1 Summary

A Theremin is one of the oldest electronic instruments. It is played with no physical contact, and has continuously variable pitch and loudness ranges. The Theremin is perhaps most famous today as science-fiction accompaniment, however, throughout its history, it has been used in genres from pop music to orchestra. Played by a master, the Theremin has a timbre and style comparable to vocals, or the violin. The electronic design is simple, using common radio components: oscillators are sent into a mixer to generate an audio-frequency signal. The biggest design challenges in a Theremin are getting a clean tone with little distortion (yielding a neutral timbre), and extending the low-frequency range as far as possible to avoid phase-locking distortion. The design described here does very nicely on both counts, producing a mildly distorted sine wave output, with a minimum output frequency near 1 Hz.
## Contents

1 **Summary**  

2 **Introduction**  

3 **Chassis**  

4 **Oscillators**  

5 **RF Mixers**  

6 **Output Amplifier**  

7 **Adjustment**
2 Introduction

A few months ago, I decided, enough was enough. I’ve used $10 RadioShack soldering irons for the better part of my life. They’re too hot, they’re too cold, and the tip dissolves away in no time. I used them for so long because they’re cheap enough not to matter, and, something mumbled about adversity (I’ve always been the kind of person to makes do with less). After the last iron dissolved down to a nub, I bought a Hakko FX-888 soldering station.\footnote{Which works nicely. In case you were wondering, the performance, construction and pricing are comparable to the Weller WES51; either is a worthwhile investment.} As something of an inaugural project, I realized, \textit{hey, I haven’t built a Theremin in a while.} And since I’ve been building radio projects as of late, it should be a cinch to put together something really nice.

3 Chassis

![Figure 1: The beginnings of a chassis, fabricated from copper clad stock.](image)

So, I grabbed some copper clad off the shelf and started cutting and tacking pieces together (Figure 1). Whereas my radio breadboard projects are mostly discrete boxes strung together with wires, I decided to build this in a holistic manner. Also, to echo the standard styling of a Theremin, the top has a sloped shape to it.

As you can see, the two variable oscillator coils are already in place. The tuning screw is detailed in Figure 2 and Figure 3.

This is my preferred method for prototype adjustments. It’s assembled as follows:
Drill a 5/32” hole in the PCB (for a #6-32 screw)

Solder a nut over the hole (inside preferred), making sure a fillet forms all the way around

Thread a locking nut onto the screw (see below), then thread the screw into the panel

Add hardware inside as required

In this example, “additional hardware” includes a stop nut, superglued in place near the end of the screw, and a nut at the very end to provide gluing surface on the end. A ferrite cylinder is superglued to the end. Make sure it’s centered and straight.

As it turns out, in this project, I didn’t need the range provided by the ferrite slug—so I broke it off, leaving just the nuts on the screw. This has a mixed effect: the brass screw itself will tend to reduce inductance slightly; you would imagine the un plated steel nuts should tend to increase it, but steel isn’t very magnetic at high frequencies. The overall effect is, it tends to reduce the inductance. A competing effect is the increased capacitance from winding to screw, which tends to oppose the reduction of inductance, but this is a small effect. Overall, eddy currents win out,
and inserting the screw acts to raise the resonant frequency. One or two brass nuts would be better here, and sure to have the same effect at any frequency.

## 4 Oscillators

I started this project by winding the coils. According to this excellent calculator, I got about 40 µH, which is kind of low among Theremin coils, and means my operating frequency will be on the high side. I don’t think this is a problem; 1 mH air-cored coils are certainly a pain to wind (I don’t have any quality RFCs handy), and a higher frequency will just make it that much more sensitive (and that much more unstable, but we’ll see).

One problem I identified early: I didn’t put taps on these coils, so I have to use a Colpitts rather than Hartley topology. That’s fine, but I’d like one end grounded, so I can get maximum sensitivity by connecting the antenna to the opposite end. Also, any savings I can make on coupling capacitors or RFCs comes in handy.

A JFET follower was added to improve isolation between mixers and oscillators. Cs was added, in series with the tuning coil, to effectively reduce the tank capacitance, raising the resonant frequency. This helps compensate for the added capacity of the antennas, and any other differences between units. The volume oscillator (which had a slightly misshapen coil, and needs a larger frequency difference from the local oscillator) ended up needing a rather large adjustment, a 470 pF capacitor in series (effectively reducing the total tank capacitance, raising the resonant frequency). The pitch oscillator got 1.5 nF in series, while the local oscillator got none (Cs shorted). Note on
capacitors: polypropylene or polystyrene film, C0G ceramic or silvered mica are required for all tuning components. Generic ceramic types or polyester films are much too drifty, even if you get lucky enough to have them all drifting in the same direction at any given point in time.

The oscillator was constructed on a chunk of copper clad (Figure 5). Nodes are isolated by carving a perimeter around the pad with a utility knife. I chose to build with THT components, even though they end up SMT’d anyway, for ease of assembly and rework (ease being a relative thing with this kind of assembly).

5 RF Mixers

The general scheme of a Theremin is to mix two variable frequency oscillators (VFOs) into a third, the local oscillator (LO) (or use two pairs, one LO for each VFO, though I don’t really see the point of adding a fourth oscillator), obtaining two independent products. One product is detected for frequency shift somehow, while the other is used directly for pitch. Typical frequency detection methods include the slope detector or the ratio detector. A variable gain amplifier is used to control the pitch’s amplitude, which might be the pitch mixer itself.

The schematic used for the volume mixer is shown in Figure 6. (The output ports from the volume VFO and LO connect directly up to the mixer via short, unterminated coax cables.) A single balanced BJT mixer was chosen because double-balanced diode mixers require transformers, and the high port isolation, power gain and current-source output are advantageous. The detector is also combined, being a simple slope detector, using a resonant tank and a voltage doubler detector (aside from a capacitor or two, the BAT54S is the only proper SMT component in the project, as I don’t happen to have THT schottky diodes handy).

The finished circuit is shown in Figure 7. Instead of carving out pads (except for the detector
diodes), as on the oscillators, this was built using a combination of self-supported components and “Manhattan” construction. A lot of resistors and capacitors go to ground, so these act to anchor nodes that are otherwise floating in space (a good analogy for their electrical purpose, too). “Manhattan” construction refers to the technique of soldering down small cut pieces of PCB, acting as the ground floor of a skyscraper, supporting a node. The supply node (green wire, bottom right, and associated components) is supported in this manner.

The pitch mixer is pictured in Figure 8. The mixer itself is essentially identical in design...
Figure 8: Pitch mixer and volume control, as built.

(some resistor values changed for convenience, with little effect on operation), with the major change
that, instead of the VFO port being biased from a fixed voltage source, its voltage divider is supplied
from the volume detector’s output voltage. In this way, when the volume VFO is tuned away from
the detector’s resonant peak, no bias is developed and the mixer goes to cutoff. Approaching
resonance, a small voltage is developed, biasing the mixer on (it remains partially in cutoff, resulting
in a somewhat distorted waveform at the output). The pitch VFO’s output is also attenuated with
a series resistor, which minimizes distortion, most significant at full output, where a nearly pure
sinewave is produced.

Since the output is a pull-down current, a current mirror converts this current to a pull-up
sense, which is sent through a resistor to generate signal voltage. This voltage is AC coupled to the
volume control potentiometer, and from the pot to the amplifier.

6 Output Amplifier

Finally, to buffer the audio output and bring it up to enough drive for a cable run, or headphones,
a small power amplifier. This one circuit uses almost as many transistors as the rest of the circuit
(seven transistors, by coincidence), just because it’s a fully formed operational amplifier.

The schematic, Figure 9, is a pretty standard class B amplifier design. Only 5V is available
in this particular project, so a single-supply approach was used. This has disadvantages due to
all the coupling capacitors required, being reduced PSRR (power supply rejection ratio), and the turn-on “pop” that occurs when first charging those capacitors. Still, the results are good.

The construction method follows from the mixers, with a flatter layout this time (Figure 10). Minor testing reveals response up to about 1MHz (1 V \text{pp}, slew rate limited), reasonable linearity (no obvious sloping or kinks on the waveform) and enough output capacity to do what I need. It drives common 32Ω headphones very nicely.

The finished chassis is pictured in Figure 11 and Figure 12. It plays very nicely, though I'm
not going to even try waving out a tune for a general audience!\textsuperscript{2}

Lastly, the complete schematic is shown in Figure 13.

\textsuperscript{2}That said, here’s a quick demo of the unit, including the output waveform, which as you can see is an excellent sine wave: \url{http://youtu.be/ZEcCvzN4Mcc}
Figure 13: Complete schematic.
7 Adjustment

This is, of course, easier if you have a frequency counter or something like that, it’s just more tedious the regular way. The procedure: First, you need to get all three oscillators in the same range. If you leave the LO alone, you can add or remove capacitors from the VFOs to adjust them in large steps, or use a variable trimmer capacitor to cover a wide, continuous range. Tank capacitance can be increased by adding capacitance from the antenna to ground, while it can be reduced by placing capacitance in series with the coil. The more in series with the coil, the smaller effect it has, so the 1440 pF with the pitch coil causes a small shift (about 3% higher frequency), while the 660 pF with the volume coil causes a larger shift (about 6.2%). The approximate shift can be calculated from:

$$\text{Percent} = 100 \times \sqrt{\frac{C_s}{C + C_s}}$$

Where $C_s$ is the series capacitor added, and $C$ is the equivalent total before the change (which, for a Colpitts type oscillator, is the equivalent capacitance of the two tuning capacitors in series).

If you don’t have a frequency counter, you can determine the direction of adjustment by making two assumptions: 1. Proximity to the antenna always drops frequency; 2. the tuning screws (without ferrites) tend to increase frequency. If you can observe a blip of a beat frequency on approaching the antenna, then it has to be brought lower. If you don’t observe a blip, it’s too low and has to be raised by adding series capacitance.

The volume VFO has the special behavior that it can have a double-humped response if tuned to the higher peak. This is probably undesirable (for a given volume setting, there are up to four frequencies you can choose—depending on which slope you tune to!). It should be tuned to the center of the lower-frequency peak, so that, on approaching the antenna, you can only push it further and further from resonance. Some people prefer a passive-off state, which can be achieved by tuning to the valley between peaks; this circuit can be used that way, but if you go past the peak, the amplitude drops again. The best way to do that would be to change the slope detector from bandpass to a notch type filter.

Since the pitch oscillator might be way off initially, defeating an audible tuning attempt, a volume indicator LED was added so adjustments can be made visually. First, find the volume oscillator peak (maximum LED intensity), then adjust the pitch oscillator until you can hear the beat frequency. Adjust it near zero, then tighten down the locking nut partway. Holding the nut with a pair of pliers, use a screwdriver to turn the screw ever so slightly until it’s good. Final adjustments in place are best made by moving metal objects around the antennas—this won’t impact the sensitivity of the antennas, and environmental sensitivity is obviously important regardless. Might as well take advantage!