5$$

Mixer
This circuit is designed to serve as a 'subtractor,' taking the difference between frequencies from variable and fixed oscillators. When the hand distance is assumed to be infinity (far distance away), the variable frequency should match the fixed frequency, giving $\approx$ 0 Hz, while hand at near distance would vary the variable frequency, thus giving a frequency difference in the desired range, greater than 0 Hz, thus a tone is heard.
This mixer is achieved by a single-transistor (BJT) topology. Using an n-channel BJT (2N3904), it feeds in fixed signal to the base to serve as the control signal and variable to the collector. Since the fixed signal we are outputting is a square wave, at the collector is just the multiplication of variable signal by fixed signal, when the BJT is forward active. This is then sent to a 1st order LPF to remove any DC bias with cutoff frequency at around 2 Hz, to a 2nd order LPF to remove high frequency sinusoids with cutoff at around 12 kHz, and to a non-inverting voltage amplifier to increase amplitude that has been attenuated to some degree to an audible level.

Design and Implementation Procedure

Module - Variable Pitch Oscillator

The inductor in series with the antenna is placed to help with linearity concerns for the input. The LC tank in parallel plays a key role in the oscillator model. As the capacitance in the antenna changes, it adds capacitance to the LC tank, thereby changing the resonant frequency as well–this is what produces a unique tone. In order to produce some sinusoidal waveform from the LC tank, a feedback must be applied. The purpose of this feedback to an LC sine wave oscillator is to maintain the amplitude of the oscillations is maintained constant by feedback energy replacing the lost for each cycle. Ideally, to keep this stable, the overall gain for LC tank and feedback should be close to unity.

While measuring the variable pitch oscillator performance, the antenna posed several difficulties in providing a proper signal that we expected. It intermittently stopped giving any signal at the right frequency, and sometimes added undesirable noise added. There were also fluctuations in the input frequency; this was most likely caused by parasitic capacitance from wire connections and improper setting of LC tank connected to the antenna. Such nonlinear behavior obtained from the antenna prevented from further analysis of the oscillator circuits in detail.

List of Components

Components	Count
LF356	3
Straight Antenna	1
2k Potentiometer	1
100k Potentiometer	1
9.1k Ω Resistor	1
1k Ω Resistor	1
0.1 uF Capacitor	6
120 pF Capactor	1
23.5 mH Inductor	1
3.3 mH Inductor	1

- LF356 opamps are used exclusively for their high speed and 0.1 uF capacitors are inserted between the power and ground to remove potential noise.

Circuit Implementation

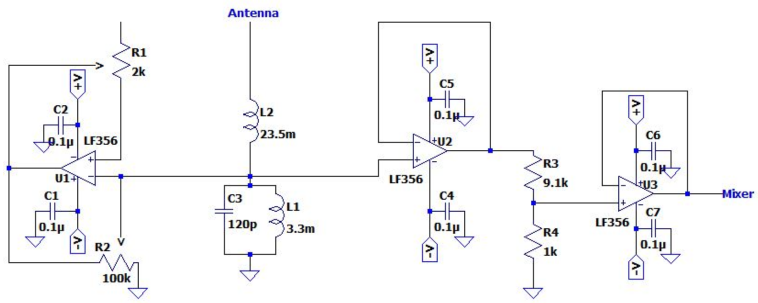

Figure 2: Variable Pitch Oscillator Schematic

Circuit Simulations

The waveforms of the LC oscillator for near and far hand distances are shown below. The input signal from the antenna demonstrate instability and noise-filled signal. This could potentially be due to improper connection and interferences from other electromagnetic waves in the surroundings. We exhibited changes in frequency, as intended, but the voltage was too low to drive the subsequent stages.

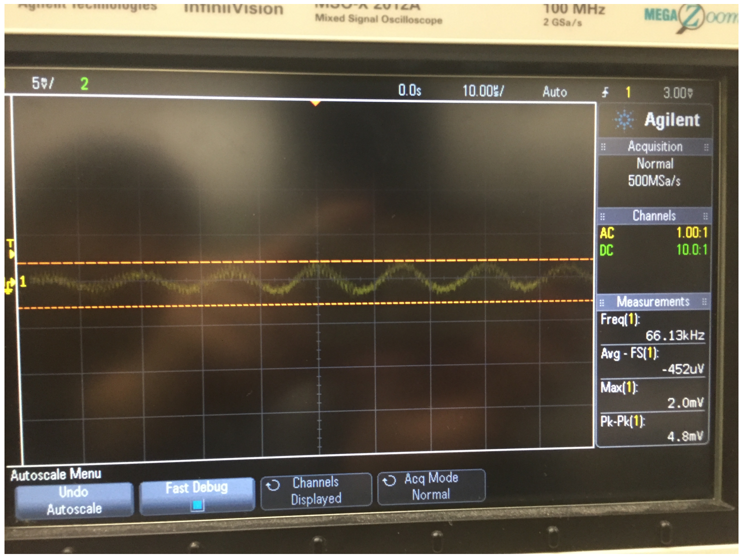

Figure 3: Pitch - Hand at far distance

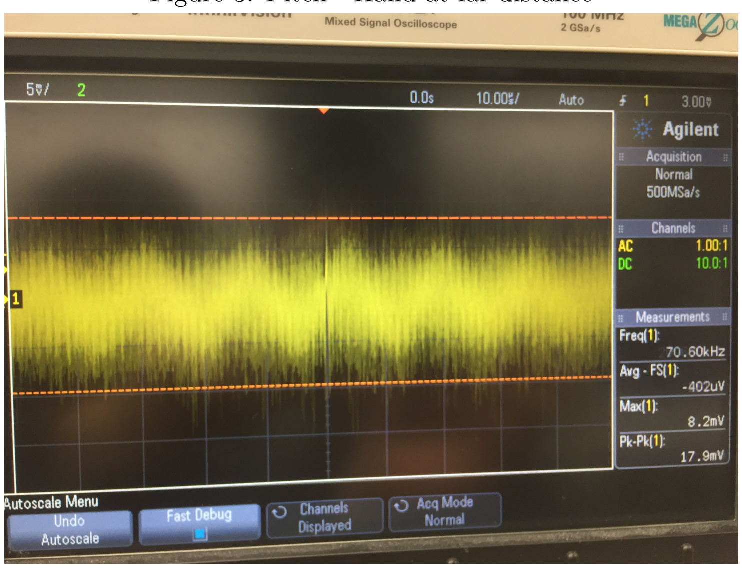

Figure 4: Pitch - Hand at near distance

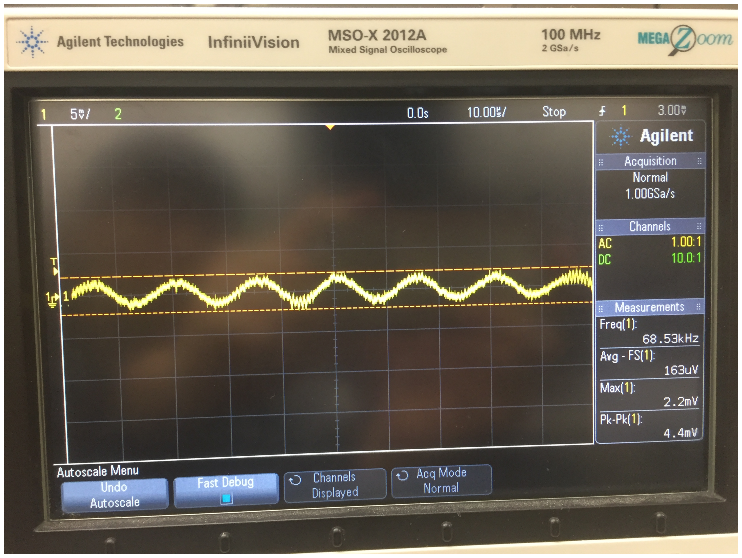

Figure 5: Pitch - Hand at far distance (single)

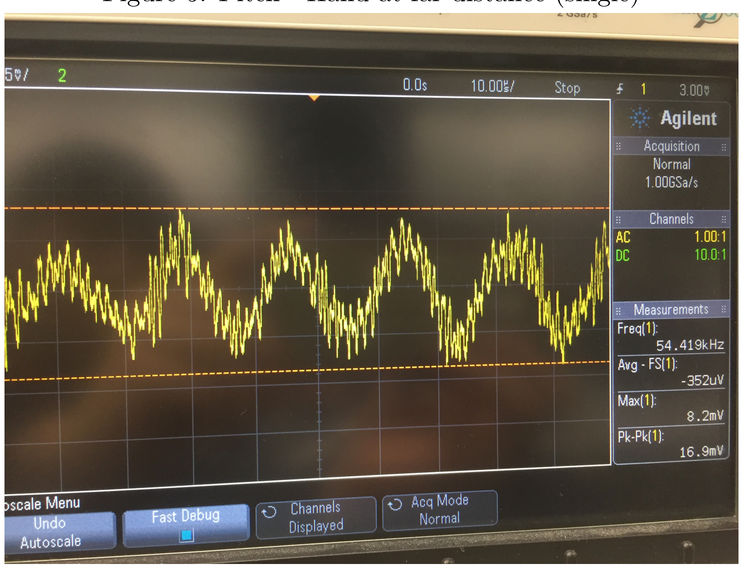

Figure 6: Pitch - Hand at near distance (single)

Challenges
Initially when the antenna with the LC tank in parallel gave constant sinusoidal waveform, the feedback stage had improper resistances for stability, and when the functional resistances were found experimentally the antenna's input was an issue. Another part was mounting the antenna so that it is in constant contact with the connecting wire. Attempts at connecting with raw wire and with a

ring of the right size and screwing in tightly still gave inconsistent input signals, either giving its sinusoid or negligible wall signal.

Results

The variable pitch oscillator did not perform as well as expected due to misconfiguration of the antenna input. A likely reason for inconsistent antenna behavior could be not connecting it to the wire tight enough that the contact is maintained throughout the experiments, or just the antenna failing to give enough signal at the desired frequency through the series inductor. With the antenna feeding in properly as the hand distance varies, matching with the resonant frequency would have been easier; the LC sine wave oscillator by itself provided signal. While the variable pitch oscillator did not work in the final implementation, the circuit had yielded noticeable results at one point, with an amplitude of roughly 300 mV at 170 kHz. This low voltage is not what was expected however since the peak to peak should have been 24 volts, but there was an overall linear behavior with a total frequency change of 3 kHz at the output stage.

Module - Fixed Pitch Oscillator

The voltage comparator that we used to generate a constant-frequency square wave is LM311, which was readily available and operates within +/- 15 V supply and performs at high-speed. The base topology is an RC oscillator, as demonstrated in Lab 10, which outputs a square wave of frequency $f_{osc} = \frac{1}{T} = \frac{1}{2RC\ln(1.19)} \approx f_{resonant}$.

List of Components

Components	Count
2 k Potentiometer	1
100 k Potentiometer	1
4.7 k Resistor	1
15 k Resistor	1
1.2 k Resistor	1
100 k Resistor	1
0.01 uF Capacitor	1
0.1 uF Capacitor	2
LM311 Op amp	1

Circuit Implementation

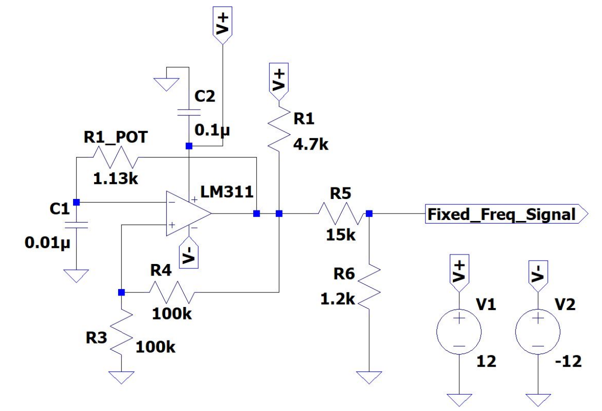

Figure 7: Fixed Pitch Oscillator Schematic

Challenges
As this RC oscillator is performed as part of Lab 10, it was rather easy to build; one thing that needed to be taken into account was the adjustment for amplitude using voltage divider network.

Results

The fixed-pitched oscillator worked as expected in the implementation since a very similar circuit was constructed as part of lab 10. The frequency was tuned with the op amp and while this frequency was very sensitive, it had worked correctly to test at 165 kHz. The voltage divider to scale the voltage had worked correctly as well, in order to allow the mixer the circuit to function correctly.

Module - Volume Oscillator

The general circuitry is similar to the variable pitch oscillator. As discussed in the description, the original plan to use a variable capacitor to adjust for ambient capacitance variance is omitted due to trouble working with the component, which performed less desirably. Another difference is allowing for the output swing to be adjusted slightly through a potentiometer after the first buffer stage. Overall, this generates a sinusoidal waveform with LC oscillator circuit with the antenna, with the resonant frequency higher than the pitch to account for detection of miniscule change in capacitance.

List of Components

Components	Count
LF386	3
Loop Antenna	1
2k Potentiometer	1
100k Potentiometer	1
10k Potentiometer	1
0.1 uF Capacitor	6
120 pF Capactor	1
1 mH Inductor	1
10mH Inductor	1
3.3 mH Inductor	2

Circuit Simulations

As with the variable pitch, the waveforms of the oscillator display a mixture of sinusoidal and significant noise factor. Although there is some change in voltage between near and far hand distances, the ampiltude itself is too low to be detected and to run the transistors in the following stages.

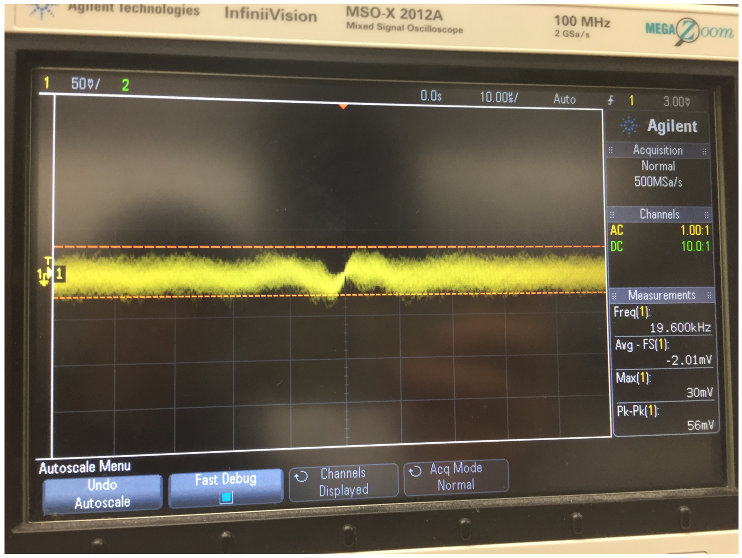

Figure 8: Volume - Hand at far distance

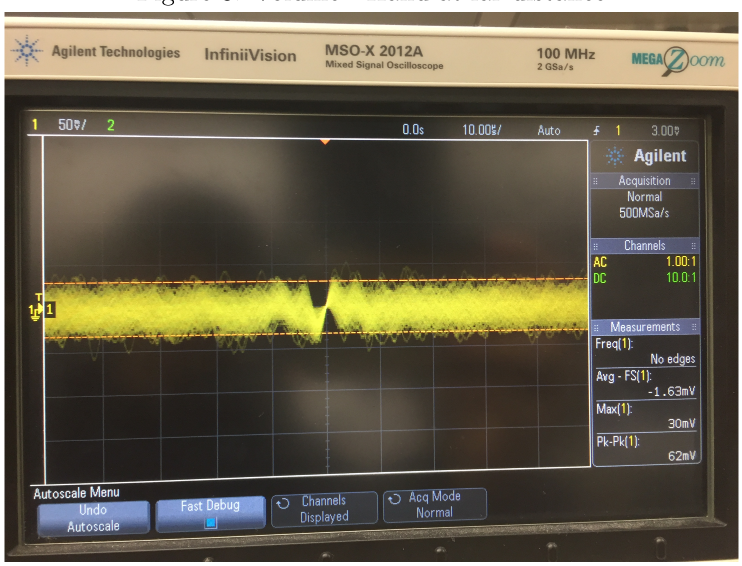

Figure 9: Volume - Hand at near distance

Circuit Implementation

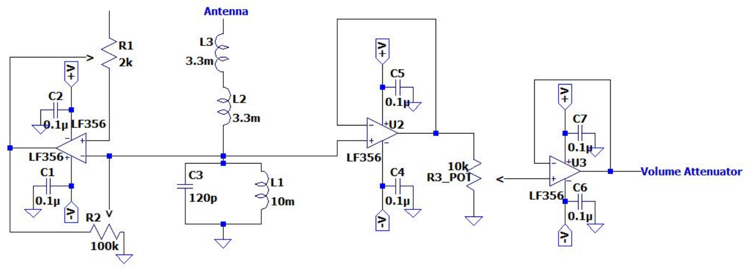

Figure 10: Volume Oscillator Schematic

Challenges
Volume oscillator has almost identical topology as the variable pitch oscillator, except that the LC network and resistance after buffer stage is varied for this circuit, thus it faced similar challenges as those while working with variable pitch oscillator. The antenna configuration as well as mounting, and working with variable capacitor posed some troubles as they all output unstable values at times.

Results

As with the variable pitch oscillator, the antenna was a serious issue for the volume oscillator as well. The loop antenna gave the input signal with significant noise added, when connected to the LC tank in parallel. The voltage was significantly lower than expected (2 mV) and the frequency of operation was difficult to pinpoint due to seemingly aperiodic waveform and noise.

Module - Freq to DC Converter

The first stage for attenuation is obtained by 3rd order LPF. This attenuates the signal above the cutoff frequency of 300 kHz by -60 dB/dec; the cutoff frequency should be lower than the volume oscillator frequency. The reason for 3rd order is to perform a large range of attenuation on a signal with small perturbations in the frequency. Then the peak detector circuit makes use of a diode (1N914) to rectify and then low pass filter.
Then the summing inverting amplifer with a gain of < 1000 allows for the volume to be completely attenuated when the capacitance is close to 0. This is designed to yield output in the negative voltage range to serve as the control for JFET in the attenuator stage. The output of this amplifer then goes through another 2nd order LPF to filter out 60 Hz noise, with cutoff frequency set at 6 Hz.

List of Components

Components	Count
9.1 k Resistor	1
68 pF Capacitor	1
13k Resistor	1
150 pF Capacitor	1
7.5 k Resistor	1
15 pF Capacitor	1
LF353	5
1N914 Diode	1
1.5 nF Capacitor	1
1k Resistor	3
100 k Resistor	1
5.1 k Resistor	1
1 Meg Potentiometer	1
250 k Resistor	2
0.1 uF Capacitor	1

Circuit Simulations

See embedded video video in the presentation slides.

Circuit Implementation

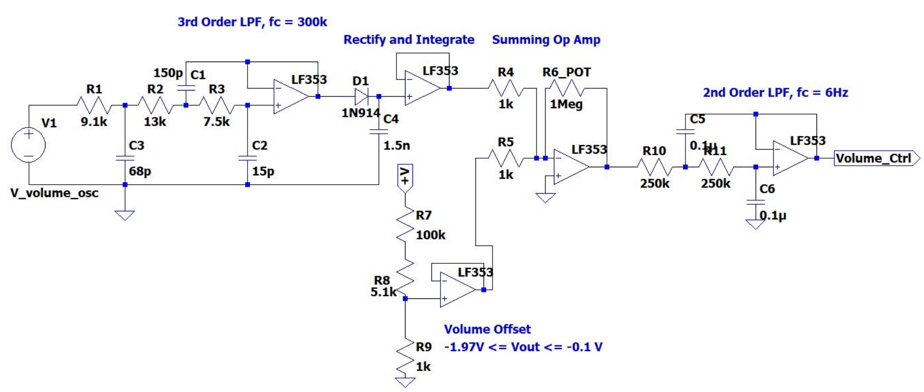

Figure 11: Frequency to DC Converter

Challenges and Results

Some challenges faced when designing and building was how to make sure we had a proportional DC value from our frequency. Additionally we had to be mindful of the next stage of the theremin where a DC value is used as a control signal for the attenuator. This was achieved with a summing circuit from an adjustable DC voltage value. At the end of the entire stage we initially forgot to filter out the inherit 60 Hz from the wall. We solved this frequency problem by using a Sallen-key filter with cutoff at 6 Hz.

Module - Mixer

The mixer component was made using a bipolar junction transistor where the two signals were sent into the base and collector. The output was then passed into a lowpass filter at $f_c = 20kHz$, which is the limit for the audible range. The next filter is a high pass filter at 200 Hz which is a decibel above the lower limit of the audible range. The final operational amplifier is a buffer to prevent the return of the next stage from interfering with the mixer component

List of Components

Components	
2N3904 NPN BJT	1
LF353 Op Amp	3
1k Resistor	1
5.1K Resistor	2
620K Resistor	1
13K Resistor	2
10k Potentiometer	1
1nF Capacitor	2
0.1μF Capacitor	1

Circuit Simulations

See embedded video video in the presentation slides.

Circuit Implementation

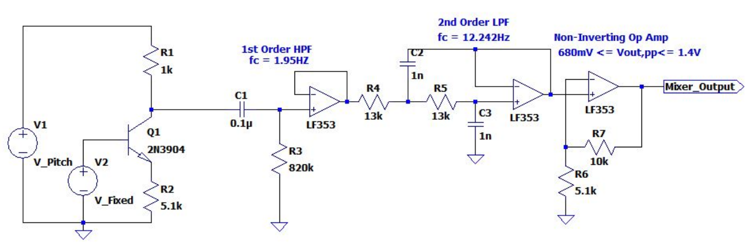

Figure 12: Mixer

Challenges

When designing the mixer, the main concern was to keep the frequency in the audible range, which required precise cutoff at frequencies out of range with the high- and low-pass filters. To that end, each filter was individually tested with different waveforms, and the first stage with BJT was also verified with square wave inputs of various frequencies arond the set pitch resonant frequency (a couple kHz offset). Such experimental testing ensured that inputs with noise could pass through this stage successfully.

Results

This mixer stage successfully output the difference of the two input frequencies was present in our implementation. When we measured at the collector of the BJT, the oscilloscope showed a sine wave imposed on the square wave. This result also matched the spectrum analyzer result where we saw two frequency ranges of peaks. Additionally, the filtered result made the upper frequency attenuate to the point where the analyzer no longer picked it up. Similar to the actual implementation, the LTSpice simulation shows that 3 kHz is the output frequency of the mixer when 168 kHz and 165 kHz are the input.

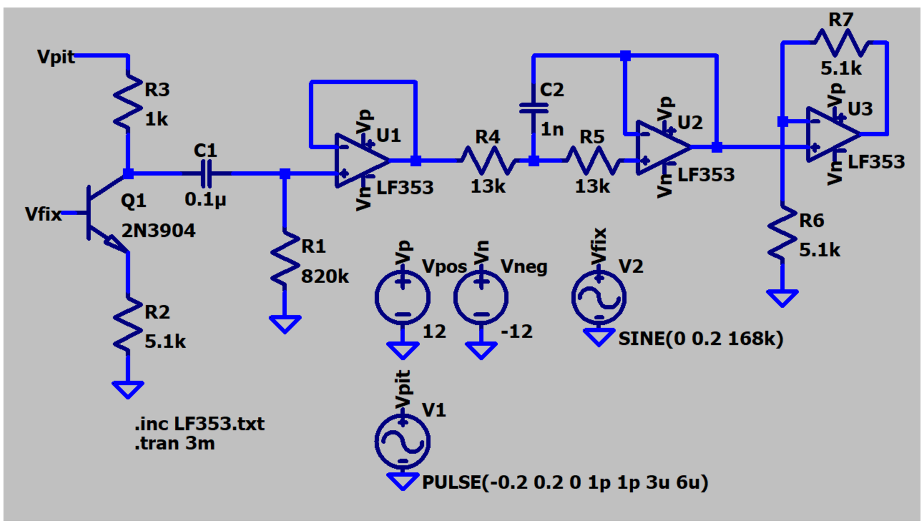

Figure 13: LTSpice Schematic

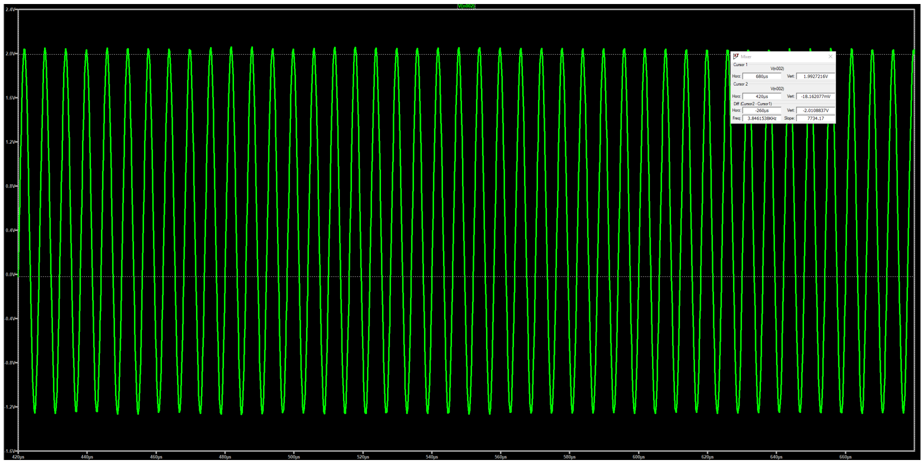

Figure 14: LTSpice Simulation Resulting waveform

Module - Volume Attenuator

The JFET used is 2N5457 because it was readily available in the lab, and it provides high AC/DC Input Resistance. The property of JFET we are interested in primarily lies in the drain resistance that can vary by the gate voltage (control).

List of Components

Components	Count
2N5457 JFET	1
470 k Resistor	2
10 k Resistor	1
LF353 Op amp	1

Circuit Simulations

See embedded video video in the presentation slides.

Circuit Implementation

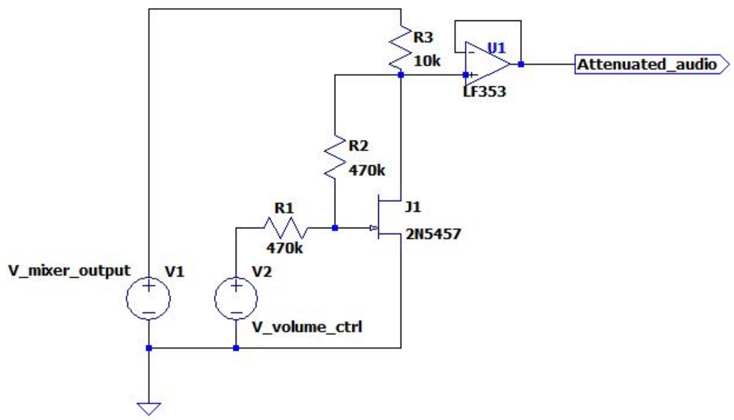

Figure 15: Volume Attenuator

Challenges and Results

As the initial design employs a control circuit out of the volume oscillator into the attenuator, the conversion from AC to DC stage was crucial for controlling the attenuation in volume (subsequent stage). Although the volume attenuator did lower the input voltage (the mixer output), the output voltage swing from the previous stage was not enough; this implies that a differential amplifier would be better suited for the task of increasing the output voltage sweep.

Module - Voltage-Controlled Audio Amplifier

The purpose of this circuit is to be able to adjust volume of the output in case of a too week signal. The op amp for this should be able to provide low input bias and offset currents, and low offset-voltage temperature coefficient.

List of Components

Components	Count
10k Resistor	3
0.001 uF Capacitor	2
25 k Potentiometer	1
LF411	1

Circuit Simulations

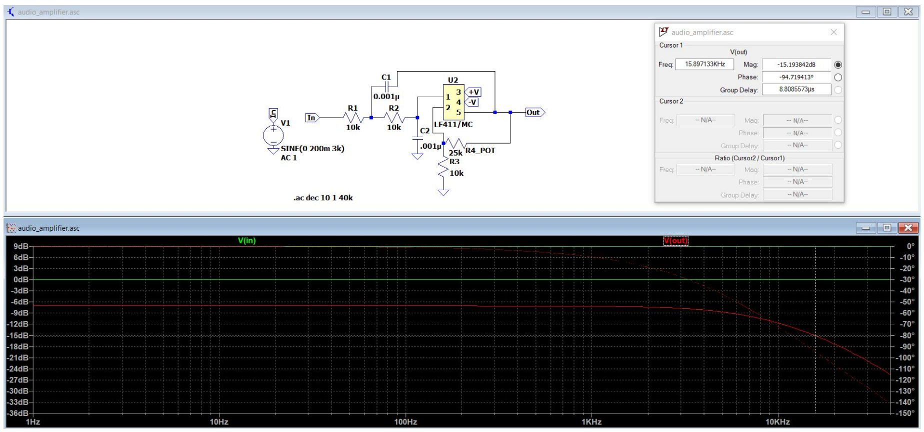

Figure 16: Audio Amlifier AC Sweep, $f_{cutoff} = 15\text{kHz}$

Frequencies higher than the cutoff frequency of 15,915 Hz are attenuated, and the signal is amplified by at most gain of 3.5.

Circuit Implementation

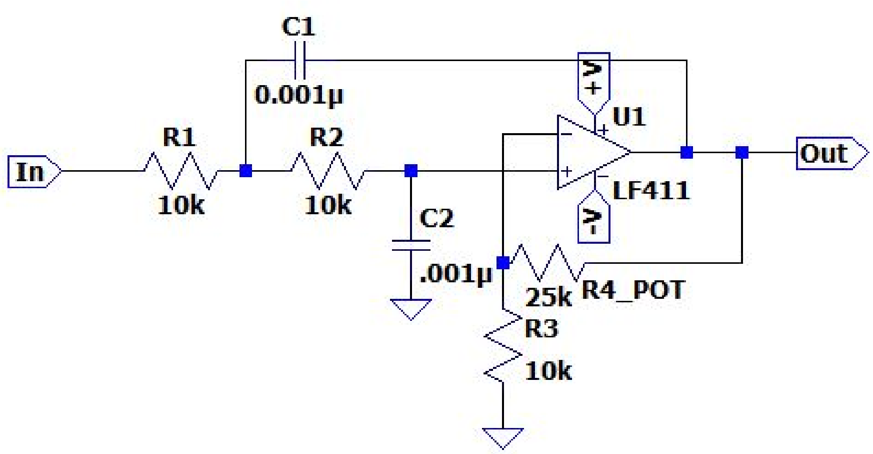

Figure 17: Audio Amplifier

Challenges
This circuit was fairly simple to build without debugging. Initially a simple closed-loop non-inverting amplifier was tested, but for better stability and removing unwanted noise this configuration was employed.

Results

The voltage controlled audio amplifier circuit had functioned correctly, providing a gain of 3 to the input signal which allowed the sounds from the theremin to be more pronounced. While this part of the circuit was not able to be used in conjunction with the antenna circuit, it had functioned correctly with the mixer circuit, using a function generator to produce a simulation of what the antenna signal would have been.

Overall Results

The final theremin in integration with all sub circuits faced troubles configuring the antenna in the oscillators for input, and thus this prevented from proceeding further into the successive stages. Although other stages worked by themselves very well, the correct input signal could not be run through them to test if they work properly with the actual signal generated by waving hands around the antenna. The nonlinearity and noise embedded in the signal was fairly difficult to work with, and required debugging with various pairs of LC and feedback networks. In addition, the susceptibility of each stage built on breadboards posed difficulties as well through the inherent lack of consistency in the response and potential coupling capacitance effects at times.

Resonant Frequency Matching
In testing variable pitch oscillator functionality with the antenna, the resonant frequency was experimentally chosen to be 253 kHz, with L = 3.3 mH, C = 120 pF, which at some point the pitch antenna was able to produce. The purpose of matching the frequency from the antenna at resonance is to mitigate producing of sound when there is no change in capacitance from the antenna. For volume oscillator, $f_{resonant}$ = 459 kHz, with L = 1 mH, C = 120 pF. (values based on references).

Ideally, the desired responses that result due to deviations from the specified resonant frequencies include:
For pitch:
- Hand closer: capacitance increases, frequency decreases, causing beat frequency

For volume:
- Hand closer: capacitance increases, frequency decreases, out of resonance, de-

creases voltage across inductor in LC tank, lowers volume control DC voltage, attenuates the amplitude.

Closer Look at Oscillators with Antenna
Although unsuccessful at tuning the frequency of the antenna, we were able to point out that the amplitude of signal from the antenna was too low to work with (around 2 mV).

Conclusion and Future Work

Although a theremin circuit consists of pretty simple-to-build subcircuits, tuning and driving with the intput from two antennas ws the most important and difficult aspect of the project. Having antennas of no specifications provided, it was somewhat troublesome in determining the right resonant frequency at which the variable frequency matches such that no signal is output from the oscillator when the hand is infinitely far away. However, we were at the same time able to acquire insights in working with conversion to DC to control JFET-based attenuator, mixing two signals using a FET, closely matching LC tank resonant frequency with given antenna input signal.
Had we been provided with more time and resources, we could have obtained a rather stronger-input-giving antenna and tried to match it to the resonant frequency of an LC sine wave oscillator, with L and C values determined from precise measurement of the antenna's capacitance as in Equation 1 and 2.

References

[1] Barkhausen Stability Criterion. (2002, November 14).
Retrieved from http://web.mit.edu/klund/www/weblatex/node4.html

[2] Brito, P., Gomez, D., & McCabe, P. (2012). 6.101 Final Project (Rep.).

[3] The Harrison Instruments 302 Theremin. (2017).
Retrieved from https://harrisoninstruments.com/302/302_description.html

[4] Theremin. (n.d.). Retrieved from http://web.physics.ucsb.edu/ lecture-demonstrations/Composer/Pages/60.17.html