Physics of the Theremin

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We discuss some of the interesting physics behind the design and operation of the Theremin electronic musical instrument. To complement the theory we present details of a parallel effort to construct two versions of this remarkable instrument. One of these designs remains fairly faithful to the traditional beat frequency oscillator approach that first inspired Theremin's invention, while the other contains more modern electronics that helps make more reliable the setting up and use of the instrument. The emphasis on the physical principles continues into a comparison of the two instruments. Following completion, the Theremins have been extensively used in public and schools science exhibitions and in lecture demonstrations.

I. INTRODUCTION

In 1921 the Russian physicist Leon Theremin gave the first public demonstration of his musical instrument that has since become known simply as the Theremin.[1] Theremin died in November 1993, but his instrument lives on through the occasional concert performance or soundtrack use.[2] The Theremin is unique in that it is played without there being any physical contact whatsoever between the performer and the instrument. The pitch of the instrument is controlled by the proximity of the player's hand to an antenna (mounted vertically in the original design). A second antenna (traditionally mounted horizontally) senses the proximity of the player's other hand and controls the volume of the tone.

The experience of playing the device is quite different from that of performing music with most other types of instrument. A seasoned performer is able to associate points in space with given notes, rather like having the ability to see a piano keyboard that is invisible to everyone else. For both experienced and beginner players, the playing technique is akin to a continuous negative-feedback mechanism; the position of the player's hands defines an auditory input which the brain then processes, whereupon the positions of the player's hands change in order that the desired note can be converged upon and sustained. Expert Theremin players have been few and far between[3,4] with only a few names reflected upon when the instrument is mentioned. Perhaps not surprisingly, even the renaissance of the instrument in popular music circles over the past few years has uncovered no real original style or talent to rival the virtuoso performers that there have been.[5]

In this article we will discuss some of the physics behind the design and operation of the Theremin. The instrument is commonly regarded as rather difficult to construct well, and indeed many enthusiasts believe that nobody has been able to surpass the quality of operation of those early vacuum tube instruments built by Theremin himself and subsequently commercially produced under patent. However, we can attempt to use some basic physics in order to overcome some of the common design problems, and to help with this, we will present two successfully built versions of the instrument, photographs of which are shown in Fig. 1. While our article would be incomplete if we did not offer these designs to stimulate further experiment, we do not want to lose sight of the physics here. Thus we will avoid communicating lengthy technical detail, leaving that instead to personal requests with which the principal author will be pleased to assist.

II. PHYSICS OF THE THEREMIN ACTION

At the heart of the original Theremins and indeed most of the subsequent designs, there are one or more beat-frequency oscillators (BFOs). These are used either directly or indirectly to generate the tone of the instrument and control its volume. There are many publications detailing such designs[6,7] but for now we will concentrate on the physical aspects of the BFO action. Let us first consider the production of the tone with a BFO containing two oscillators generating independent signals at angular frequencies ω_1 and ω_2. The basic concept is shown schematically in Fig. 2.

A. The beat-frequency oscillator

The outputs of the two oscillators may be expressed mathematically as $A_1 \sin \omega_1 t$ and $A_2 \sin \omega_2 t$. The BFO action is that of a heterodyne mixer which multiplies these two signals together providing an output V_{out} given by

$$V_{\text{out}} = A_1 A_2 \sin \omega_1 t \sin \omega_2 t, \tag{1}$$

which can be expanded using a standard trigonometric identity to yield

$$V_{\text{out}} = \frac{A}{2} [\cos(\omega_1 - \omega_2)t - \cos(\omega_1 + \omega_2)t], \tag{2}$$

where $A = A_1 A_2$. Thus the output signal of the BFO has two frequency components; one at the difference of the individual oscillator frequencies and another at the sum of the oscillator frequencies. By using a low-pass filter, the signal at the sum of the oscillator frequencies can be almost com-

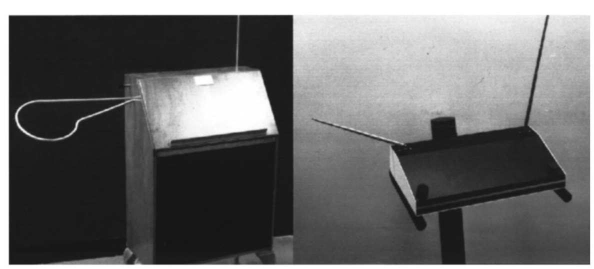


Fig. 1. Photographs of the completed Theremins. The instrument on the left is based on an analog design quite similar in theory to Theremin's original designs. The instrument on the right contains more sophisticated electronics including many digital ICs, although the fundamental physical principles that form the player's interaction with the device remain the same.

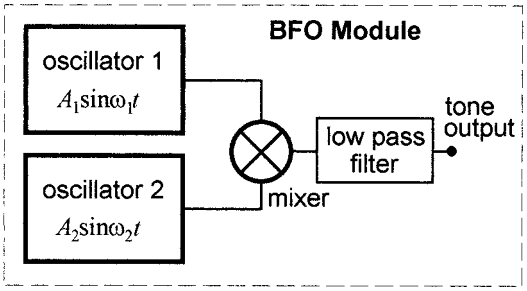


Fig. 2. Simple schematic of a BFO used as a building block in Theremin design.

pletely attenuated, leaving only the Fourier component at the difference frequency

$$V_{\text{out}}=\frac{A}{2}\cos(\omega_1-\omega_2)t. \tag{3}$$

The basic Theremin action is to alter very slightly the frequency of one of the two oscillators so that the beat frequency in Eq. (3) changes also. In practice this is achieved by building one of the oscillators in such a way that the capacitive effect on the pitch antenna by the player's hand slightly tunes the oscillator. Now, the presence of the player's hand is not a very significant effect, resulting in a capacitance change of order a few picofarads, as we shall see later. However, if the oscillator frequency is arranged to be very high, say around 1 MHz, then we require only a frequency change of 1:1000 to give an offset in the beat frequency of 1 kHz. This is a significant fraction of the musical scale, being over four musical octaves above the lower threshold of the audio hearing range (around 50 Hz).

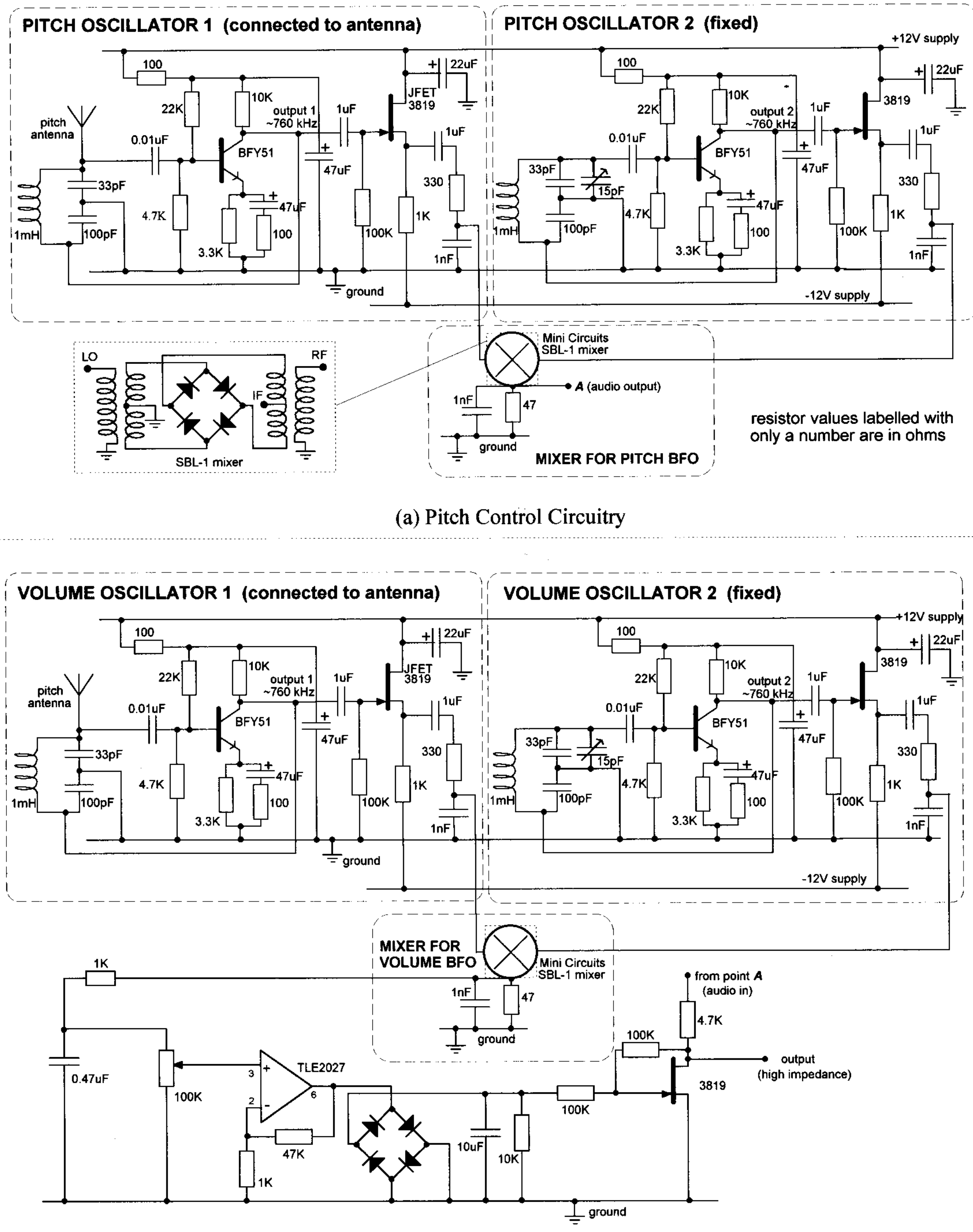
Let us pause for a moment to clarify some of the physics in what is going on in the above signal mixing process. It is important to realise that the above mixing is not the same as adding the two signals, perhaps an obvious enough observation at first. However, adding the signals will also lead to the production of beats, as can be found in most introductory physics texts under superpositions of waves, and as pointed out to us by many students who were puzzled when shown that simply adding the two oscillator signals produced no tone in a speaker. The point to realise, which perhaps often goes unemphasized but which comes to light immediately with experiment, is the following: When adding (superposing) two waves of slightly different frequency the beats produced are amplitude beats, modulating only the power of the combined waveform. There is no actual power at the beat frequency in this case. However, in taking the product of two waves, you do actually channel power into new frequencies, namely the sum frequency and difference (beat) frequency. Another way to look at it is in terms of a Fourier expansion which, for a given signal, indicates the distribution of amplitude or power over frequency. In the case of a superposition, the Fourier expansion is already determined by the terms that represent the signals you start with, whereas in the case of our product here, it is the terms in Eq. (2) that form the Fourier components. We could mention in passing that the superposition idea can work to produce real signal power at the difference frequency, but only if we introduce some sort of nonlinearity into the adding process. For example, a signal proportional to the square of $A_1 \sin \omega_1 t + A_2 \sin \omega_2 t$ would generate cross terms that can be reduced to identify a wave with frequency $(\omega_1-\omega_2)/2$. In practice such nonlinearities can be introduced simply by a semiconductor diode. Of course, these are the principles employed in the early radio demodulation circuits which relied upon the nonlinear properties of ''cat-whisker'' junction diodes to channel signal from a high carrier frequency down to (audio) sideband frequencies.

We should take stock of some of these important principles of physics that turn up in radio theory, and it is not surprising that we should come to them so rapidly here. After all, Theremin originally had the idea for his instrument while working on short-wave radio equipment and capacitive sensing apparatus during the Civil War in Russia. Fortunately, he was encouraged to work on his instrument, achieving acknowledgement for his first musical demonstrations at the Eighth Electrical Engineering Congress in Moscow in 1921. Over the following years, much advancement in radio research, particularly in Russia, was motivated by darker military applications,[8] but the instrument had already been sufficiently well introduced to the world, and three companies including RCA had engaged in its mass production by the late 1920s.

Returning to Eq. (3), we could state that the cleverness of Theremin's idea is summed up in the discussion following this equation, that the small capacitive effect of the player's hand is up-converted to a perceptively significant change in audio frequency. The practical issues perhaps become more evident; we seek to build two independent oscillators one of which is very stable, the other being linked to the pitch antenna. The nominal frequency of each should be high, certainly radio frequency, and identical when no player is near the instrument, whereupon the fractionally small change in antenna capacitance introduced by a player's hand transfers to a significant change in the beat frequency. In a well-designed instrument the beat frequency can be increased essentially from zero when no player is near to many kilohertz when the player is almost touching the antenna. We will now discuss some aspects of the capacitive effect on the antenna that is so crucial to achieving a good Theremin action.

B. Capacitive influence of the player

Before we can investigate the effect of the player on the antenna capacitance, we first must appreciate the effect of the antenna capacitance on the actual oscillator frequency, and hence the Theremin pitch. In order to do this, it is better to have a design to make reference to, so now we will introduce our first version of the instrument: the ''traditional'' analog machine. The circuit schematic is shown in Fig. 3. The schematic includes the electronics for both the pitch and volume control, but for now we are interested only in the pitch circuit. We have sectioned the schematic in Fig. 3 to highlight the important circuit blocks. We need to consider the block titled pitch oscillator 1, for it is the frequency of this ocillator that depends on the antenna capacitance. Although the circuit looks complicated, the basic physics can be extracted from only a few components located around the pitch antenna, at the left-hand side of the diagram. For clarity we will make reference to Fig. 4 which shows the basic oscillator in greater detail. This is a Colpitts oscillator which uses off-the-shelf components and can be more readily made than many other popular designs, such as the Hartley circuit which requires a specially tapped inductor. The oscillation frequency is given by



(a) Pitch Control Circuitry

(b) Volume Control Circuitry

Fig. 3. The complete analog Theremin circuit showing (a) the pitch control circuitry and (b) the volume control circuitry.

$$f_0=\frac{1}{2\pi\sqrt{L}}\left(\frac{1}{C_1}+\frac{1}{C_2}\right)^{1/2}, \tag{4}$$

where C_2 can be regarded as a parallel combination of the circuit component value C, the antenna capacitance C_A, and all other stray capacitances between the circuit and the antenna C_S. It is the value of C_A that our Theremin player will adjust. The instrument is initially set up so that C_2 takes a value that causes f_0 to match the resonant frequency of pitch oscillator 2 in Fig. 3 when the player is at a suitable initial distance x_0 from the pitch antenna; we will denote the value of antenna capacitance for this case as $C_A(x_0)$. When the player's hand is a closer distance x from the antenna, we will denote the modified capacitance as $C_A(x)$. In view of Eq. (4) and the fact that $C_2(x)=C+C_S+C_A(x)$, we can then write the frequency of the Theremin tone f_T as

$$f_T=\frac{1}{2\pi\sqrt{L}}\left[\left(\frac{1}{C_1}+\frac{1}{(C+C_S+C_A)}\right)^{1/2}\right]_{C_A=C_A(x_0)}^{C_A=C_A(x)}. \tag{5}$$

Now we need to consider what antenna capacitance we might expect for a typical design. In our analog Theremin shown in Fig. 1, the pitch antenna is mounted as a vertical rod, around 0.5 m high. The capacitance of such an antenna

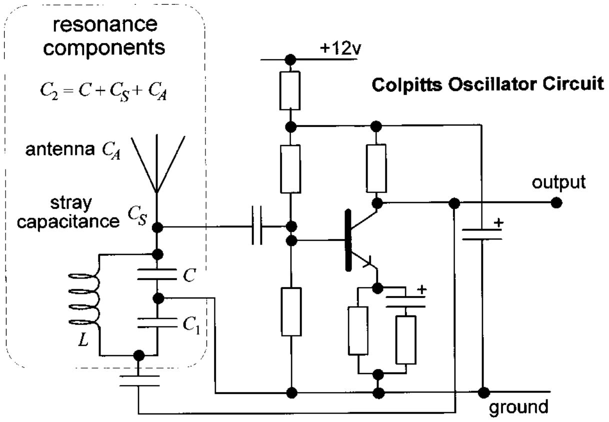


Fig. 4. Diagram of a transistor oscillator following the Colpitts design, highlighting the components that determine the resonance frequency, and hence affect the Theremin pitch.

can be deduced from potential considerations regarding cylindrical lines of charge in space. However, invariably these calculations do not consider the complex effect of the antenna being near earth and it is more appropriate to cite results from the field of radio engineering where formulae exist for the capacitance of vertical antennae in realistic configurations. For example, after converting the expressions found in Terman[9] to SI units, we can obtain the capacitance of the antenna in the absence of any player, which we will denote by $C_A(\infty)$, using the formula

$$C_A(\infty) = \frac{2\pi\epsilon_0 h}{\log\left(\frac{2h}{d}\right) - k}, \tag{6}$$

where h and d denote the height and diameter of the rod antenna respectively, ϵ_0 is the permittivity of free space (8.85×10^{-12} F m^{-1}), and k is a constant depending on how far above the ground the antenna is mounted ($k\sim 0.4$ for an antenna mounted almost at ground level). Taking the values $h=0.5$ m, $d=0.01$ m, and $k=0.4$ we obtain $C_A(\infty)\approx 7$ pF. We can neglect the stray capacitance for now since it will most likely be small compared with C_1 in the oscillator circuit (100 pF in Fig. 3).

Next we should investigate how much change in antenna capacitance might be expected when a player brings his or her hand near the instrument. One approach would be to consider the player's hand as a ground plane (of infinite extent) approaching the antenna. This will give a many-times overestimate but at least allows us to make some initial headway into the problem. In Fig. 5 the presence of the player's hand (ground plane) can be modelled as the addition of an image antenna whereupon the extra capacitance can be deduced from standard results for a twin-cylindrical conductor.[10] The extra capacitance ΔC_A is given by

$$\Delta C_A \approx \frac{\pi\epsilon_0 h}{10\log\left(\frac{4x}{d}\right)}, \tag{7}$$

where it is assumed that the player proximity x is somewhat larger than d. We have included a reduction factor of 10 in Eq. (7) to balance the overestimate that the formula would otherwise give. We justify this in terms of further modelling

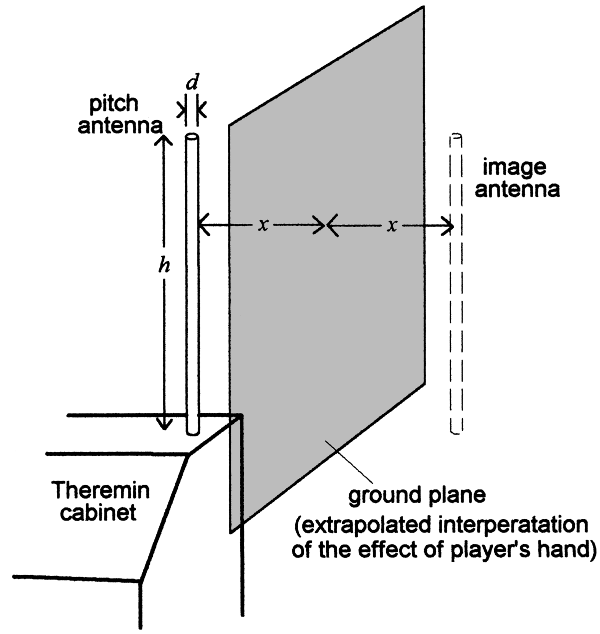


Fig. 5. A first approximation to the effect of a player's hand on the capacitance of the antenna can be deduced if we extrapolate the vertical hand to a ground plane and model the result using an image antenna.

the player's hand and arm rather like a horizontal strip along the ground plane of Fig. 5 with a width typically around a tenth of the antenna height. Since the contributions to the capacitance decay with distance, we can neglect the correction caused by the arm not being infinitely long, and take the antenna height to be the reference rather than the infinitely high ground plane in judging the correction factor. To obtain some idea of the magnitude of the effect, we can calculate that a player holding his or her arm 10 cm from the vertical antenna produces an additional capacitance of only 0.4 pF.

The modified antenna capacitance $C_A(x)$ is thus given by $C_A(\infty)+\Delta C_A$, and with the help of Eq. (5) we can now derive a relationship between the Theremin pitch and the player's proximity to the antenna. It is instructive to view this dependency graphically for the parameter values relevant to the instrument described here.

We have done this in the plot of Fig. 6 which shows the musical ''air-key-range'' of the instrument vs playing proximity for an instrument that has been initially tuned so that f_T is nearly zero for a player standing 1 m from the antenna. Note that at this distance it is the player's body that forms the dominant capacitive effect, and therefore we cannot take the lower bound in Eq. (5) to be $C_A(\infty)$ as perhaps might at first be thought.

Figure 6 shows that the Theremin's musical key pattern is quite linear over a reasonable range but deviates from this linear behaviour when the player is very near to the antenna (the linear behaviour is also deviated from when the player is very far from the antenna although this is not so obvious from Fig. 6). The behaviour shown in Fig. 6 agreed rather well with experimental data gathered from the instrument itself. The musical transfer function suggested by Fig. 6 is realised when trying to play the instrument, for it is always easier to perform in a key transpose which occupies the centre of the linear range. If, during a performance, the player begins to veer toward the antenna, then the movements of fingers, let alone the entire hand, cause rather large pitch

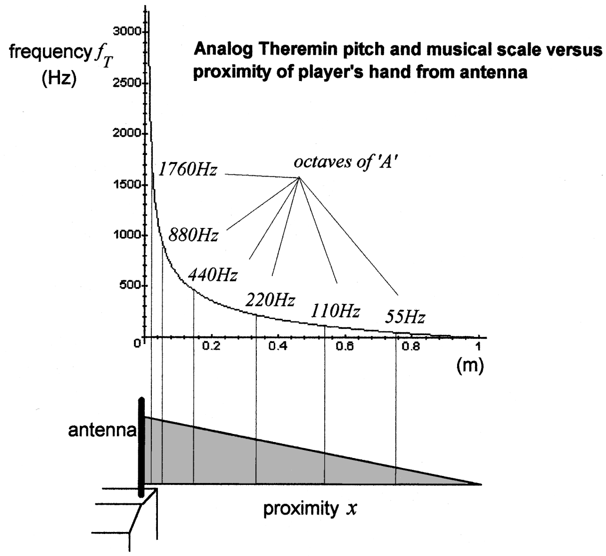


Fig. 6. The relationship between the Theremin tone frequency and the proximity of the player's hand to the pitch antenna, and how this relates to the effective musical key range for the instrument.

excursions. A characteristic of the Theremin playing style is the ease with which a player can induce vibrato on the tone. In view of Fig. 6 it is not surprising that a small tremor of the hand is enough to produce this effect, which has become a hallmark of the Theremin sound.

C. Lock-in effect and low frequency performance

In this section we will show how some basic physics can help draw attention to a common problem with Theremin low frequency performance, ahead of any construction. The effect that must be suppressed is the tendency for two free oscillating systems of similar frequency to synchronise together and run at a common frequency. In the Theremin, this would cause a problem if the locking happened at a beat frequency above the hearing threshold, causing a sudden cessation in tone, rather than a smooth decrease in pitch when the player moves further from the antenna.

The locking phenomenon is seen in various physical systems. For example, in a ring-laser-gyroscope, a signal proportional to the absolute rotation of the device is derived from the difference in mode frequencies of two counter-rotating laser beams in an optical ring cavity.[11] In this case, the scattering of light at the mirrors causes a small quantity of light to be exchanged between the two modes, reducing performance at small rotation speeds where the mode frequencies become similar. On the other hand, the effect of lock-in is used to advantage in high power Nd:YAG laser systems, where a high power but noisy laser cavity is locked to a quieter more stable low power laser through the injection of some of the stable light into the high power laser cavity.[12] What we want to emphasize here is that the concept of locking is very much a general principle of physics, although the precise coupling mechanisms for a given situation can be quite different.

In the case of the Theremin BFOs, we might have capacitive or inductive cross talk between the oscillator circuits, or ground currents and power supply ripple to contend with. The diagram in Fig. 7 shows qualitative linewidth curves for the Colpitts oscillators in Fig. 3. The locking effect is made more problematic when the linewidth is wide compared with the frequency offset from the other oscillator, as is the case for the fairly low-Q circuit of Fig. 4. However, some simple steps can be taken to reduce the problem. First, electromagnetic cross talk can be suppressed significantly by separately screening each oscillator. Ground currents have to be avoided as much as possible by the use of a good common ground mecca to which all oscillators are connected. Power supply decoupling must be included which can take the form of series inductors with capacitors to ground at the power entry points of each oscillator; this will attenuate any high frequency ripple on the dc supply lines.[13] Without these measures, the Theremin circuit of Fig. 3 would lock at a few hundred hertz, seriously affecting the useful range of the instrument. In Fig. 3 the 100-Ω resistor and 47-μF capacitor to ground in each oscillator form a decoupling filter, where the components are connected at the power supply entry points to each oscillator. In addition, series inductors in the power line outside each oscillator provide additional decoupling (not shown in Fig. 3). With the system carefully decoupled, modularised, and with each block screened as shown in Fig. 8 we managed to push the locking effect down below 50 Hz so that the player is unaware of it.

D. Tuning and playing the analog Theremin

The broad linewidth of the oscillators in an analog Theremin design permits a large drift of running frequency, influenced, for example, by thermal drifts in component values. The instrument can often require tuning when switched on and possibly fine adjustment thereafter. In order to avoid the inconvenience of having to open the cabinet and trim an oscillator frequency every time the instrument required adjusting, we included a novel electromechanical tuning control. The control shown in Fig. 9 consists of a simple disk capacitor which appears in parallel with the antenna. The

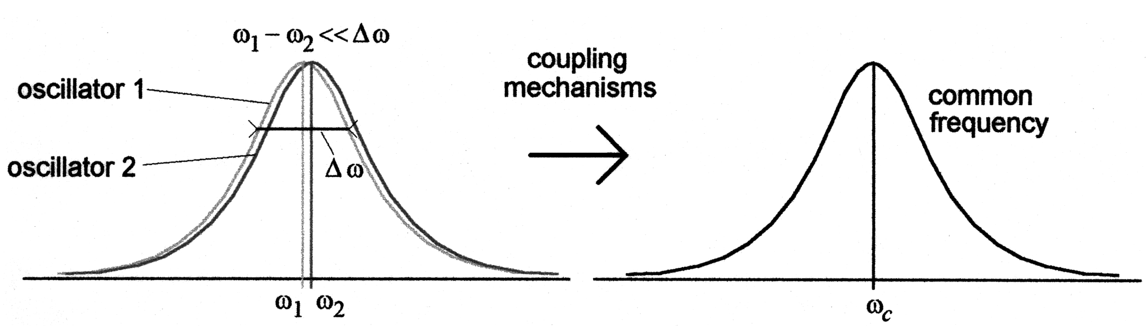


Fig. 7. Coupling mechanisms, which may be of relatively high order in the system, can lead to the synchronisation of the two free running oscillators.

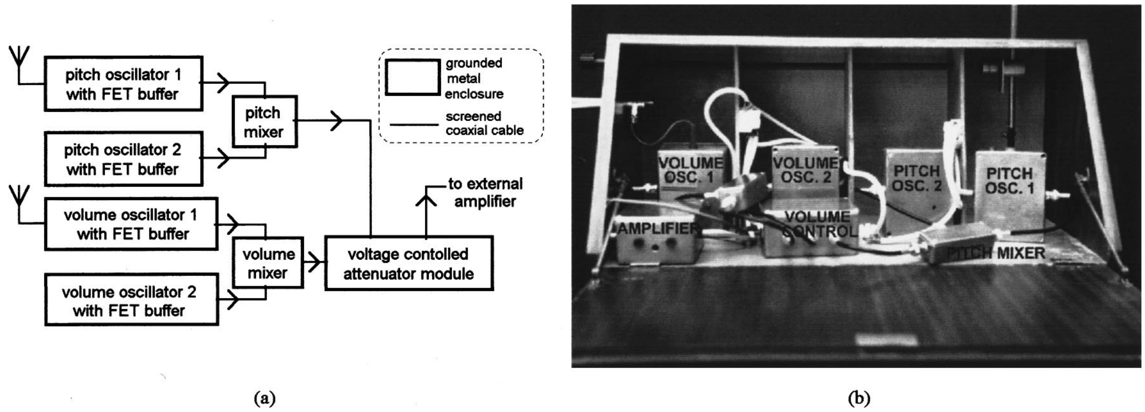


Fig. 8. Block diagram and photograph illustrating how the various circuit modules of the analog Theremin were individually screened and interconnected. The ground originates from the power supply and is used to ground the chassis of each fixed oscillator box (i.e., the oscillators not connected to the antennae). Subsequent ground lines are made via the shielded cable carrying the signals to other boxes.

disk spacing is controlled by a long plastic shaft which is terminated via a threaded collar on the left-hand side of the cabinet. The long shaft was included so that the player can turn the tuning control without confusing the adjustment by coming too close to the pitch antenna. By turning the control knob, the spacing between the plates is finely adjusted, the extra capacitance given by

$$C_S = \frac{\epsilon_0 \pi r^2}{a}, \tag{8}$$

where we are considering only air as the dielectric. Notice that C_S could be regarded as a changing stray capacitance in the previous discussion. We implemented such a control with $r = 2$ cm and $0 < a < 1$ cm, giving the ability to trim the capacitance to any value above $\sim$1 pF. During initial setup, this control is set to $a \sim 2$ mm, giving $C_S \sim 6$ pF. This gives a wide range of control to correct for drifts of both polarities in the BFO output.

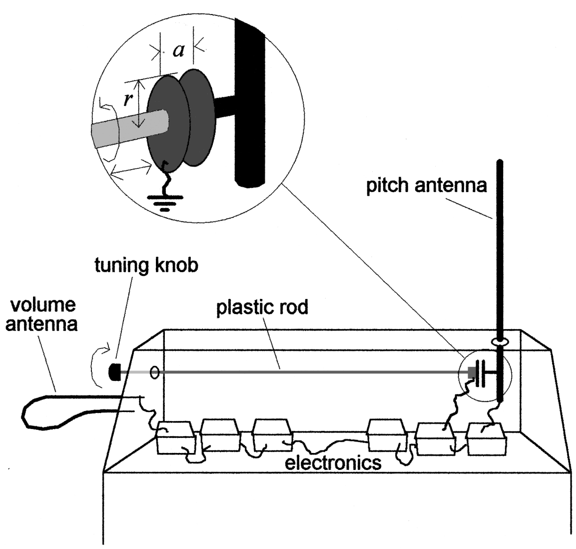


Fig. 9. Mechanical means to adjust the capacitance between each antenna and ground, illustrated here for the pitch antenna. Initial coarse tuning is achieved using the trimmer capacitors in each fixed oscillator, but then subsequent adjustments can be made without the need to reopen the Theremin case.

Now that tuning the instrument is relatively straightforward, there is nothing to prevent practising and playing music with the Theremin. However, we should note that another potential problem is the detection of radio signals, and the pickup of other electromagnetic fields, by the antennae of the instrument; we observed this phenomenon for some time in our own machine before retuning the oscillators. It may be wise to research the frequencies of local radio stations before deciding on the frequencies for the BFO oscillators. However, we have found that performing the instrument in an area of poor radio reception and away from fluorescent lighting is the best safeguard against such interference.

Finally, we reflect upon the fact that we have not yet discussed any method of controlling the volume of the Theremin tone, even though we have introduced a circuit for doing so in Fig. 3(b). It is fitting now to introduce a more stable design of instrument which addresses many of the factors we have discussed above, and this is doubly convenient in that our new design is best introduced via the discussion of the volume control technique.

III. BUILDING BLOCKS OF A MODERN THEREMIN

As with practically any instrument, the facility to adjust volume adds a great dimension of expressiveness to the musical sound produced. This facility is particularly important in the Theremin since without it, the transition from one note to another would necessarily always be a portamento or pitch-bending effect. We will now discuss the volume control circuit for our analog Theremin as this lends itself well to introducing the conceptual building block for a more advanced design; the concept is that of a proximity-to-voltage converter.

A. Volume control

Consider again the analog Theremin circuit shown in Fig. 3. The volume circuit is shown in Fig. 3(b) and contains the same BFO design as the pitch control circuit in Fig. 3(a). The output of the volume mixer is passed through a low-pass filter with a corner frequency of about 1 kHz. This produces a signal with frequency and, more importantly here, amplitude that varies in response to perturbations in the antenna capacitance. This filtered signal is amplified and rectified and

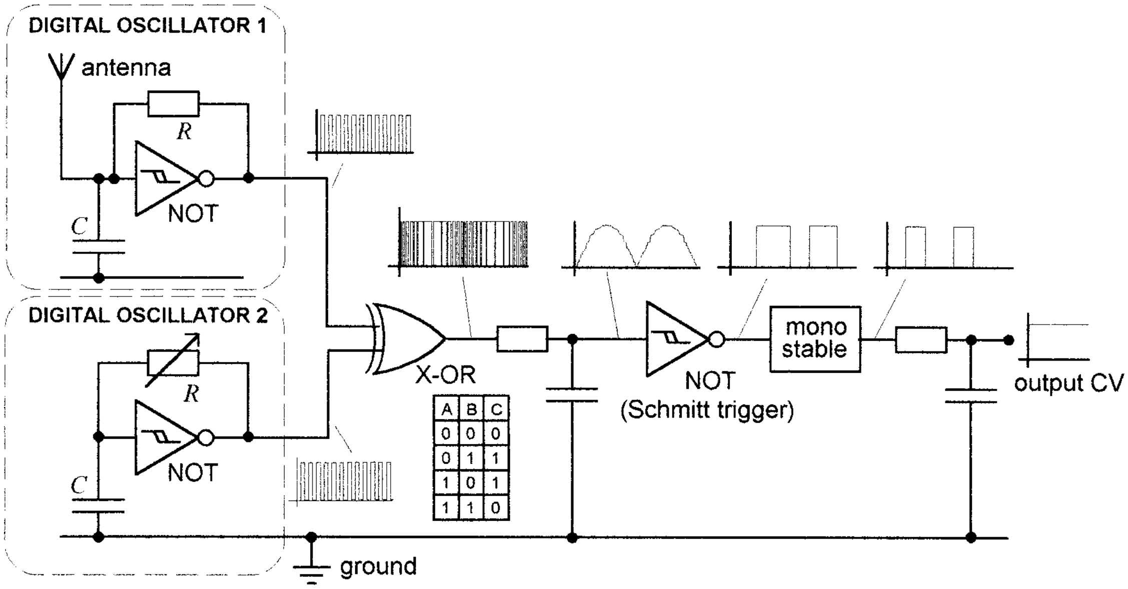


Fig. 10. The various stages of the digital control module whose function is to generate a dc voltage that depends on the proximity of the players hand from the antenna. This circuit block will be referred to as a proximity detector (PD) in the text.

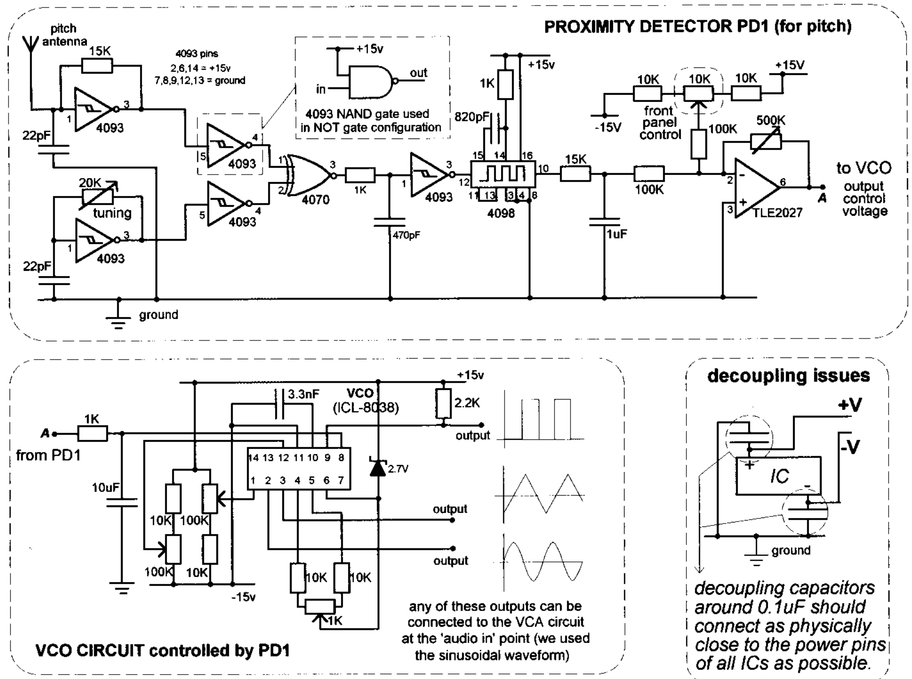
passed through a simple integrating filter which provides a dc control signal. This dc signal is a direct function of the filtered signal amplitude which in turn depends on the position of the player's hand. The integrator time constant must be chosen so that fluctuations in the dc level can respond to the fastest movement of the player's hand and is taken to be about 0.1 s here. Once a control signal has been obtained from the BFO in this way, it can be used to control a wide variety of electronic devices. In the circuit of Fig. 3(b) the dc control signal is processed so that it changes from 0 V (close proximity to antenna) to −4 V (far away from antenna). This constitutes a convenient control voltage range to apply to a JFET in voltage-controlled resistor (VCR) mode. The JFET and the 4.7-kΩ resistor form a potential divider across which the audio tone from the pitch circuit is connected. The output is taken from the middle and ranges in amplitude from almost full input signal when the JFET resistance is high (−4 V applied to its gate) to practically no signal when the JFET resistance is low (0 V applied to its gate). This configuration allows the volume to be attenuated by moving closer to the antenna, as in the early RCA units. We measured a 40-dB suppression in volume using this simple design. However, all the problems of lock-in and drifts in tuning apply also to the volume BFO. Therefore we will now introduce a more modern approach motivated by the idea of control-voltage production described above.

B. Proximity-to-voltage converter

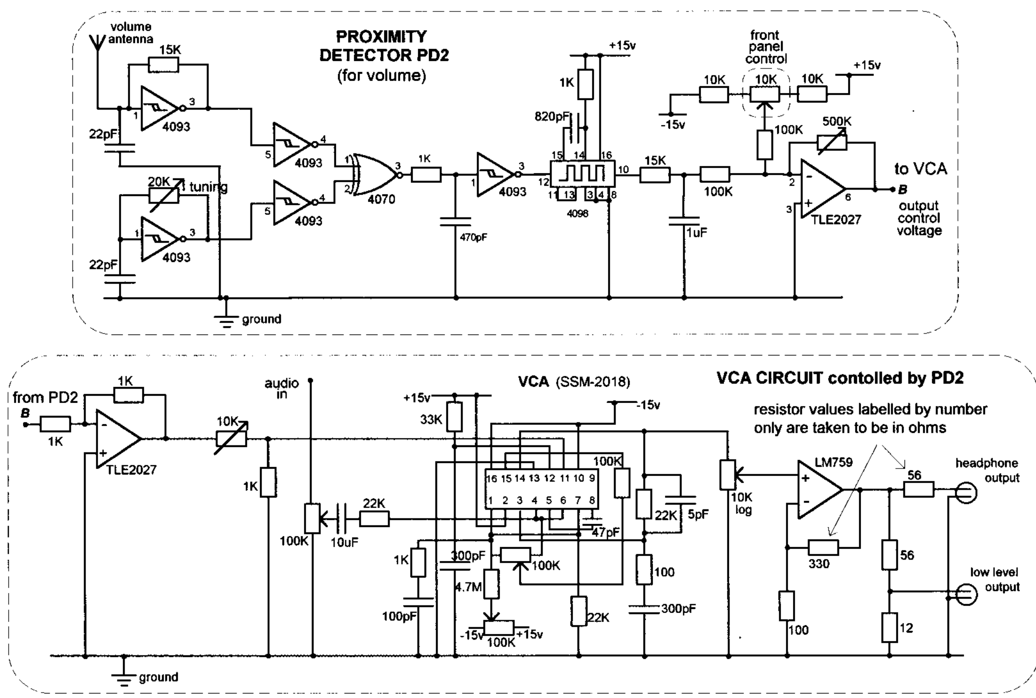
A key feature of the analog Theremin design discussed so far is that the output sound is directly related to the characteristics of the high frequency signals generated by each pitch oscillator.[14] Some argue that this is what gave the original Theremins their distinctive sound, with distortion and nonlinearities in the vacuum tubes all contributing to the output waveform. However we may not wish to carry this feature here; therefore one aim of our modified circuit is that it distances the final output sound from the waveforms produced by the BFO blocks. Instead, the modified equivalent of the analog BFO is used merely to generate a dc control voltage (CV), rather like in the volume control circuit of Fig. 3(b). These CVs can then be used to feed into a wide variety of devices including voltage-controlled oscillators (VCOs), voltage-controlled amplifiers (VCAs), and possibly even voltage-controlled filters (VCFs). In addition it is a simple extension of our design to produce a CV with suitable range to pole the CV gates of analog synthesizers. We could call the functional block that generates each CV by the name of a proximity-to-voltage converter or proximity detector (PD). In the simplest Theremin, we would require only one PD and one VCO to generate music. To emulate the properties of a ''traditional'' machine, we would require two PDs, one feeding into a VCO for pitch control and the other controlling a VCA for volume adjustment.

A schematic of the PD unit that we have built is shown in Fig. 10. The output of each digital oscillator is a square wave with frequency set by the values of *R* and *C*. Two such oscillators are used in the PD, one of which is connected to the antenna. The outputs of these oscillators can be combined by feeding them via buffers into an exclusive-OR (X-OR) gate. By considering the truth table for this gate, given in Fig. 10, it becomes apparent after some careful thought, that the output will be a signal whose rising edges occur roughly at the sum of the input frequencies, but whose duty cycle varies at the difference of the input frequencies. Therefore by integrating the output of the X-OR gate with a suitable low-pass filter, it is possible to recover a signal whose primary Fourier component is at the difference frequency. The signal is fed through a Schmitt trigger to produce a square wave, which is then passed to a monostable trigger which produces a series of fixed-width pulses at the difference frequency. Finally, these are integrated with a second low-pass filter to yield the output CV. Initial frequency matching between each oscillator is achieved by the use of the variable *R*. Since there are no inductors and a minimal number of capacitors, we can employ precision resistors and a stable type of *C* in order to achieve much less drift in this design.

Having introduced the basic PD building block, the applications are best left to the imagination of individual experi-



(a) Pitch Control Circuitry



(b) Volume Control Circuitry

Fig. 11. The complete digital Theremin circuit showing (a) the pitch control electronics and (b) the volume control electronics.

menters; however for completeness we will present our own design for a digital Theremin with pitch and volume controllers.

C. Digital Theremin circuit

The schematic is shown in Fig. 11 with the pitch and volume control blocks shown in Figs. 11(a) and 11(b), respectively. We will refer to the pitch circuit first of all. We used the ICL8038 VCO from Harris Semiconductors.[15] This device produces a frequency sweep of 1000:1 when its control voltage input is varied from about two-thirds of its supply voltage to a few tenths of a volt more than its positive supply voltage. The necessary control voltage is produced by a PD of the type discussed above together with appropriate CV processing using a simple operational amplifier circuit to

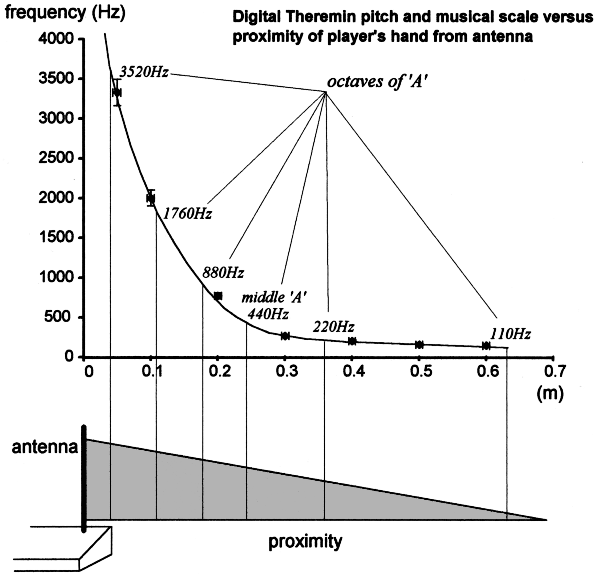


Fig. 12. The relationship between the digital Theremin tone frequency and the proximity of the player's hand to the pitch antenna, and how this relates to the effective musical key range for the instrument. It is interesting to notice that the octave interval remains fairly constant up to much higher frequency than for the analog Theremin.

perform relevant algebra. After initial tuning, the basic PD generated a CV of 0 to +1 V as the antenna was approached. Subsequent adjustments could be made using the 10 and 500 kΩ variable resistors around the op-amp following the PD. These can correct for any drift between the two oscillators in the PD and effectively replace the tuning control of the analog design. In fact it was found that only the 10-kΩ resistor needed adjustment and so it appears on the front panel, as far from the pitch antenna as possible. We found that we could achieve a sweeping of the 8038 frequency from around 100 Hz to over 10 kHz over a playing range of around 0.6m with the circuit of Fig. 11(a).

The relationship between playing position or proximity to pitch antenna and the frequency of tone produced is difficult to predict for the digital device, because it will involve the transfer function of PD1 as well as the VCO in Fig. 11(a). Therefore, in order to produce a diagram equivalent to Fig. 6 for the digital instrument, we experimentally measured the transfer function from playing position through to output frequency; the results are shown in Fig. 12. It can be seen that our digital Theremin preserves a constant octave interval up to a much higher frequency than does the analog design. However, the very low frequency behaviour was not as good as that seen with the analog Theremin and this perhaps reflects the extra effort we put into decoupling in the analog case to avoid lock-in and achieve the sub-100 Hz performance.

Returning to Fig. 11(b) it can be seen that the volume circuit is identical to that for the pitch control, up to the end of the PD block. The extra inverter stage after PD2 was found to be necessary for purely technical reasons stemming from the requirement that touching the volume antenna should produce zero volume. Again, the 10-kΩ offset control is mounted on the case, this time far from the volume antenna. The VCA chosen here is based on the SSM-2018 chosen for its relatively low cost and robust performance.[16] Maximum and minimum gain for this VCA corresponds to pin 11 being brought, respectively, negative and positive by a few tenths of a volt with respect to ground. The output from the 8038 VCO can only drive rather high impedance inputs, and this accounts for the unusually high choice of a 100-kΩ potentiometer used to attenuate the signal at the input of the VCA. In normal operation this potentiometer should be set so that when the VCA has maximum gain, no clipping of the signal takes place. However in practice it was decided to allow the input signal to be sufficiently high so as to result in clipping of the output signal for the maximum gain of the VCA chip. This results in a square wave at the output when a sinusoidal wave is present at the input, and thus effectively generates new harmonics in the sound. These harmonics are suppressed when the gain of the VCA is reduced, whereupon a sinusoidal wave as pure as the input waveform is produced. Further reduction of the VCA gain results in a normal decrease in volume of this sinusoidal wave. We found it possible to produce a volume sweep of over 80 dB with the SSM-2018 IC resulting in a range that begins at inaudibility (when the player touches the antenna) and ends with around 20-dB amplification of the input signal (when the player is distant from the antenna).

D. Comparison of the analog and digital Theremin

Finally, we may compare the relative attributes of the analog and digital designs. From a teaching-aid point of view, the analog Theremin is better suited for conveying the physics of the instrument. There is a clear overlap with radio theory and associated principles, as well as the other examples of applied physics outlined in Sec. II. Nevertheless, the analog Theremin of the basic design in Fig. 3 does suffer from disadvantages of component drift and susceptibility to external interference. In the digital design, we sought to produce an easier to operate instrument, using a control-voltage approach borrowed in essence from the analog circuit's volume section. In doing so, we found the digital Theremin to offer a more linear octave range up to higher frequency, at the expense of reduced range at very low frequency. The degree of linearity of the musical ''air-keyboard'' can be deduced from the plots of Figs. 6 and 12. Perhaps a clearer way of comparing these plots is to graph the logarithm of frequency for each instrument, since a truly linear keyboard range will be reflected in this graph as a straight line. We have done this for the playing range up to 0.6 m in Fig. 13. An even clearer way to visualize the implications for playing music is shown in Fig. 14 where we have shown the effective key ranges over a 0.6-m playing range for each instrument. The top key range represents five octaves of a normal piano range, and the relative distortions are shown for the analog and digital Theremins underneath. Our experience has been that beginner players find the analog device the easiest to play, probably because there is a larger range of linearity all the way out to 1 m from the antenna, making it easier to converge on a given note. However, once a feeling for the playing style has been established, the more linear upper octaves of the digital Theremin can be more skillfully used.

The volume control in both instruments felt to have quite similar transfer functions from playing position to attenuation of volume, although we did not make any quantitative measurements of this. However, the option of setting the maximum volume of the digital device so that the signal clips at the VCA output allows more expressive playing style

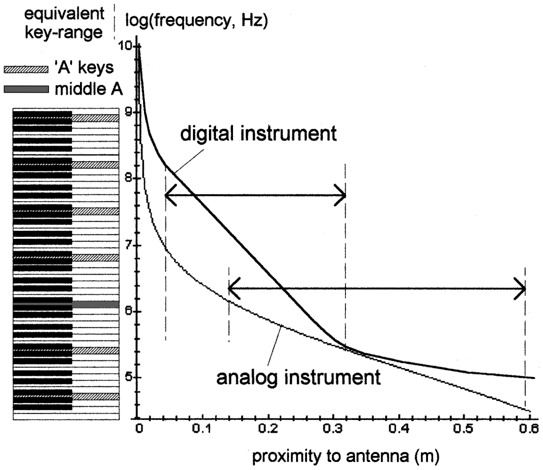


Fig. 13. Plots of the logarithm of frequency (equivalent to a piano key range) against proximity to the pitch antenna of each instrument. Musically linear playing ranges are indicated with the arrow intervals. These intervals can be projected onto the vertical keyboard to show immediately the musical key range over which each instrument offers good linear behaviour. Of course, the whole musically useful playing range for each instrument is much wider than these linear intervals, but skillful playing requires much practice in order to become familiar with the entire transfer function of each instrument.

to be achieved. Lastly, as perhaps might be noticeable from our photographs in Fig. 1, we tried to forge a stylistic difference between the analog instrument and the digital device, endeavouring in particular to keep the analog instrument quite similar to the look and feel of the commercially produced Theremins of the 1920s.

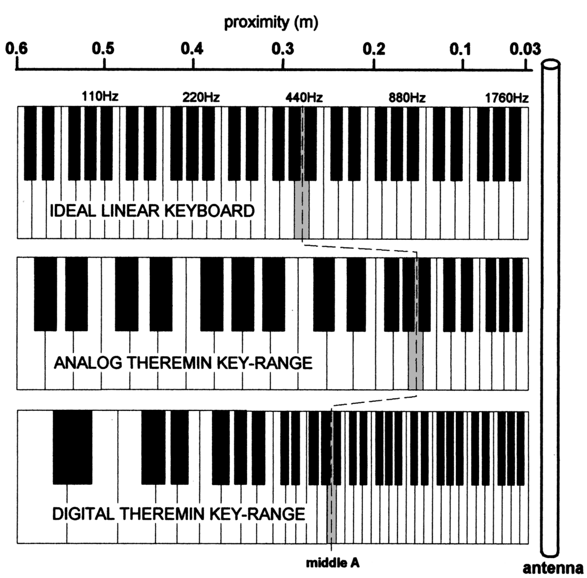


Fig. 14. A qualitative illustration showing the distorted key ranges for the analog Theremin (middle) and digital Theremin (bottom) compared with the playing range that an ideal linear keyboard of roughly the same number of octaves might provide (top). This picture clearly shows the merits of the analog instrument at lower frequencies while also highlighting the advantages of the digital design over the higher octaves. Note that unlike previous diagrams, the proximity decreases to the right here in order to enable the keyboards to be drawn intuitively.

IV. CONCLUSION

We have outlined the physical concepts behind the design and operation of the Theremin, making reference to an analog design and taking the opportunity to present a more innovative digital device. The overall number of octaves that each instrument could cover was approximately the same, however the analog Theremin possessed better low frequency performance, concentrating the upper octaves into a narrow playing range. The digital instrument had a fairly linear playing range extending over three octaves above middle A. The volume circuit was arranged in both instruments to null the sound level when the player's hand was touching the antennae.

The digital circuit has much scope for expansion using external control sources to affect the Theremin sound. For example, adding the output of a drum machine to the dc control level for the VCA (through a resistor into the virtual ground of the inverting adder) allows the sound level to be pulsed to the beat. The pitch can be modulated in a similar fashion by adding in a signal through a resistor to the virtual ground of its inverting adder stage. If variable sinusoidal signals are applied to these same points, then the result would be an adjustable tremolo and vibrato. We have achieved an interesting variety of sounds using a combination of these techniques. Another possibility is the control of modern digital synthesizers via the addition of a commercial CV to MIDI converter using the PD to generate the CV. By employing a third antenna and another PD, a VCF or resonant filter block could be included to produce even more interesting sounds; however we leave the implementation of such upgrades and expansions to enthusiastic experimenters elsewhere.

We should not forget that the Theremin is first and foremost the musical instrument that stimulated the birth of music using electricity. Although it is strictly speaking an electronic musical instrument, we can still regard it in many ways as being more closely related to a ''passive'' instrument than is say, the electronic synthesizer. This is due in part to the simplicity of the tone produced, but we might also argue that it is because so many aspects of its operation can still be described by principles of applied physics, rather than of electronics which can so often appear more of an art than a science. Indeed, some of the early analog Theremins were unique in providing a tone that was closer to a pure sine wave than almost any other acoustic instrument you could mention. Its sound is remarkably distinctive, and in one sense, much more characteristic than the sounds from today's digital synthesizers which are sold largely on their ability to achieve very complex timbres or realistic instrument sounds. The effect of adding harmonics to the basic Theremin-style sound is well demonstrated by our digital design, where the signal levels from the amplifier can be made to clip. There is teaching value to this demonstration, which could be related to the role of overtones in defining the acoustic timbre of other types of musical instrument. In addition, many other aspects pertaining to the principles of operation have teaching value, and as we mentioned earlier, the simplicity of the analog instrument affords its strength in this area.

Finally, we acknowledge that an interest in Theremin's instrument would not be complete without due consideration of the remarkable events in the life of the physicist himself. His story is one of the most amazing scientific biographies of the twentieth century, perhaps because it enrobes an enduring passion in science and society. This passion continued despite the interval of a generation when Theremin was involuntarily isolated, not only from the people he knew and loved, but also from the research field toward which he had chosen to direct his knowledge of physics.[17]

ACKNOWLEDGMENTS

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[1]G. Anfilov, *Physics and Music* (MIR, Moscow, 1966). This rarely cited book was translated from Russian by B. Kuznetsov and describes Theremin's early research in Moscow, although it does not describe the amazing course that Theremin's life took after 1938, when he vanished without trace from his New York apartments.

[2]Since Theremin's death, there has been an ever-increasing band of popular musicians that seem to have just ''rediscovered'' his instrument's value as a source of ''cult sound.'' However, the Theremin has been used occasionally in popular music for many decades; one famous example is the Beach Boys hit ''Good Vibrations'' where the Theremin and cello provide backing melody.

[3]T. Rhea, ''Recordings; Clara Rockmore: The Art of the Theremin,'' Comp. Music J. **13**, 61–63 (1989).

[4]R. Moog, ''Theremin Virtuoso Clara Rockmore—Recollections of Genius,'' *Keyboard Magazine* (February 1994).

[5]In the early twentieth century there were around seven-hundred professional Thereminists registered with the musicians' trade union. It should also be noted that Leon Theremin's great niece, Lydia Kavina, is an accomplished present-day Thereminist.

[6]R. Moog, ''A Transistorized Theremin,'' *Electronics World* (January 1961).

[7]R. Moog, ''A Transistorized Theremin,'' *Elementary Electronics* (May/June 1972). Of course, this and the previous reference are only two examples from a multitude of Theremin designs spanning many decades; a comprehensive list may be found using Ref. 17.

[8]Theremin's disappearance from his New York apartments went unexplained for over 50 years. His wife and most of his closest friends presumed him dead. However in 1991, research for Steven Martin's video documentary *Theremin: An Electronic Odyssey* (Orion Classics Release, 1993) led to a remarkable chance encounter with the physicist, then aged 95, in Moscow. In the film, Theremin explains how he was abducted by the forerunner of the KGB, an act motivated by the need in Russia at the time for expertise to expediate technological military developments. *Theremin: An Electronic Odyssey* was premiered on UK's Channel 4 Television. Just one day after the thought-provoking film was shown, Leon Theremin's death was announced in Moscow.

[9]F. E. Terman, *Radio Engineers Handbook* (McGraw–Hill, New York, 1943).

[10]G. P. Harnwell, *Principles of Electricity and Electromagnetism* (McGraw–Hill, New York, 1938).

[11]K. D. Skeldon, ''A Museum Scale Ring-Laser-Gyroscope to Demonstrate the Sagnac Effect,'' University of Glasgow Vacation Project (Internal Report 1991).

[12]A. E. Siegman, *Lasers* (University Science Books, Mill Valley, CA, 1986).

[13]P. Horowitz and W. Hill, *The Art of Electronics* (Cambridge U.P., Cambridge 1990), 2nd ed.

[14]The waveforms of each oscillator and the resulting beat waveform produced by the chosen mixer all have an impact on the sound. In the analog Theremin circuit, we used SBL-1 mixers (Mini Circuits Laboratory, *RF Designers Handbook*, 1994). In this implementation, the two oscillators in each BFO provide the radio frequency (rf) and local oscillator (LO) inputs to the mixer, and the intermediate frequency (IF) output from the mixer (which is nonstandard in being down near dc here) provides the tone. We arranged the signal levels at the SBL-1 to be just below clipping (around 1.2 V) whereupon the output waveform was reasonably sinusoidal above a few hundred hertz, beginning to distort more toward dc. However, we found the output sound timbre to be very authentic compared to recordings of early Theremins.

[15]Harris Semiconductors have their main home page at http://www.semi.harris.com and information for the ICL8038 can be obtained using the data-sheet links found therein.

[16]Precision Monolithics Inc, Data Book-Analog Integrated Circuits, 1990.

[17]The Theremin home page can be found at http://www.nashville.net/~theremin and contains many sources of reference on Theremin's life and work, including much on his ''missing years.''

ENTHUSIASM

As a graduate student at the University of Hawaii, [Heidi Hammel] recalls, she was ''chided'' by the committee reviewing her thesis for her excessive enthusiasm. ''I think the way one guy put it,'' Ms. Hammel laughs, ''was that I spoke with exclamation marks when I talked. It's just the way I talk. I can't help it.''

''I worry sometimes when I give talks at scientific meetings, because the style is to stand up there,'' she adds, her speech growing slower and deeper, ''look very serious, and present your results because they're so very important.

''I don't care,'' she says, ''I just get up there and have a good time. I wonder if sometimes people lose the message of what I'm talking about, because it's so different from the normal scientific style, which is *so boring*.''

Kim A. McDonald, ''The Comet Drama's Biggest Hit,'' The Chronicle of Higher Education, 27 July 1994.