Constructing a Theremin

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Spring 2016
Physics 406

Introduction

The theremin is an early example of an electronic instrument. Invented by Leon Theremin in 1928, it applies the principle of heterodyning to two signals in order to generate a tone in the audio frequency range. The key to its invention, however, was the hand capacitance effect, which Theremin noticed as he was working with a device which was generating an audio tone. As he moved his hand with respect to the device, the pitch changed. From this, he designed the instrument which would become known as the theremin. The general goal of this project was to explore the design and build process of this fascinating instrument.

Principles of Operation

The two essential concepts in the operation of a theremin are heterodyning and oscillator design. The first comes from radio signal processing, and works because of the following trigonometric identity:

$$\sin\theta_1 \sin\theta_2 = \frac{1}{2}\cos(\theta_1 - \theta_2) - \frac{1}{2}\cos(\theta_1 + \theta_2)$$

This can also be understood in the frequency domain as follows:

$$f(t)\cos(\omega_o t) \leftrightarrow \frac{1}{2}F(\omega - \omega_o) + \frac{1}{2}F(\omega + \omega_o)$$

Where the lower case f represents the time domain function and the upper case F represents the frequency domain function. Essentially, a multiplication by a single-frequency sinusoid simply acts as a frequency shift, so by multiplying a sinusoid by a sinusoid, the result is two shifted sinusoids. This principle is also used in devices such as the superheterodyne radio receiver.

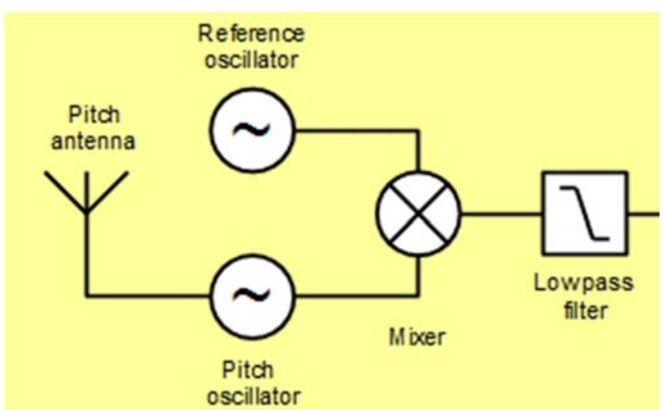

Figure 1: Basic Theremin Concept
Image under Creative Commons Share Alike License – author DF5GO on Wikipedia

Oscillator design comes into play because of how the pitch is altered on a theremin. There are two oscillators which are at nearly the same frequency. One is altered via a change in capacitance. For example, a Colpitts oscillator in a common collector orientation will oscillate according to the following equation:

$$f_o = \frac{1}{2\pi\sqrt{L\left(\frac{C_1 C_2}{C_1 + C_2}\right)}}$$

This has an obvious dependence on the capacitance of the circuit. Even without an antenna, this oscillator will shift if one's hand is brought near it, since the body basically acts as one plate of a capacitor connected to ground. By adding an antenna to one oscillator, it can be shifted with respect to the other oscillator. This allows the heterodyned signal to be somewhere in the audio range.

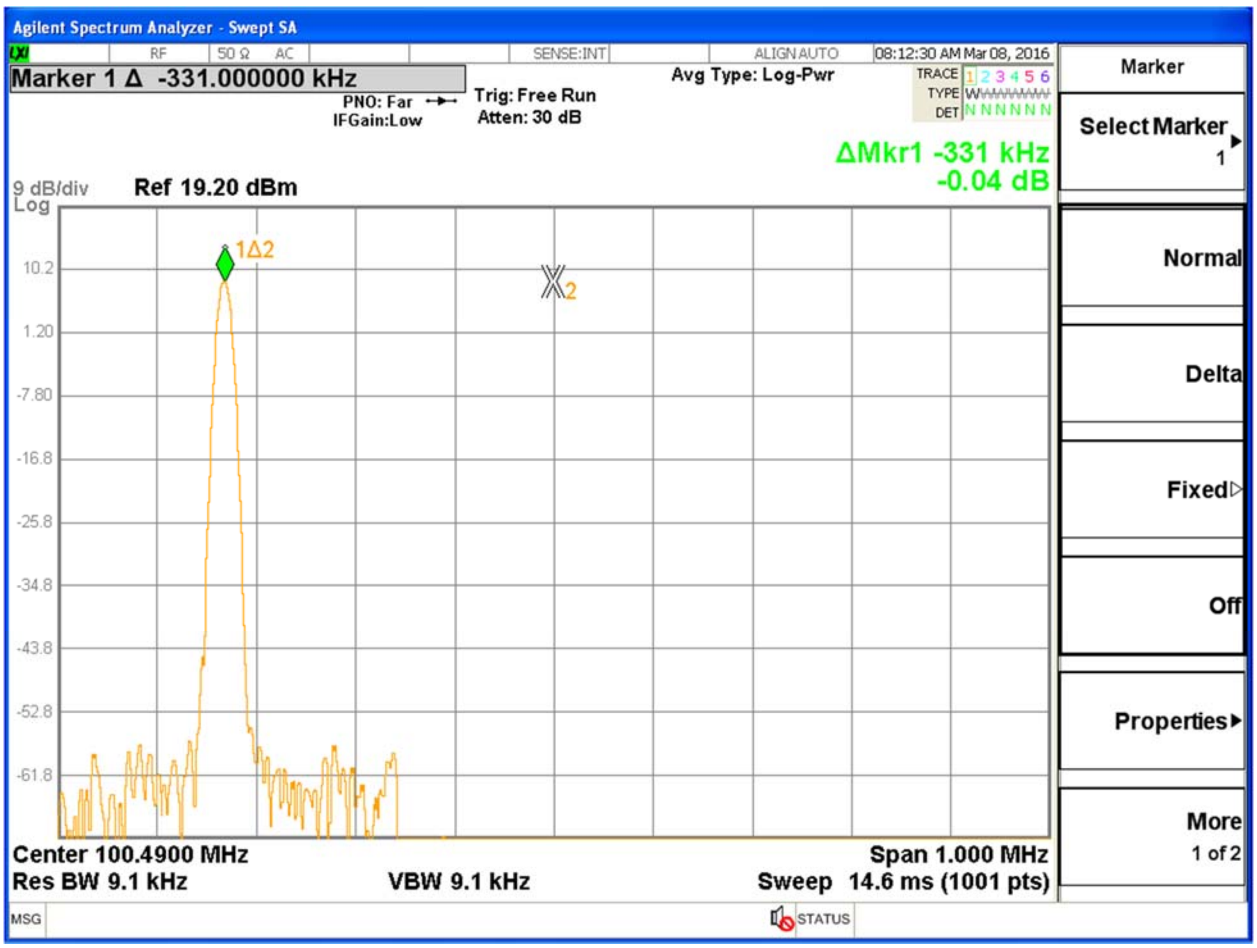

Figure 2: Demonstration of Hand Drift in Voltage Controlled Oscillator - >300 kHz drift

This was done in ECE 453 lab, using a VCO built in that lab

Starting Design

In the interest of saving time, this build used a starting design found on ThereminWorld.com. This particular design was chosen because it manages to be quite simple while still remaining familiar to me, as I have experience with oscillators and mixers built with lumped components. It was designed by Thierry Frenkel.

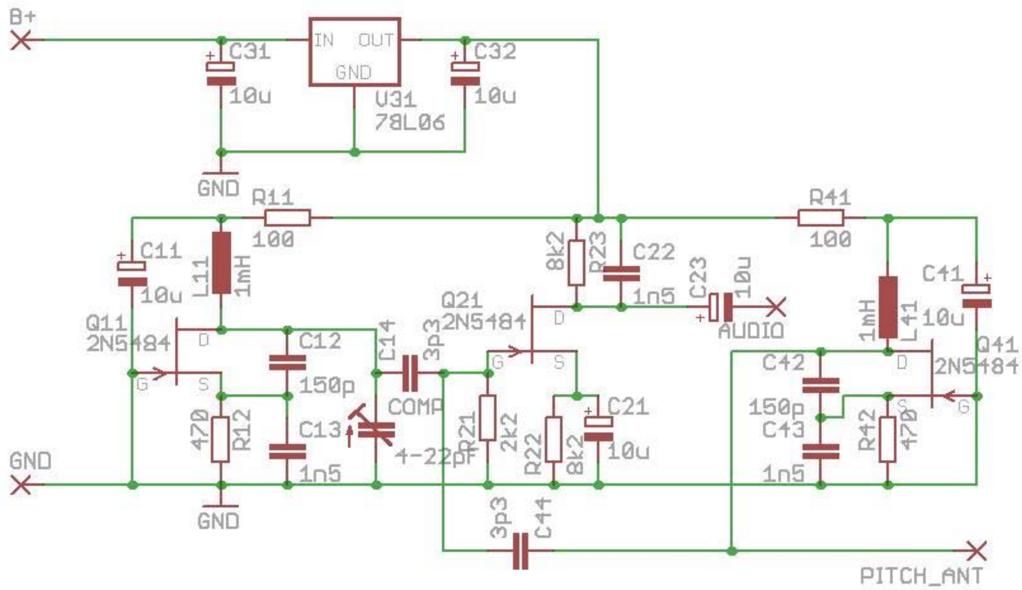

Figure 3: Starting Design by Thierry Frenkel

This design was tweaked in order to better suit parts that were more easily available than the ones in the original design. For example, the original 2N5484 transistors are out of production. These were eventually replaced by 2N4393 transistors, but not before problems with NTE466 (2N4392) transistors were used instead. The NTE466s were much easier to find, but did not function properly in the complete circuit. They do, however, work individually in parts of the circuit – they work just fine when replacing a single transistor in the entire circuit. The other most significant change was that the DC blocking capacitors were changed to 0.1 MFD instead of 10 MFD. At 400 kHz:

$$X_{0.1\text{MFD}} = \frac{1}{2\pi(400\text{ kHz})(0.1\text{ μF})} = 3.9788\ \Omega$$

$$X_{10\text{MFD}} = \frac{1}{2\pi(400\text{ kHz})(10\text{ μF})} = .039788\ \Omega$$

While this means that there is a difference between the two choices, at the oscillation frequency, they are both low impedance, especially since the other impedances in the circuit are usually on the order of 100 Ω. That exact voltage regulator was not used either, although this doesn't make much of a difference.

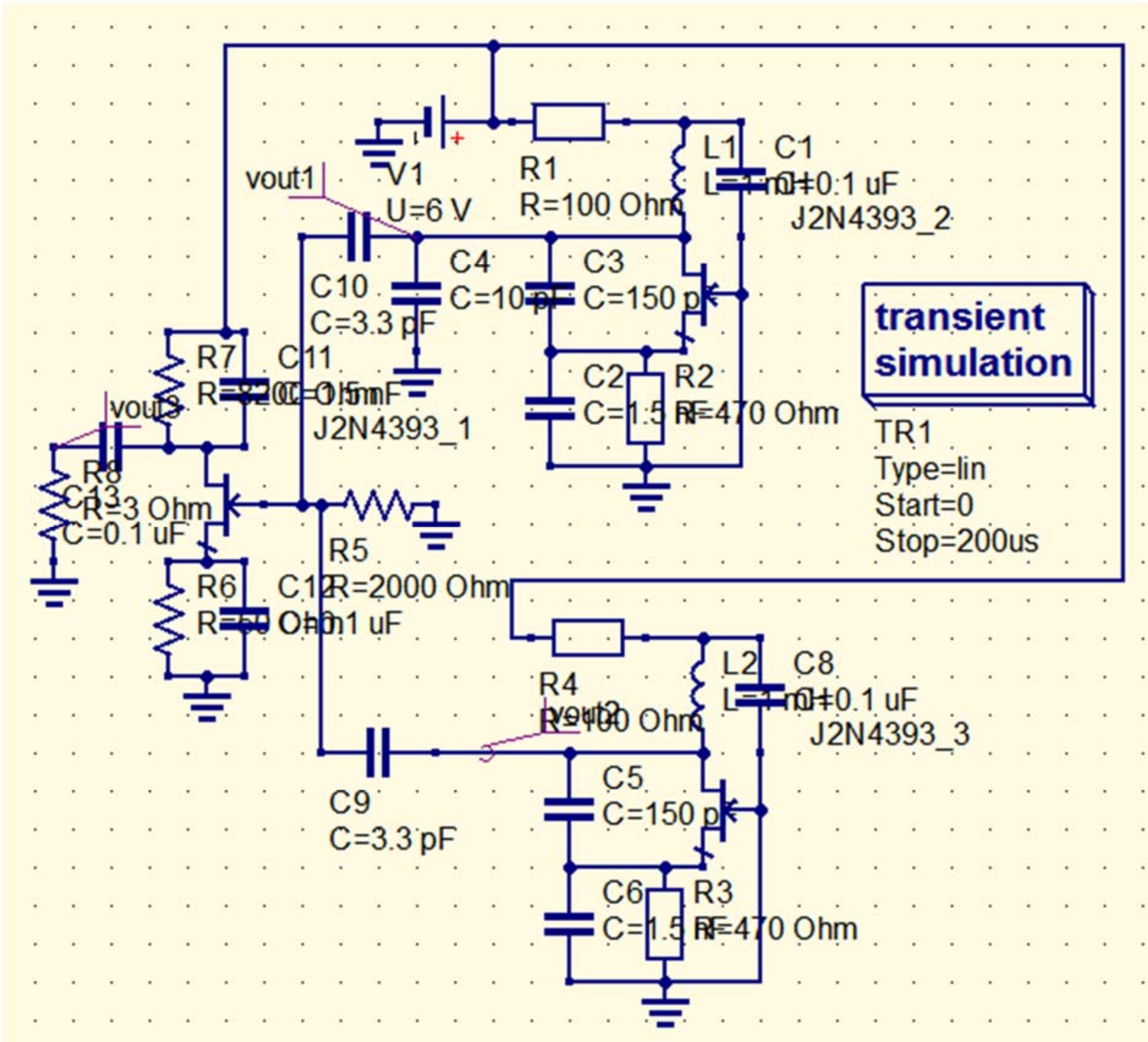

Figure 4: Design as Constructed – this omits the tuning capacitor
Capacitor C4 represents the antenna

Simulations

To back up the changes made as detailed above, the circuit was simulated in the "Quite Universal Circuit Simulator," or QUCS. This assured me that the 2N4393 transistors would work. Due to misreading the circuits, it also convinced me that NTE466s would work. They do not, but because they were easy to find, they wound up in the original prototype anyway.

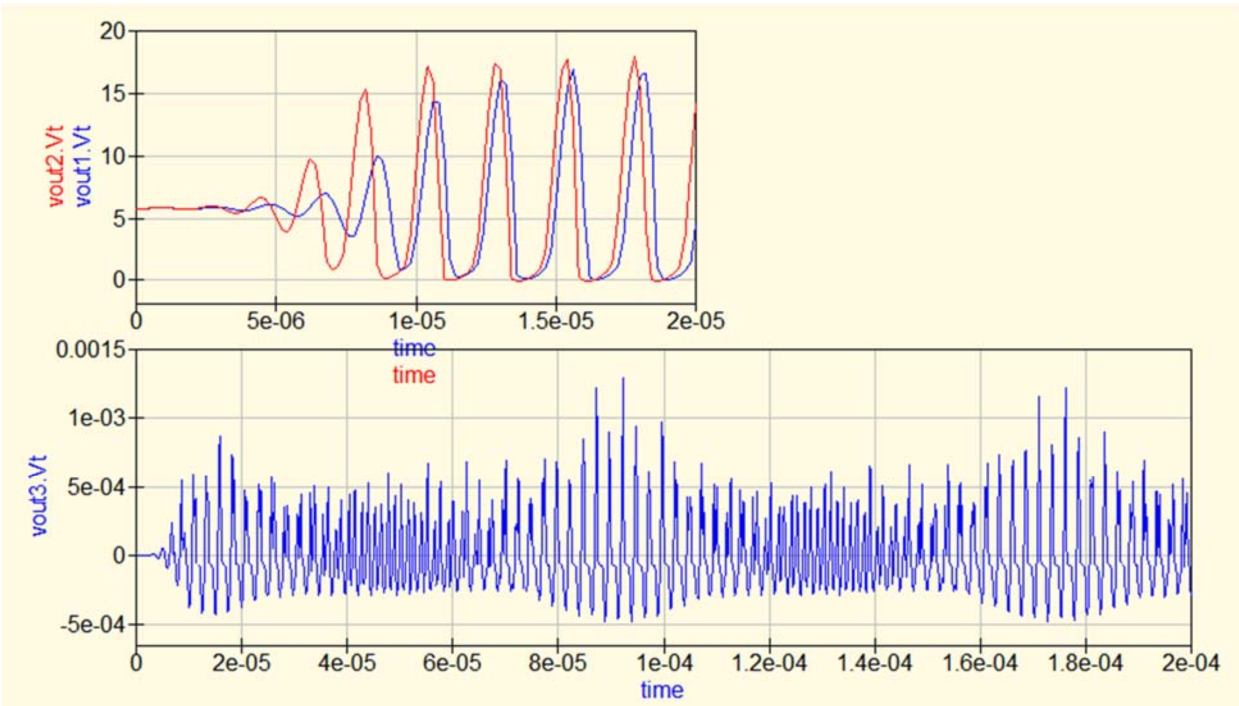

Figure 5: Simulations. Top: Outputs of both oscillators; Bottom: Total output.

The high-frequency noise that shows up in the output arises from the two inputs of ~400 kHz. This time domain plot was used because the voltages of the outputs were also under test.

Construction

This circuit was soldered directly onto a protoboard. While it could technically have been breadboarded, the increased parasitic capacitances in the setup would likely have cause problems in the circuit. This is a problem which begins to occur as frequency increases, since the stray capacitances present in a breadboard begin to look increasingly like short circuits as the frequency increases. It is still possible to create stray capacitances while using a protoboard, but the likelihood is lower, especially if the layout is carefully considered or the oscillation frequency is not tremendously high. In this case, the oscillation frequency is not high enough to necessitate much special care beyond not breadboarding, and would likely be fine into the low megahertz range. The original result is below:

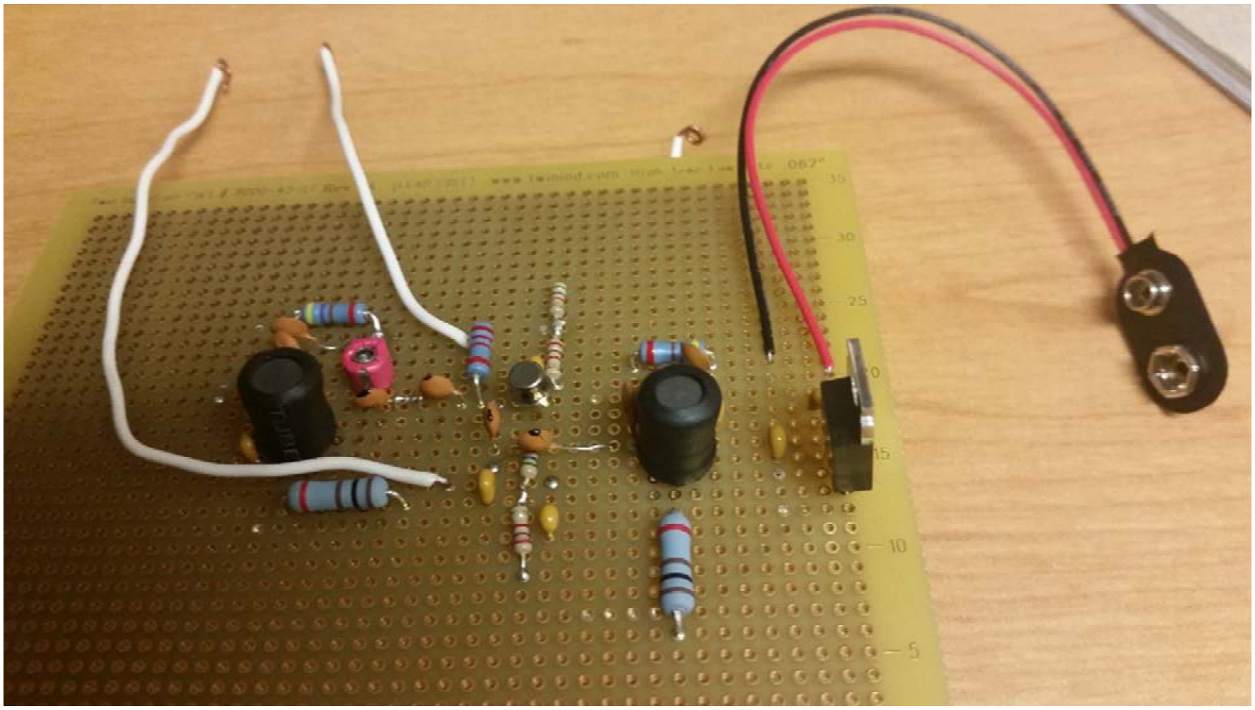

Figure 6: Theremin with NTE466 Transistors
White wires, from left to right: Audio Output, Audio Ground, Antenna Connection

This used NTE466 transistors, which are not the correct transistors. It was therefore necessary to cut them off and insert 2N4393s in their place:

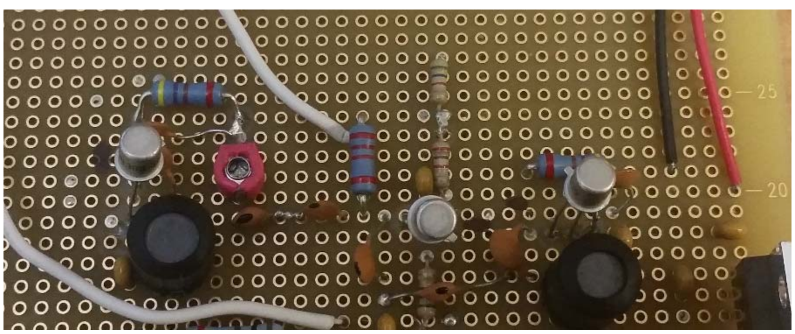

Figure 7: Theremin with 2N4393 Transistors

There is not a board mounted audio jack because one could not be found whose leads fit in the protoboard's holes.

Playing

Now that the correct transistors are inserted, the theremin generates actual audio frequency tones. These tones are very high in pitch, and somewhat unpleasant, but adjustment of the tuning capacitor can make them somewhat tolerable. The issue now lies in the exact oscillation frequencies of the two oscillators, and in the capacitance of the antenna. With only a ~25cm copper wire as the antenna, and the tuning capacitor set correctly, the pitch can be shifted, except it works opposite to that of a normal theremin. This is either because the variable oscillator is too high in frequency or the fixed oscillator is too low in frequency. Since the problem is fixed with the addition of additional capacitance to the antenna, it seems likely that the variable oscillator is too high, since its oscillation frequency decreases with additional capacitance. Below is a playable configuration:

Figure 8: Playable Antenna Configuration

The three tools are acting as part of the antenna. Off-camera to the left is a spool of solder which is attached by the leftmost pair of diagonal cutters. This is also part of the antenna. With all this added capacitance, the playable area extended about a foot from the antenna. Ignoring the impracticality of this setup, another issue was the tremendously nonlinear performance. This was expected, as it was guaranteed to be nonlinear, but when playing within a few inches of the antenna, twitching slightly will change the pitch. This can be tempered with series inductors, but this was not tested since the antenna is not permanent anyway. The range was around A4 up to A7, although the last 1.5 octaves are basically uncontrollable since they are played so close to the antenna.

For the Future

The main task for the future is obviously to fix the antenna such that it works without impromptu modifications needed. This can probably be done by mounting it with a plate at the end, which would act as one end of a parallel plate capacitor. This fix should allow the theremin to be played. The next step is attempting to make the response more linear, which can probably be done with series inductors, but this will need further investigation. Beyond that, volume control should be added, but at the moment there is none besides whatever outside amplifier and speaker combination the theremin is attached to.

Overall, this project taught me a lot about application of things like heterodyning and oscillators. It was also very interesting attempting to play the instrument, and I look forward to fixing up the antenna and being able to actually play a tune.

References:

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