Understanding and calibrating

The Theremin Front-End

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Scope of this document:

This document relates to 'conventional' Heterodyning Theremins, particularly those employing LC oscillators and inductance for 'antenna' linearization / equalisation, it is intended as a non-mathematical guide to principles of operation and calibration of the "front-end" circuits, and more specifically these circuits related to pitch.

The primary scope of this document is the Antenna, Equalizing coil, and variable oscillator.. Issues relating to the reference oscillator, heterodyning mixer, and other following circuits will (first) be lightly covered, and **you will need to be fully familiar with the contents of the next 3 pages to understand the following pages!**

Theremin Overview:

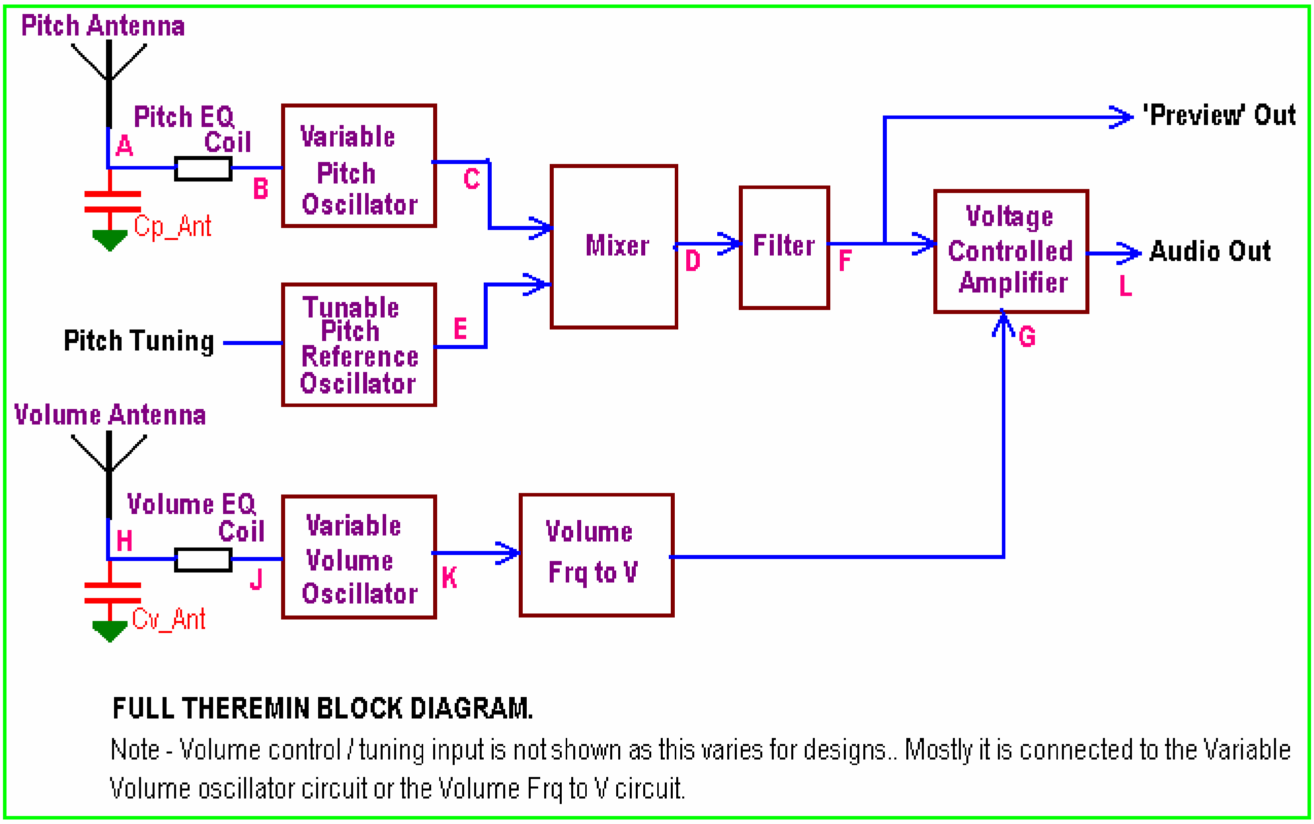

FIGURE 1.

Figure 1 shows a block diagram for a complete Theremin.

To avoid confusion, the accepted term "Antenna" is used, and is the term I will use in following discussion.. However, for the sake of scientific correctness, I wish to state that these are NOT antennas in the way this word is commonly used and defined – These "antennas" are one plate of a capacitor, which, in combination with their circuitry, form a capacitance sensor.. This is THE mechanism by which a Theremin works – other factors such as EM radiation play such a miniscule part in the correct operation of a Theremin that they can be completely ignored.. The ONLY time that the term "Antenna" is actually applicable is when the plate / plates actually act as an antenna and pick up radiated signals from other devices (or other Theremins) and this is an undesirable effect to which all long-range capacitance sensing circuits suffer to some degree. (digital error checking / synchronous rectification and other elaborate schemes not applicable to this musical instrument can be applied when capacitance sensing is used in safety-critical applications)

A.) Pitch Antenna, Pitch EQ Coil, Variable Pitch Oscillator:

Cp_Ant is the combined capacitance of the Pitch Antenna, wires etc connecting to this antenna, and the performers body.. all with reference to GROUND (or Earth is it is called in some countries). Ground is a subject worthy of its own document – but let us assume that the Theremins internal electronics is grounded to the same potential as all other 'grounds' in the vicinity of the player.. And note that a good connection between the Theremins internal ground and 'real' ground is essential for optimum performance.

This antenna is (on most common, reasonable quality Theremins) connected to a high frequency variable oscillator via a Linearizing / Equalizing coil. The function of this coil will be discussed in detail later, but in essence this coil:

1.) Increases the sensitivity to capacitance changes on the pitch antenna (a tiny change in capacitance at **[A]** will cause a much larger change in oscillator frequency than the same change in capacitance would make if this was applied to **[B]**).

2.) Changes the capacitance to frequency law.. Capacitance is the inverse square of the distance between plates, and if no (correctly tuned)* Equalizing coil is fitted **(in all further discussion about the equalizing coil, assume it is correctly tuned unless otherwise stated – a lot will be said about tuning the EQ coil and antenna later)*, the frequency of the oscillator is a function of this highly non-linear capacitance – distance relationship.. When the Equalizing coil is fitted, the capacitance "seen" by the oscillator is changed making the capacitance – distance relationship more linear (effectively it appears like the dramatic change as the player gets close to the antenna is damped, and tiny change for movement further from the antenna is amplified) and the oscillator's distance to frequency relationship gets quite close to the ideal exponential law required for 'linear mapping' of musical intervals.

B.) Reference Oscillator, Mixer, Filter:

The Tuneable Pitch Reference Oscillator is set to a frequency which is the same as the frequency from the Variable Pitch Oscillator when the player is at their maximum distance from the pitch antenna (hand is furthest comfortable distance from antenna).. This is called the "null point" and Theremins have a user adjustment to facilitate setting this point.

Outputs from the Pitch oscillators **[C]** and **[E]** are taken to a heterodyning mixer, which produces an output on **[D]** comprising of the sum of the frequencies of **[C]** and [E] (and all their harmonic components) and the difference of the frequencies of **[C]** and **[D]** (and all their harmonic components).

The Frequency from **[C]** will generally vary by less than 6kHz, and be in the order of 150kHz to 550kHz (depending on the Theremin design. If we take a Moog Etherwave Standard Theremin as an example, The reference oscillator frequency set to 285kHz, and the variable oscillator frequency will be 285kHz at the null position, and about 282kHz with the hand close to the antenna (See http://www.moogmusic.com/manuals/HotRodEtherwav.pdf).

It can be seen that the sum frequencies **[C+E]** will vary from 567kHz to 570kHz (harmonics of these will be at even higher frequencies) and that the difference frequency **[E-C]** will vary from 0Hz to 3kHz .. **[D]** is a mixture of the sum and difference components, and the filter following the mixer removes all frequencies above audio, leaving only the audio (0 to 3kHz) signal **[F]** which is fed to the Voltage (or current) controlled amplifier and optionally taken to a 'preview' (monitoring) output.

It can be seen that, at the "null point", both **[C]** and **[E]** are at the same frequency, so there is no difference component from **[D]**, only the sum component which is filtered out, so there will be no audio signal on **[F]**. As the player approaches the antenna, the frequency of **[C]** will drop, and the difference frequency will increase, so the pitch [on **F**] increases as the antenna is approached.

C.) Volume circuits:

The volume circuits are less standardized than the pitch circuits – In essence, the objective is to produce a voltage or current which changes proportionally to the players had position over the volume antenna, and to use this voltage / current to control the gain / attenuation of an audio amplifier.

Probably the most common means of implementing this function is by effectively duplicating the pitch antenna / equalizer / oscillator circuits, but having these operate at a higher frequency which does not interfere (has no important overlapping harmonics) with the pitch oscillator, and then converting the frequency variation from this oscillator to a varying voltage or current.

Fig 1. Shows the volume oscillator output **[K]** driving the Volume F to V.. The Volume Frequency to Voltage block generally consists of a band-pass filter tuned so that as the frequency increases, the signal from this BPF increases.. This signal is then rectified and integrated, and the output **[G]** is a voltage which increases as the frequency increases.. The frequency increases as the hand is moved away from the volume antenna. The voltage **[G]** is used to control the gain of the VCA, so that output loudness increases as the hand is lifted away from the volume antenna.

It should be noted that the BPF does, by itself (due to the shape of transfer function) implement a degree of linearization – Many Theremins do not have a Volume EQ coil fitted and have a reasonable / good volume response curve. *It should also be noted that the law required for the volume response is FAR less critical than what is required for accurate control of pitch.. We can (it is claimed) hear a change of 1/100th of a semitone – a change in volume of this degree would not be heard at all .. even a change in volume equating to a pitch change of 1/3 semitone would not be heard at all. (here I am comparing the changes in frequency of the variable oscillators – as in, a Theremin covering 3 octaves = 3600 cents.. This, on the volume circuit, would [given an 120db volume range with perfect sonic linearity] give better than 0.034db resolution / accuracy.. As we can only hear changes of 1db.. We can be 30x cruder with our volume linearity than we can with the pitch accuracy before we even have any chance of noticing it – and even then, if we did notice a more gross error, it would be of far less significance than a smaller noticeable pitch error.)*

This ends the general description of the Theremin – The following page goes into more depth about the “front-end”.

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The Front-End

This is where the real fun starts! ☺ .. But in order to fully use what follows, you should download the spreadsheet http://www.element-14.com/community/docs/DOC-16832 as I developed this to 'automate' the Maths which, sometimes, one cannot escape from! ☹ .. I will be pasting from this spreadsheet, but if you don't download it you could get a bit lost!

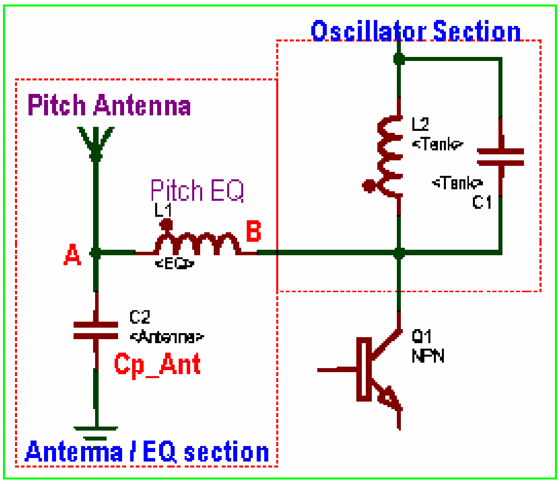


Figure 2. Typical Antenna / Equalizer / Oscillator arrangement.

Fig 2. – First, lets look at the sections separately.. Analysis of the behaviour of the whole combined circuit is incredibly complex for so few determining components, but split into two parts it becomes understandable.

First – The Antenna / Equalizer section – This forms a series resonant circuit whose resonant frequency is determined by the (fixed value) EQ coil (Inductor L1) and the variable antenna capacitance Cp_Ant (C2). Using the values from the Moog EW Standard Theremin, I can simulate this section in isolation. (The spreadsheet allows one to derive values for other Theremin designs)

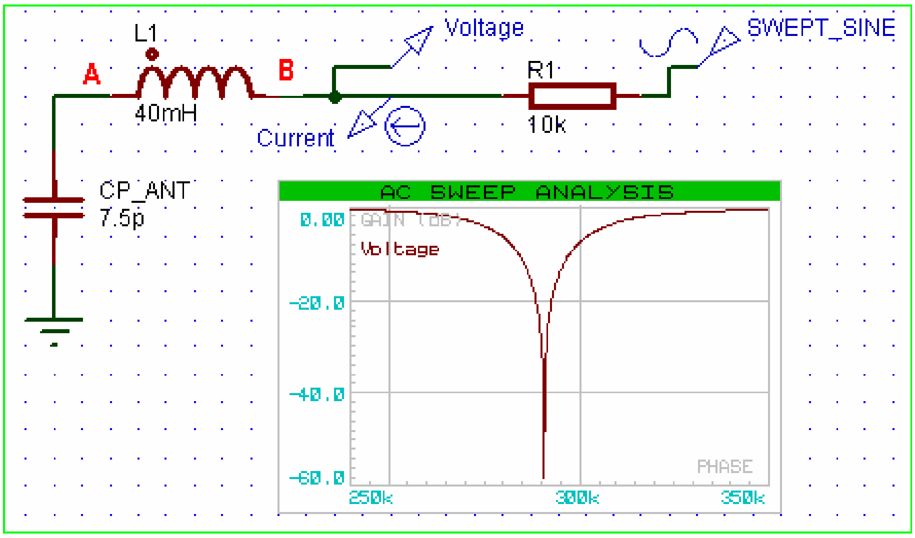
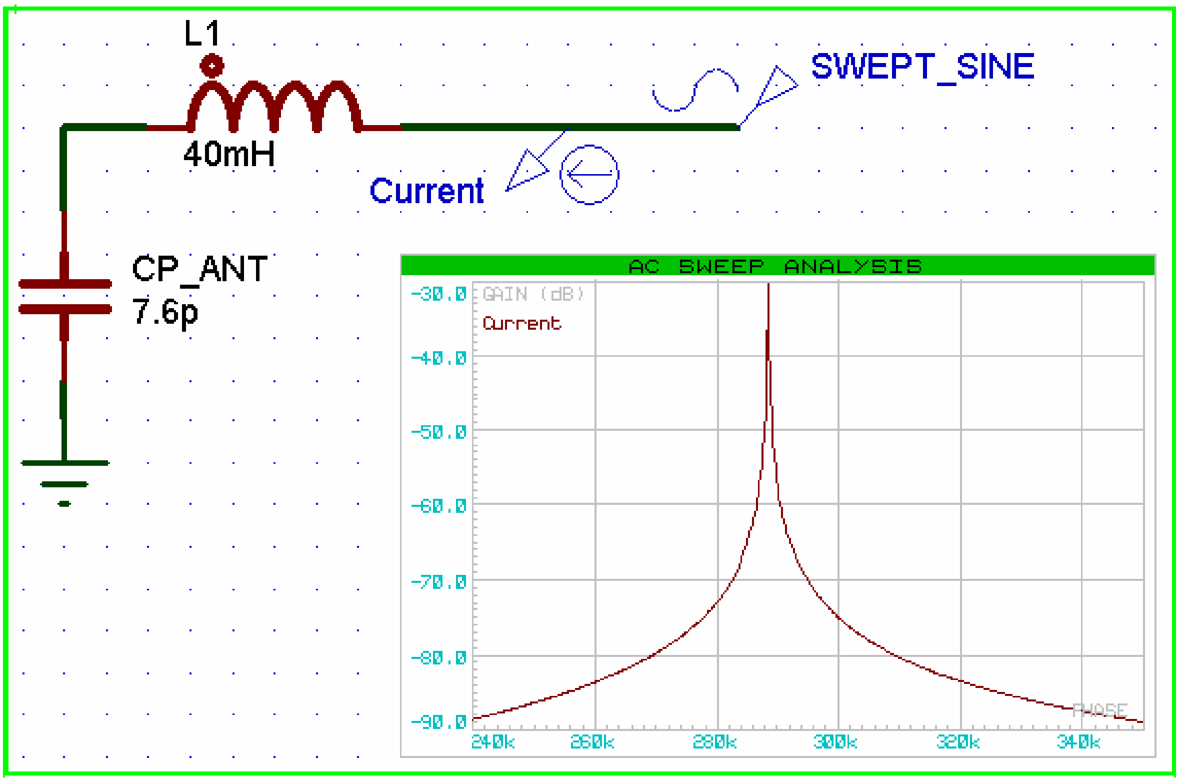


Fig 3.

This shows the loading on the oscillator as a function of frequency.. Resistor R1 is added for simulation purposes – As Cp_Ant is changed, the resonant dip shifts dramatically.. the above has its resonance at 290.6kHz, Changing Cp_Ant to 7.6pF reduces this frequency to 288.6kHz .. this would equate to a sensitivity of 4kHz / pF.

A better representation of the loading function can be seen by looking at the current from the oscillator..



In simplistic terms, a LC circuit has two reactive components – the capacitor, whose impedance decreases as frequency increases, and the inductance who's impedance increases as frequency increases – And using this perspective, one could say that the primary component of impedance in a series LC circuit at frequencies below the circuits resonance, is capacitive – and that the primary component of impedance at frequencies above the circuits resonance, is inductive…

Ok – let me be honest here.. I can see how huge 'amplification' and linearization is achieved – and, more to the point, have seen this in practice.. But in order to understand the exact relationships when oscillator / Eq. inductance and Antenna capacitances are coupled together is too complex for me to explain to myself, let alone anyone else! – This is an area where it seems a few pages of (to me) incomprehensible maths is called for.. So rather than waffle and prove what an idiot I am, I will move on to the oscillator, and eventually return back to some form of description regarding combining the two sections, and what this achieves, and how to set this up on a real Theremin.