The Theremin

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Bachelor of Science in Physics
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By
Derek G. Fleck
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David P. Belanger
Technical Advisor

David P. Belanger
Supervisor of Senior Theses

David P. Belanger
Chair, Department of Physics

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Introduction

The Theremin, or Aetherophone as some called it, is a musical instrument that creates tones and pitches through the free movement of a person's hands. This instrument may seem magical at first, but it simply works through two simple processes, capacitance and heterodyning oscillators. The goal of this project is to understand, build, and later improve upon the resulting Theremin, using CAD software as well as basic/traditional circuit elements.

i. History

The Theremin was named after its inventor, Leon Termen, a Soviet born physicist in 1917, however it was not until 1920 when the Theremin was made with its traditional pitch controlling antenna and volume controlling antenna. Seven years later, Leon emigrated from the Soviet Union to the US and one year later was granted a patent. From then on, RCA sold Theremins throughout the 1930's. In 1951, the Theremin became a huge hit by becoming popularized as the scary sounds in the classic movie *The Day the Earth Stood Still*. A couple of years later in 1954 Robert Moog, inventor of the Moog Synthesizer, wrote an article in Electronics World Magazine debuting his improvements on the Theremin. Incidentally, this Theremin was the inspiration for this project, and the Theremin that I will be showing is a rather simplified version of his masterpiece. Clara Rockmore is the most noted Thereminist and is one of the only few people that can make it sound pleasing. After Jimmy Page played the Theremin on the Led Zeppelin album, *The Song Remains the Same*, the Theremin died in popularity, only having a recent revival in the 90's with a documentary *Theremin: An Electric Odyssey* by Steven Martin. Today Theremins are only produced by Moog Music, in its transistorized form, and by those encapsulated by its beauty and inspired to create their own.

ii. Tubes

Vacuum tubes have become obsolete within the past few decades, after the invention of the transistor. Transistors can do most everything that tubes can do while using less power and less monetary resources. As of late tubes have come back on the rise with guitar players insisting on using tube amps. But why use tubes? There is something about tubes that just makes the experience of playing an instrument more romantic and sensual than that of transistors, though it could just be the heat they give off.

This Theremin relies on tubes as its source of gain. The structure of a triode is simple and easy to understand, shown in Fig 1 below. [1]

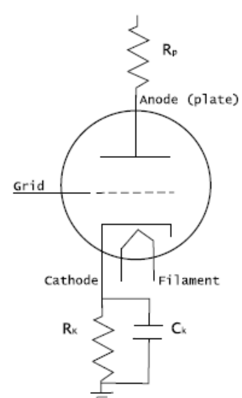

Figure 1: Diagram of a Tube Triode

The filament of the tube is the heater that heats up the cathode, and frees electrons to flow toward the positively charged anode. With nothing in between the cathode and anode, we allow current to flow no matter what, and essentially have a tube diode. The introduction of the grid allows a source to control the flow of electrons from the cathode to the anode. This is done by making the grid more negatively charged than the cathode so there is a higher potential to get over. Now if the grid were a plate, no current would flow from the anode to the cathode; but because it is a mesh or fence, points in between the mesh have a lower potential. Once these minimums in the potential become small enough so the tube isn't operating in "cutoff", electrons can flow down this "potential hill". [2] When a signal is put onto the grid, the signal is inverted, making it an inverting amplifier. This is because when the signal goes more positive, more current flows lowering the plate voltage, and when it goes more negative, the plate voltage increases. The gain of a triode is given by the expression; [3]

$$A_v = \frac{\mu R_a}{R_a + r_p} \qquad \text{1-1}$$

Where R_a is the system of load resistors seen by the tube, r_p is the internal plate resistance of the tube (found on data sheet), and μ is the amplification (found on data sheet).

Another point to note about tubes is that it has some internal capacitance. Because of this internal capacitance, the tube automatically creates a low-pass filter with the previous stage load. The frequency that the signal gain drops by a factor of square root 2 is called the 3dB point and for any low-pass or high-pass filter is given by; [2]

$$f_{3db} = \frac{1}{2\pi RC} \qquad 1\text{-}2$$

For this Theremin, 4 12AU7 triodes were used, as well as a 5Y3GT tube rectifier and a 6V6 pentode power tube. The pentode will be explained further in the power amp section.

Overview

Figure 2 shows the Theremin in its entirety on the following page. The three main sections are, from top to bottom left to right, the power supply, power amp, and the Theremin.

The actual signal starts from two coupled oscillators, which are sent through three preamp tubes for initial gain. The last of these preamps is controlled by another high frequency oscillator which very similar to the signal oscillators. From here, the output is taken as a common-cathode amplifier and then sent to the power section and then to the speaker.

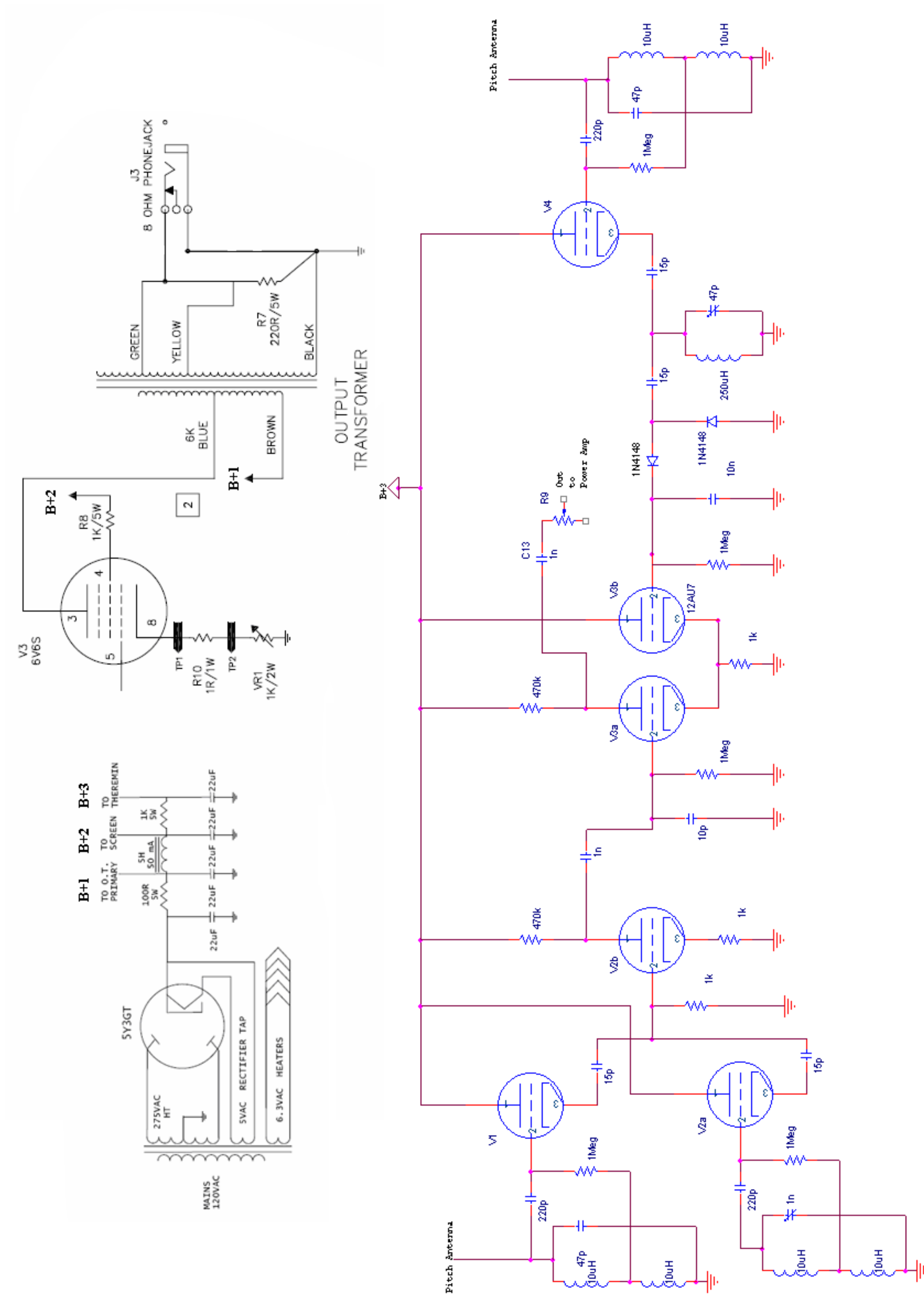

Figure 2: Schematic of Theremin [4][5]

Breakdown

i. Hartley Oscillator

The Hartley oscillator is an LC-oscillator whose frequency goes like,

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad 3\text{-}1$$

and is truly the heart of this Theremin. The advantage of the Hartley oscillator over other LC oscillators is that they are usually made with a variable capacitor for exceptional tunability; however, only one of these oscillators in the Theremin is made with an air-gap capacitor for reasons that will be explained later.

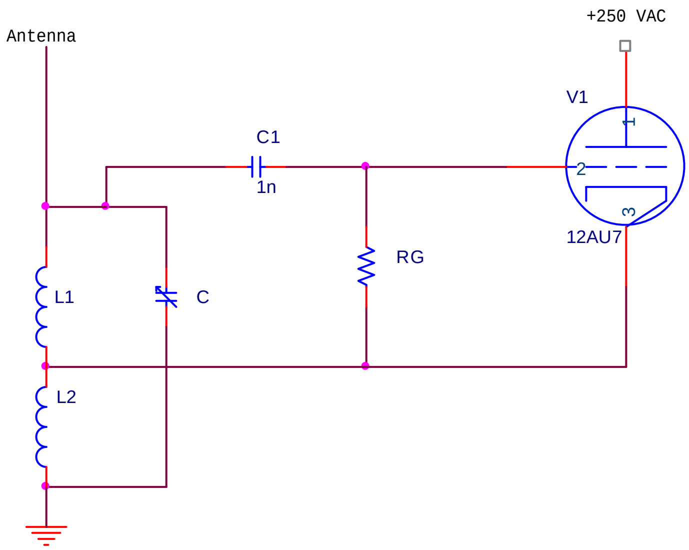

Figure 3: Hartley Oscillator

Figure 2 shows a generic Hartley oscillator used for the Theremin. The inductor of the oscillator that determines the frequency is a tapped inductor, which in the figure below is represented by two inductors in series, where L=L1+L2. At first glance, this circuit seems like it should not oscillate, because all of the voltage should be stored on the plate. The way the Hartley oscillator works is that it relies on the grid leak bias to operate, which is determined by choosing specific values of C_g and R_g at which to operate the tube. C_g acts as a coupler to apply the ac signal to the grid of the 12AU7. When the signal is positive the grid becomes positive relative to ground, thus creating a current through R_g, which results in a dc-voltage across R_g being polarized, positive at the cathode. When the signal becomes negative, the grid is held negative by the discharging capacitor and the signal, so the current runs through R_g, but not to the grid, now just to the left loop to C_g again. This RC grid bias time constant should be relatively long compared to the incoming frequency, but not too long as if it is too long not enough current will flow to bring the tube out of cutoff.[6] All of the Hartley oscillators in the Theremin have a grid bias time constant of 2.2μs.

The addition of the antenna to the Hartley oscillators is the reason that there is no air-gap capacitor in the pitch control and volume control oscillators. When the antenna is added, it is essentially extending a control to one plate on the capacitor and making it have variable capacitance. By moving a grounded object, say a hand, close to this antenna you create a hand capacitance. So when the antenna side of the capacitor is negative, the antenna stores some negative charge because your hand attracts negative charge. Likewise when the signal's phase changes by 180˚ your hand will store positive charge in the antenna, overall lowering the capacitance of the oscillator, and increasing the frequency. For example, the lowest capacitance you can give this antenna would be to be relatively far away from it, about one foot; the highest capacitance that you can give it would be to make a cylinder around it. From simple electrostatics we know that the electric field per unit length for an infinitely long cylinder is given by

$$\vec{E} = \frac{\lambda}{2\pi\varepsilon_0}\frac{1}{r}\hat{r} \qquad 3\text{-}2$$

so the potential becomes;

$$V = \frac{\lambda}{2\pi\varepsilon_0}\ln\left[\frac{r_{hand}}{r_{antenna}}\right] \qquad 3\text{-}3$$

and the capacitance becomes;

$$C = 2\pi\varepsilon_0\left(\ln\frac{r_{hand}}{r_{antenna}}\right)^{-1} \qquad 3\text{-}4$$

To understand the change in frequency obtained with the addition of a hand capacitance, we can plug in some numbers; r_{hand}~ 1cm, $r_{antenna}$ ~ .25cm, and into get a full capacitance integrate over the length of a hand ~ 8cm. This gives an overall capacitance of roughly **3pF**. For the pitch oscillator, which is oscillating at a frequency of 700kHz, the addition of 3pF only changes the frequency out put by 1%, which is actually 7000 Hz. Adding this small capacitance to a much higher frequency, around 1MHz, changes the frequency by about 3%, corresponding to a 30kHz swing. This fact gives a very sensitive volume control, and moving about three inches will go from volume completely on to completely off.

At 1 MHz, internal tube capacitance does start to attenuate the signal, however for purposes of the volume this is acceptable because of the sensitivity that is made by the volume control preamp.

ii. Pitch Preamp

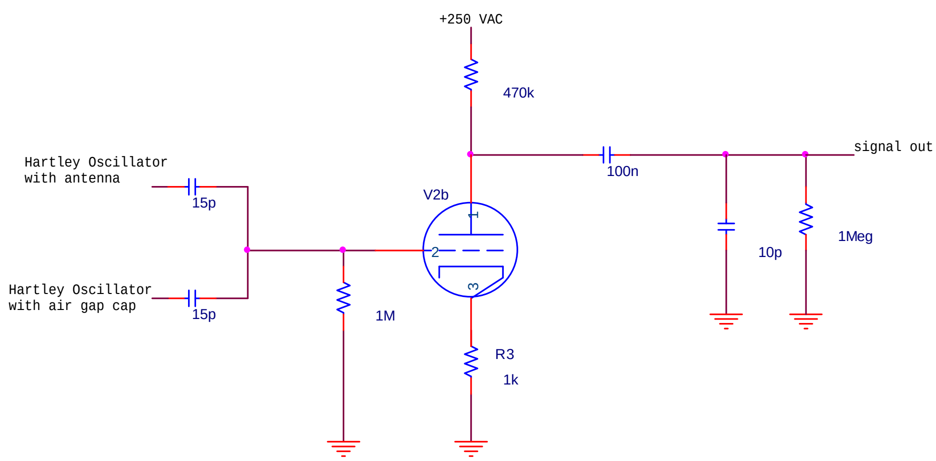

Figure 4: Schematic of Pitch Preamp

After the signal that is produced by the Harley oscillator, the signal should only be about 1V. Both signals from the two oscillators are coupled together, each with a 15pF coupling capacitor, and when they are coupled see a 1MOhm resistor, which with the coupling capacitors form high-pass filter, cutting off frequencies below about 10 kHz, created by the grid-leak bias. From here the signal controls the grid of the second triode enclosed in V2. The triode has a 470k plate resistor and a 1k cathode resistor. From the plate the output is coupled by a 0.1µF capacitor to block the DC plate voltage and keep it from affecting the grid bias on the next amplification stage. At this point the coupled signal is a combination of two sine waves of arbitrary phase, one coming from each oscillator. The superposition of these two waves creates a beat frequency that is audible which is equal to the difference of the frequencies, as well as a term that is the addition of the frequencies. The wave form then appears to be;

$$A\sin(\omega_1 t) + A\cos(\omega_2 t) = 2A\sin(\frac{\omega_1 + \omega_2}{2}t)\sin(\frac{\omega_1 - \omega_2}{2}t) \quad 3\text{-}5$$

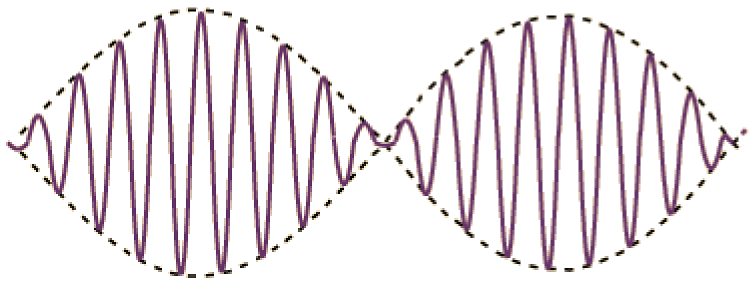

Figure 5: Superposition of Two Sine Waves

In order to block out the RF signals, a 10pf capacitor is added to ground, and in combination with the input load, creates a low-pass filter that attenuates everything above 100kHz. Using equation 1-1, the setup for this section should give a gain of 15 for frequencies less than 100 Hz.

iii. Volume Control Filtering Section

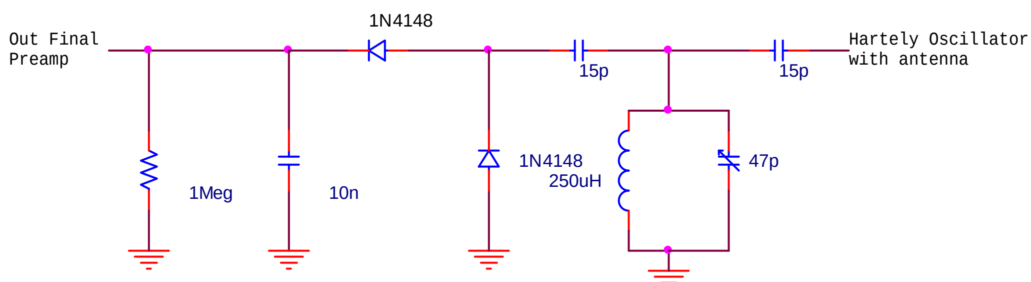

Figure 6: Schematic of Filters for Volume Control

The volume signal once again comes out of another Hartley oscillator, however tuned to a higher frequency so that it doesn't interact with the pitch oscillators. The output from the Hartley oscillator is coupled to a LC band pass filter through a 15pF capacitor to block out the dc cathode voltage. This band pass is tunable with an air gap capacitor and will attenuate all frequencies except a small range centered around the frequency of the output of the Hartley oscillator. The fact there is a sharp fall off when frequency is changed by a few kilohertz, is the main reason that the volume is very touchy. I.e. by having your hand away from the antenna you will have no attenuation and a large output voltage, and when you bring your hand closer you will decrease the output. After the LC, there is another 15pF capacitor to help the filter attenuate low frequencies. This is then connected to a system of two 1N4148 silicon diodes -- one is reversed bias to ground and the other is forward bias to the grid of the next amplification stage. This system of diodes acts as a rectifier, which cuts the waveform, and then smoothes the waveform by sending the signal to a 10nf capacitor to ground and a 1 Megaohm resistor to ground. This stage established a relatively smooth dc signal to drive the grid on V3b.

iv. Coupling of Volume and Pitch Signals

The coupling of the volume and pitch signals is quite simple. It starts from the input of a near dc signal from the volume control, which is fed into the second triode section of V3. From the output of this triode, the cathode, there is a resistor to ground as well as a capacitor to ground. The values for these elements are for intents and purposes, arbitrary. The resistor is responsible for setting the gain of the pitch signal, and the capacitor rolls of the high frequency ripples, a 10k resistor and a 1μF capacitor were used. The resulting signal out of V3b is such that when you bring your hand closer you are raising the voltage (making it less negative) coming out of the cathode of V3b, which controls the cathode of V3a. The grid is connected to the pitch output, which is now a perfect sine wave with frequency of f_1-f_2.

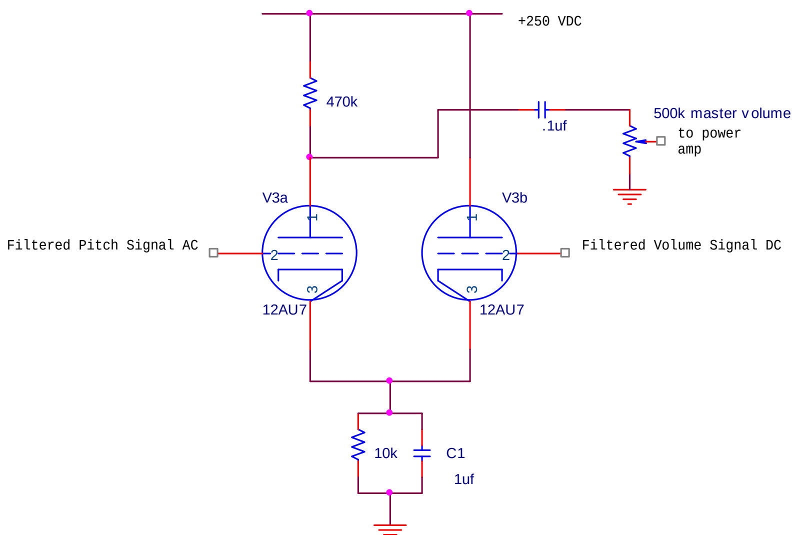

Figure 7: Circuit of Final Preamp

Because the grid is more negative than this cathode, bringing the cathodes potential less negative will only make the tube in cutoff, so by when your hand goes away from the volume antenna you bring the potential down and create a flow of electrons to the anode. Here the output is taken from the output, making this stage a common-cathode amplifier, this is then sent through a 0.1μF blocking capacitor, then to a 500 k potentiometer which is the master volume control, to make sure we don't always output at maximum power, and finally to the power amp.

v. Power Amp

The power amp is really just part of the Theremin so we can plug it into a speaker and control the power output. The schematic could stop before this and just output to a 1/8” jack to speakers that have built in amplifiers, but this Theremin is to play live or with a band through a speaker cabinet.

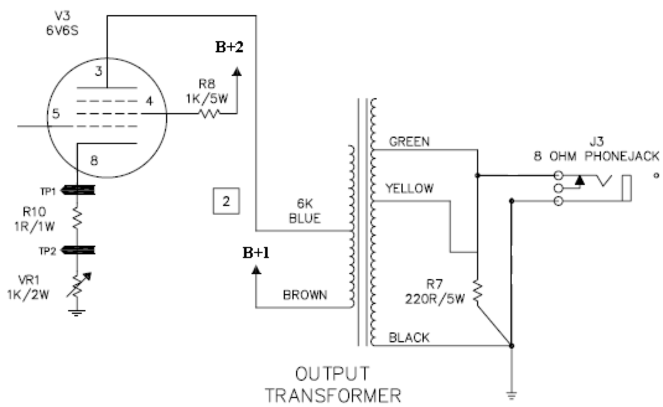

Figure 8: Schematic for Power Amp and Output

This power amp uses a 6V6 pentode tube as an amplifier. This tube has five elements, an anode, cathode and three grids. The addition of two grids, the screen grid and the suppressor grid, make the tube better suited for power amps because they are designed to give the maximum output power with minimum distortion. [2] The suppressor grid is internally died to the cathode, and therefore negatively charged, while the screen grid is tied to the plate voltage through a 1k resistor.

The cathode of this power amp is tied to a 1k potentiometer which is tied to ground, which makes this amp cathode biased. This potentiometer is used to set the quiescent current through the 6V6 to the output transformer. Because the cathode is positive relative to ground, when a signal is put onto the grid, voltage drop across the potentiometer increases thereby increasing the current through the tube. [1] This potentiometer is set for a specific tube and then forgotten, it is on the inside of the chassis unlike the master volume. There is also a 1 Ohm resistor in series with the potentiometer, but this is put there for test reasons, so when the voltage drop across it is measured, the current has the same value. The output is brought out of the anode and fed to an AES PT-31 output transformer directly to an 8 ohm ¼" speaker jack in parallel with a 220 ohm/5W resistor to ground.

The power dissipation for the 6V6 is rated at max for 14W, given by the data sheet. A reasonable and practical power dissipation would be to run it at 80%, with a plate-cathode potential difference of 300V the bias current will be given by;

$$I_{bias} = \frac{.8(14Watts)}{300volts} = 37.3mA \qquad 3\text{-}6$$

vi. Power Supply

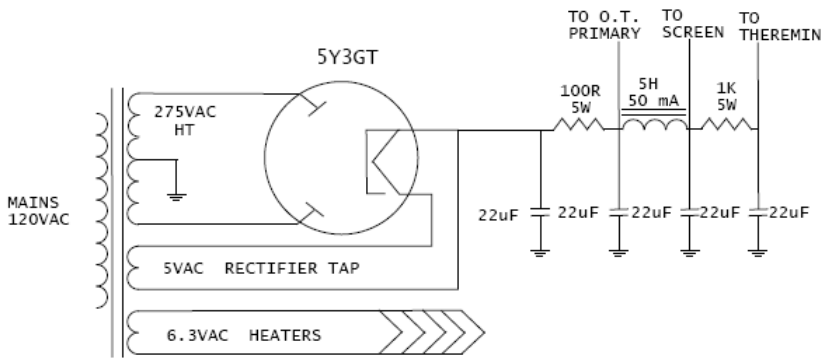

Figure 9: Power Supply for Theremin

The Power supply take 120VAC mains input with a 1A fuse in place. This input is fed into a power transformer made especially for tubes that have three output taps. The first tap is a 6.3 VAC section that is used to power the heaters for the tubes. The next tap is a 5 VAC rectifier heater tap, and the last tap is a 275 VAC tap that is used to power the plates of the rectifier tube.

Because the heaters on the tubes take 6.3 VAC, this can cause a 60 Hz “hum” in the background of every signal. This is because these heater lines are low voltage but fairly high current, about 1 A, so they form a substantial magnetic field that interacts with other circuit elements. Twisting these wire lines reduces the effect of the 60 Hz by canceling magnetic field created from the opposite wire.

The rectifier tube is a 5Y3GT full wave rectifier. The 275 VAC input signal comes out about 315 V rectified, and from there the signal is sent through a series of filters. This power supply is a four-pole power supply with all poles having a 22 μF capacitor. The first voltage signal sees only 100 Ohm resistor that creates a low-pass filter with f3db ~72Hz, since the rectified voltage now has a frequency of 120 Hz. This voltage is then sent to the output transformer primary tap. After the low-pass filter, there is a 5 H choke to further smooth out the waveform, this voltage is then connected to screen grid of the 6V6 power tube. Finally another low-pass filter is created to bring the signal very close to dc, with a 1 k resistor. This last pole powers the Theremin.

Results

i. Simulations

Simulations are an effective way to model circuits and circuit elements before building the circuit to understand how different parts behave. For these simulations, I used a program called ORCAD to design the circuits and PSPICE to simulate them. Unfortunately, I was unable to simulate the Hartley oscillators in PSPICE because I couldn't understand how to jumpstart the oscillations. When the simulation was run and the voltages at junctions were shown, the voltage on the grid showed on the order of 10-24 V, basically zero, which is not suitable for oscillations. I was unable to determine the problem, so the oscillators were trusted to work, which they did. Additionally, I was only able to simulate pieces of the circuit with only one tube at a time.

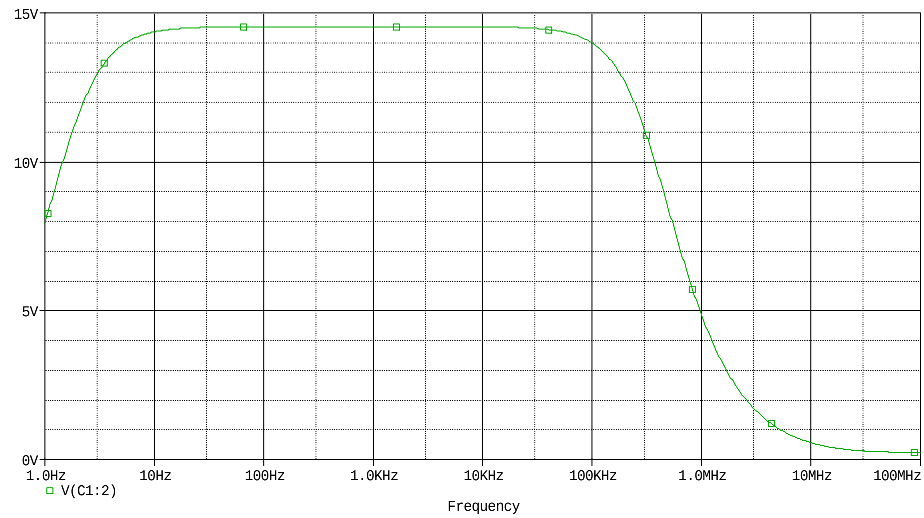

Figure 10: Frequency Response for Pitch Preamp

The first simulation that was completed was for the pitch preamp. A frequency domain sweep was done on this circuit to examine the gain of the circuit for allowed frequencies. The output is shown in Figure 10. The graph shows that this preamp gives a signal gain of 14.5, input voltage being 1V. This also tells us that this amplifier stage is strong for frequencies from about 10 Hz to 100 kHz. Even though the pitch oscillators output at 750 kHz, this signal is safe because the only part that is needed to be amplified is the difference of the two frequencies, about 10kHz. This means that the system of capacitors to filter out the high frequency addition terms worked.

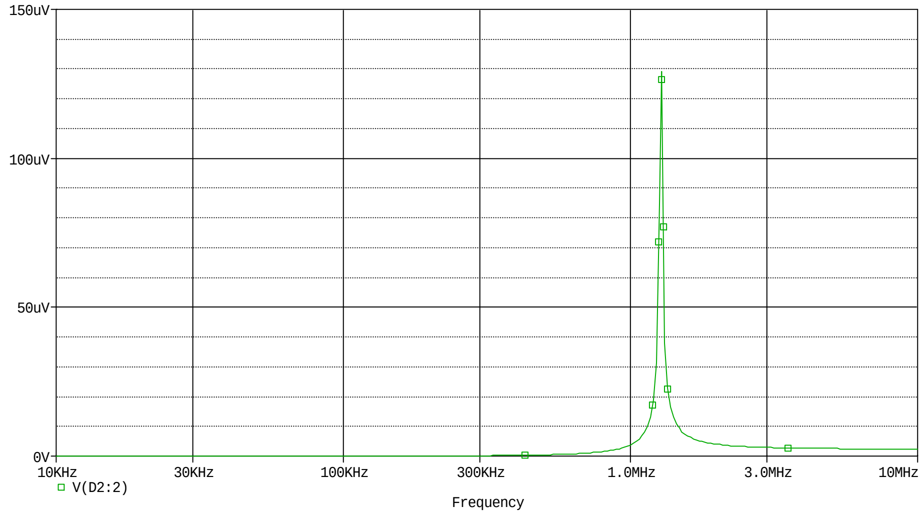

Figure 11: Frequency Response to Volume Filters

The next element simulated was the input of the volume circuit filters into the preamp. Figure 11 (above) shows an ac sweep from frequencies of 10 kHz to 10MHz. Clearly, it shows that the band-pass filter attenuates all signals except for a central frequency, around 1.3 MHz. This simulation was done with 250 µH and 47 µF, and because this has an air cap capacitor it can easily by tuned to match the output frequency of the Hartley pitch oscillator. The next simulation was a time domain response of the circuit to see what the signal looked like, shown below in Figure 12. It shows a sine wave input and the response is a dc voltage with tiny ripples, a little greater than 0V.

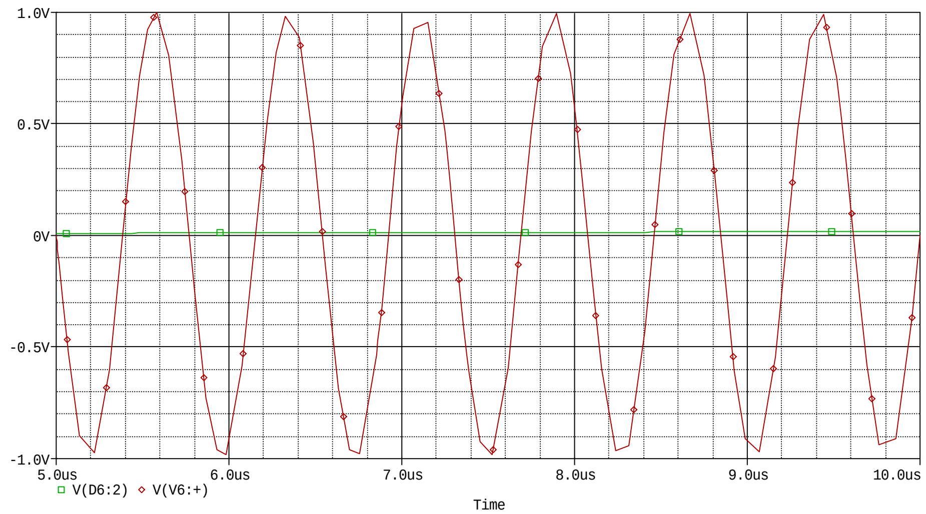

Figure 12: Response of Volume Filters to Sine Wave Input

The last simulation that is modeled is the final gain stage before the power amp. The frequency response for this is shown below. Keep in mind that only one tube was used in this simulation, so the cathode of the tube is at 3.6V above ground, when in actuality, and in measurements shown next it sits well below ground, sending a current through the tube, which increases gain because it lowers the potential needed to cross the grid.

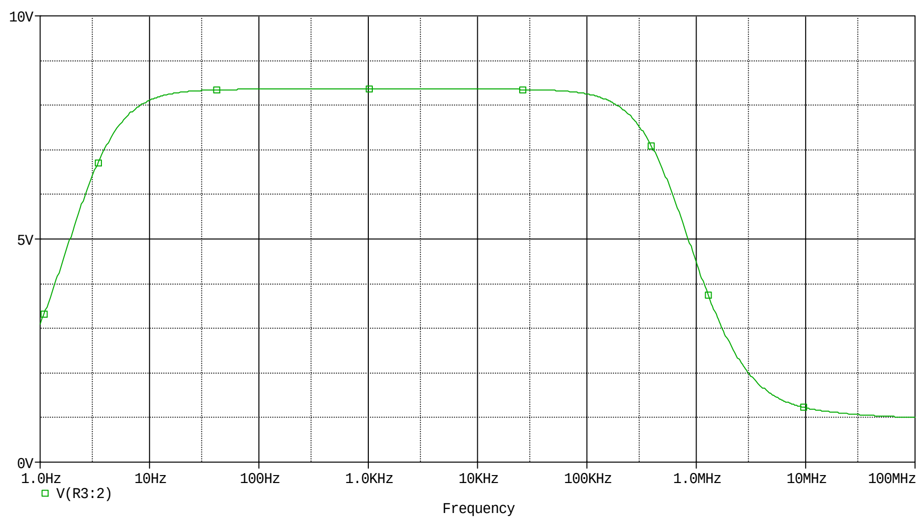

Figure 13: Frequency Response for Final Preamp Gain Stage

While looking over the work that was done before taking measurements, it was realized that the grid and the cathode had been soldered together through a 1 Megaohm resistor on V2b, with no 1k resistor to ground. I had no idea what this would do to the gain of the amplifier at that stage so I decided to simulate this, shown in Figure 14.

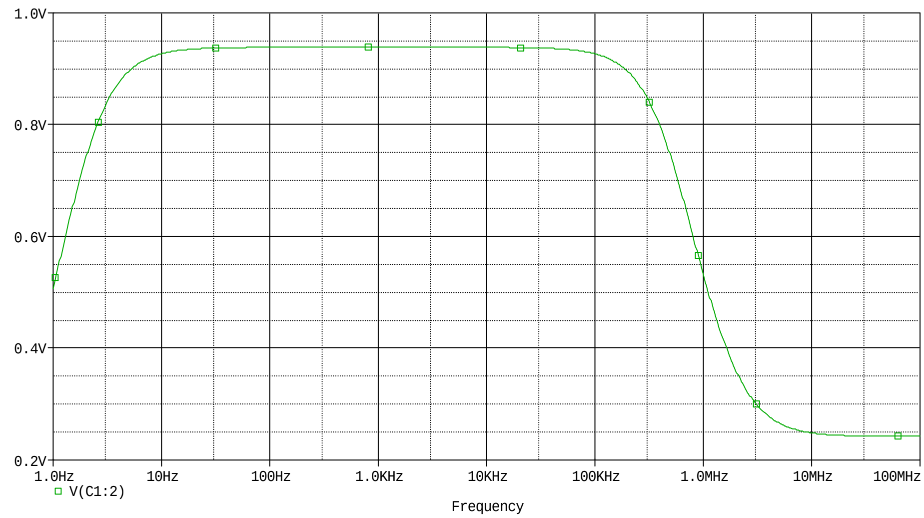

Figure 14: Frequency Response for Faulty Version of Pitch Preamp

With this flawed configuration, the graph shows us that the amplifier gives a next loss of about 10% of the signal. Compare this to Figure 10, where the correct gain is 14.5. The result was that the Theremin's output power was severely diminished.

ii. Measurements

A few measurements were taken on the Theremin to make sure that plans were working out correctly. The first measurements that were taken were the output voltages of the power supply. The rectified voltage coming out the 5Y3GT rectifier tube sat at 315V.

After the first filtering, the B+1 voltage was 309VDC, this is the voltage that feeds the power tube and output transformer. The B+2 stage, after the 5H choke, output a voltage of 305VDC. Because of this choke, the output voltage for the following stages will be much better regulated. [7] The final Theremin voltage was outputting at 254 V, which is exactly where we wanted to power the tubes at.

The next element that was checked was to make sure that the simulations were incorrect about the grid bias on the Hartley oscillator tubes. Earlier it was shown that the grid should be at a voltage less than ground and more negative than the amplitude of the signal. The grid voltage on V1 had a potential of -20.8V, V2b at -34.6 and V4a at -30.4V. This result is much more expected and works well for the grid bias for the oscillators. The frequency of the oscillations was first checked by using an AM radio, bringing it close to the Theremin and allowing it to pick up the signal that each oscillator was oscillating at. The other tubes from different oscillators were taken so as to be sure the AM signal picked up was the right oscillator. The frequencies were finally tuned to be 1MHz and 750 kHz.

Next, the power dissipation of the power tube was tested, and finally the output power of the entire Theremin. On the power tube, V_k=16.19V, $V_{P=}$301V and I_{bias}=42.9mA. The power dissipation is then given by,

$$P = (V_p - V_k) I_{bias} \qquad 4\text{-}1$$

The tube is running a little hotter than expected, but it is still within the recommended power rating, at 87% of max. Finally an 8 Ohm resistive load on a hit sink was connected to the output of the power amp and the voltage drop across the resistor was measured to be 6.69V. From this we can find the output power by;

$$P = \frac{V^2}{R} \quad \text{4-2}$$

and see that the output power of the Theremin is **5.6W**.

Future Plans

In order to better this Theremin, my plans are to lower the oscillations of the Hartley oscillators, so they don’t interact as much with AM radio frequencies. In order to do this and still have it sensitive enough to change through a wide range of frequencies, preferably more than pitch oscillator, I would like to put two LC oscillators and then couple them into V1 and V2b. One oscillator beating at around 1 MHz, and then another at about 200 kHz. The faster oscillating LC circuit would be connected to an antenna as to sweep frequencies, and the grid would oscillate at the average of their frequencies, because it would attenuate the factor that is the addition of the frequencies.

I would also like to add in tone controls and preamp gain variability in order to make the Theremin a wider range of timbre. Going along with this I plan to make an out jack and through jack that can truly by bypassed if nothing is plugged into them, which would allow me to effects petals on it as well.

Conclusion

The Theremin is a rather simple electronic instrument that has a long history. It is made up of two beating Hartley oscillators that create a two frequency tone. This beat frequency is then filtered and amplified to only leave on tone with a frequency that is equal to the difference of the two tones. This is then controlled by a pitch oscillator that changes the voltage on the cathode of the final preamp section, by moving a grounded object, such as your hand, closer or further away from the antenna. The signal is then sent to the power amp and then to the speaker. All of this is controlled by a 300V-250V regulated power supply. Though the technology used may be outdated, the look of it just seems so rich in history and has a story to tell. At first glance it appears strange or even alien, but once the physics is broken down, it all becomes quite simple.

Figure 15: The Theremin

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Acknowledgements

Steve Loyd

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