Development and Construction of a Theremin

1 Background

1.1 What is a Theremin?

A theremin is an electronic musical instrument. Unlike most instruments the musician doesn't need to be in contact with the instrument to play it, the pitch that is heard depends on where the musicians hand is compared to an aerial. One of the most famous uses of the theremin is in 'Good Vibrations' by the Beach Boys, making use of a high tone that the theremin can produce, the theremin sound was often used in old black and white horror/science fiction movies.

The inventor of the theremin was called Lev Sergeivitch Termen and in 1917 he noticed that proximity of his body to the vacuum tubes he was using caused the frequency to vary of the signal he was producing. Instead of seeing this as a problem he utilised it to make the musical instrument named after him. The prototype used switches to alter the capacitance, but in 1920 the first model to use an antenna was produced. Termen left the Soviet Union in 1927 for America and his theremin was patented in 1928.

1.2 Producing Musical Notes

The perception of a pure tone (musical note) is the result of a source of vibration at a particular frequency. A medium then transmits this vibration as a longitudinal wave, which the ear channels and turns into electrical signals that the brain interprets as sound. Good human hearing can perceive notes that have frequencies from 20Hz to 20000Hz.

When a guitar string is plucked it vibrates, this vibration is transmitted through the air and into the ear and a note is heard.

Theremins produce notes electronically. Electronically produced notes start as oscillating electric signals, this signal can be used to make certain systems vibrate. A typical example is a loud speaker that uses an electromagnet that the varying signal passes through and a permanent magnet that oscillates depending on the signal through the electromagnet. Attaching a cone to this system increases the amount of air that is vibrating creating an audible sound through the air to the ear as before.

2 Theory of Theremin Operation

2.1 Producing a Sine Wave

There are many ways to produce an electronic signal, but most theremins rely on circuits that depend on capacitance values to set their resonant frequency. An example of a circuit is the Wein-Bridge oscillator shown below,

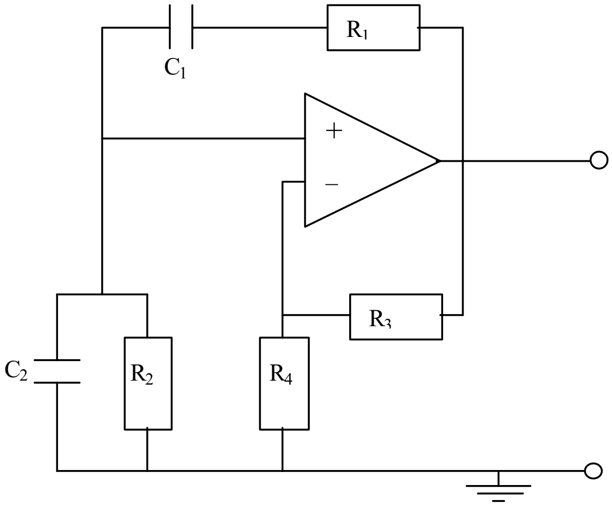

Fig 2.1 A Wein-Bridge Oscillator

By looking at the relevant components separate from the oscillator it can be understand how this circuit works.

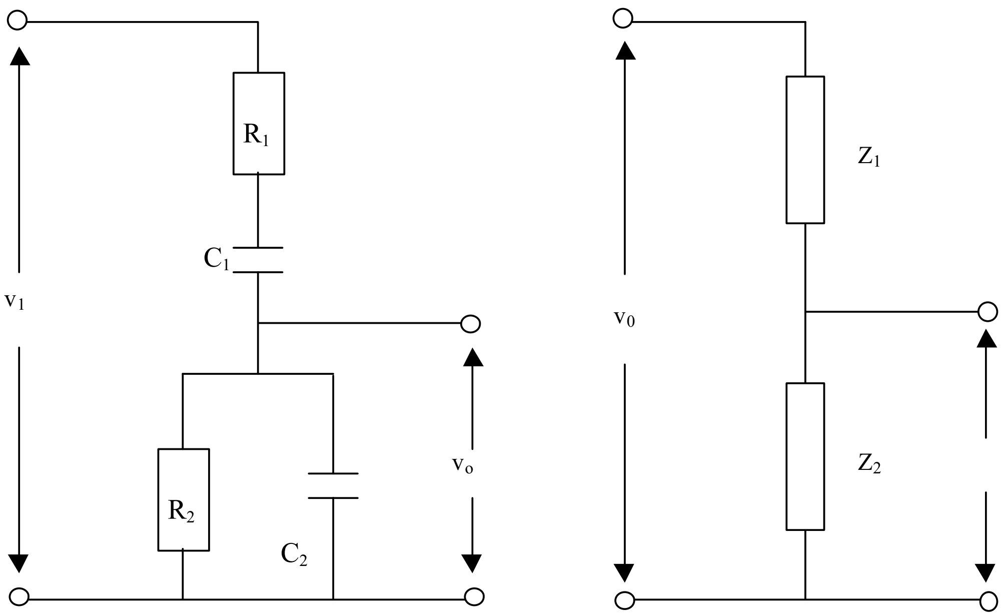

Fig 2.2 The Wein-Bridge components separate from the oscillator (left) and as a potential divider (right)

The components can be looked at as a potential divider (above right), where the attenuation is;

$$\frac{v_1}{v_0} = \frac{Z_1 + Z_2}{Z_2}$$

$$= 1 + \frac{Z_1}{Z_2} \qquad (1.1)$$

Returning the actual Wein Network,

$$Z_1 = R_1 + \frac{1}{i\omega C_1}$$

and
$$\frac{1}{Z_2} = \frac{1}{R_2} + i\omega C_2$$

$$\rightarrow Z_2 = \frac{R_2}{1 + i\omega C_2 R_2}$$

Using (1.1) $$\frac{v_1}{v_0} = 1 + \frac{[R_1 + (1/i\omega C_1)](1 + i\omega C_2 R_2)}{R_2} \quad (1.2)$$

Multiplying out gives; $$\frac{v_1}{v_0} = 1 + \frac{R_1}{R_2} + \frac{C_2}{C_1} + i\left(\omega R_1 C_2 - \frac{1}{\omega R_2 C_1}\right) \quad (1.3)$$

Usually it is the case that $R_1 = R_2 = R$ and $C_1 = C_2 = C$, then (1.3) becomes,

$$\frac{v_1}{v_0} = 3 + i\left(\omega RC - \frac{1}{\omega RC}\right) \quad (1.4)$$

The imaginary term disappears at the resonant frequency ω_0 when,

$$\omega_0 RC = \frac{1}{\omega_0 RC}$$

i.e. when $$\omega_0 = \frac{1}{RC} \quad (1.5)$$

Therefore $$f_0 = \frac{1}{2\pi RC} \quad (1.6)$$

At the resonant frequency the imaginary term equals unity, thus the gain of the system is 3, (shown in equation 1.4).

This means that the amplifier must maintain a gain above 3 to maintain oscillation. This low gain allows relative heavy negative feedback to be employed, which in turn allows for high stability of the circuit in terms of amplitude and waveform stability.

2.2 Waveform Mixing

The problem with using an oscillator that depends on the capacitance is that a hand only offers 2pF worth of capacitance when near the aerial (this is shown experimentally later). An example of values used for a typical audible signal of roughly 5kHz is 1kΩ and 30nF. Under this regime, attaching an aerial to the capacitor to change its capacitance will not alter the frequency significantly for a difference to be heard.

2.3 Superposition of Waves

When two sine waves of slightly different frequencies are added together they form a resultant wave that consists of a carrier wave frequency and an envelope frequency. This is demonstrated graphically below,

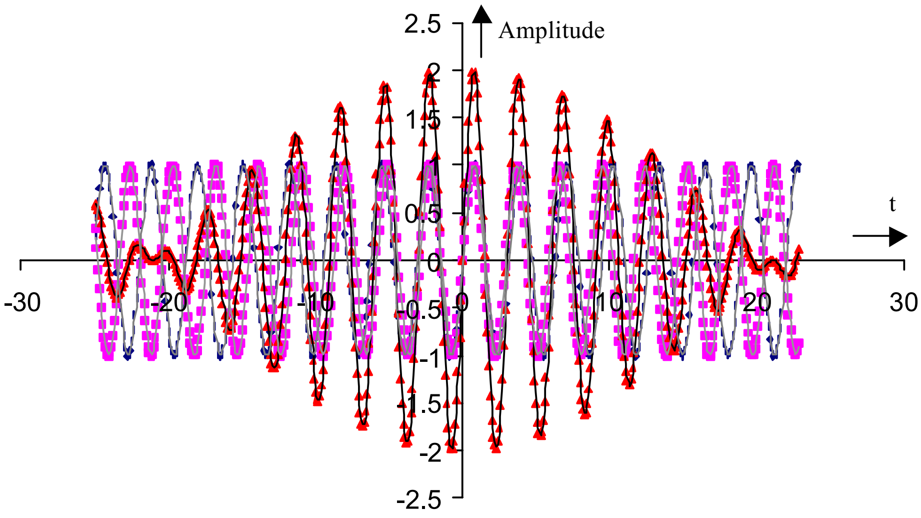

Fig 2.3 The superposition (red) of the two sine waves (pink and blue), the sine waves are in phase at x=0, y=0. Amplitude and time values are arbitrary.

The carrier wave frequency is the average of the two sine waves, this is seen as the wave that has nearly the same frequency of the two sine waves in the above plot. The envelope (beat) frequency is the difference between the frequencies of the two sine waves. Because the frequency difference between the sine waves is small, the period of the wave is large in comparison. This is seen as the slow change in amplitude of the carrier wave.

By using two ultrasonic oscillators (>20kHz) whose frequencies are similar, but not closer than 20Hz, the average frequency remains ultrasonic, whereas the beat frequency becomes audible.

Theremins use this principle, as accessing the human hearing range is a matter of making oscillators faster, in this case the percentage change in frequency becomes large compared to the audible range. Running at ultrasonic frequencies tends to use smaller capacitor values, which means a 2pF hand capacitance becomes more significant in changing the oscillator frequency.

3 Oscillator Construction

3.1 Operational Amplifier Selection

Theremin sources on the internet(2) gave typical oscillator frequencies between 0.1MHz and 1MHz. This meant that a basic 741 operation amplifier (op-amp) may struggle to maintain gain at these levels. The Bode plot (below) shows the gain reaching unity at 1MHz. We chose to use the NE5532N chip. There wasn't a Bode Plot available for this chip, but the tables that came with it said the gain reached unity at 10MHz, which was deemed expectable. It had the added advantage of containing two op-amps on the one chip, so would save space when it came to making the theremin.

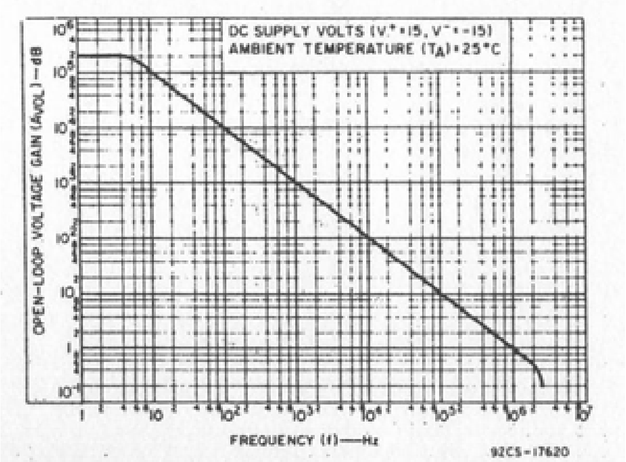

Fig 3.1 Bode plot of Gain vs. Frequency of the 741 Amplifier, whose performance at the higher frequencies was deemed too poor to use in the oscillator circuits

3.2 The First Oscillator

The first oscillator, shown below, used RC components of 1kΩ and 330pF, which gave a theoretical resonant frequency of 482kHz, but the oscillator produced 195kHz.

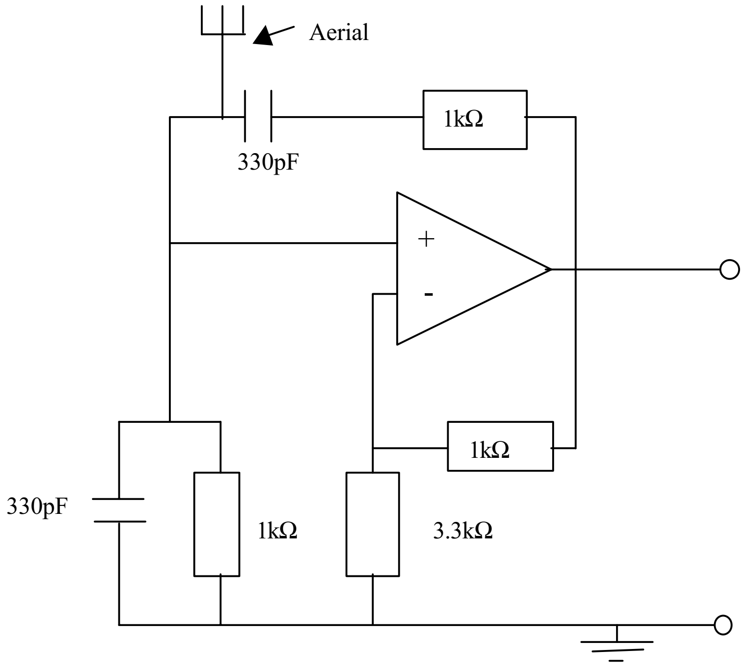

Fig 3.2 The first oscillator used to gain information on the construction of oscillators and the frequency response when an aerial was attached to a capacitor.

The value of 330pF was chosen for the capacitor values as designs found on the internet used these designs(2).

The two resistors involved in the negative feedback loop acted as a potential divider. By altering the ratio of these resistors the negative feedback could be changed.

Connecting the terminals to a Cathode Ray Oscilloscope (CRO) allowed inspection of the waveform. From this it was possible to check whether the correct amount of feedback was applied. If too much feedback was applied there would be no signal, if there was too little the oscillation would saturate at the positive and negative voltage rails at the top and bottom of the oscillation respectively. The right amount of feedback occurred when the oscillation had just stopped saturating.

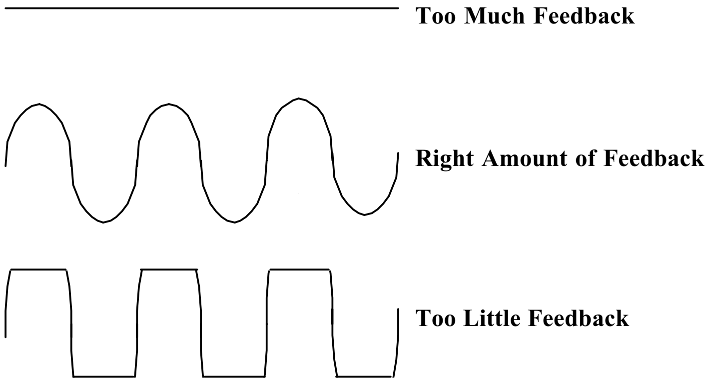

Fig 3.3 The effects of varying negative feedback on the output waveform

The aerial attached to the circuit consisted of two copper plates on top of each other roughly 0.5mm thick and 300mm square, separated by 1mm of wood.

It was noted that when a hand was placed very near to the plates the signal changed to the new frequency of 200kHz which was a frequency shift of 2.5%. When the aerial was removed it was found that the same effect could be achieved by placing a 2pF capacitor in parallel with the capacitor that the aerial was attached to. This gave the best indication as to the maximum capacitance offered by a hand over the plate. In this regime the difference was 5kHz.

3.3 The Effect of Changing the RC Component

A Circuit was set-up such that the RC components could be changed, first the resistor value was kept constant at 1kΩ while the capacitor values were changed.

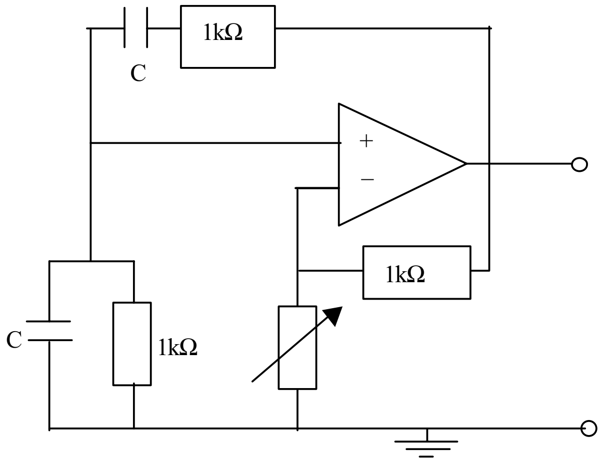

Fig 3.4 The Circuit used for testing the effects on Frequency by changing the Capacitor Values

The variable resistor was used so the feedback could be tuned so the signal wasn't saturated or attenuated too much.

3.3.1 Changing the Capacitance Values

This experiment changed the RC component by keeping the R Value constant at 1kΩ, and varied the C Values of the Wein-Bridge Oscillators. The frequency from the oscillator was taken just as the signal saturated. This was achieved by adjusting the feedback until this was the case. This gave the following graph.

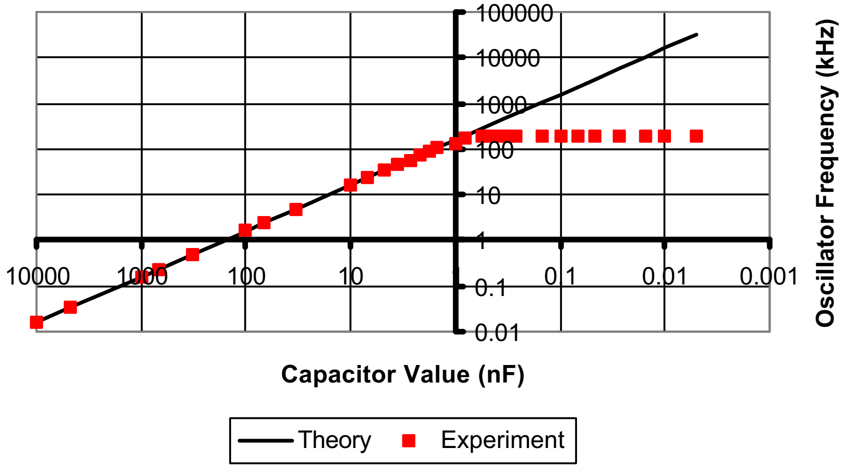

Fig 3.5 How changing the capacitance of the RC component of the Wein-Bridge Oscillator changes its frequency, whilst the R Value is held constant at 1kΩ

The graph shows that the theory holds until ~200kHz, where the oscillator frequency remains fixed at 195kHz despite theory predicting that the frequency should rise with decreasing capacitor values according to equation (1.6). In this higher regime, changing the capacitance values gave no effect on the frequency of the output signal, but the feedback tuning had to be altered for each new capacitance value used.

3.3.2 Changing the Resistor Values

To determine whether the capacitors or the circuit caused this limiting effect was determined by repeating the above experiment. This time the capacitor values were held at 330pF, whilst R Values were changed. This 330pF capacitor was chosen as it was within region where the frequency remained constant. But the value was not too small to be effected by small any capacitance caused by the surrounding environment.

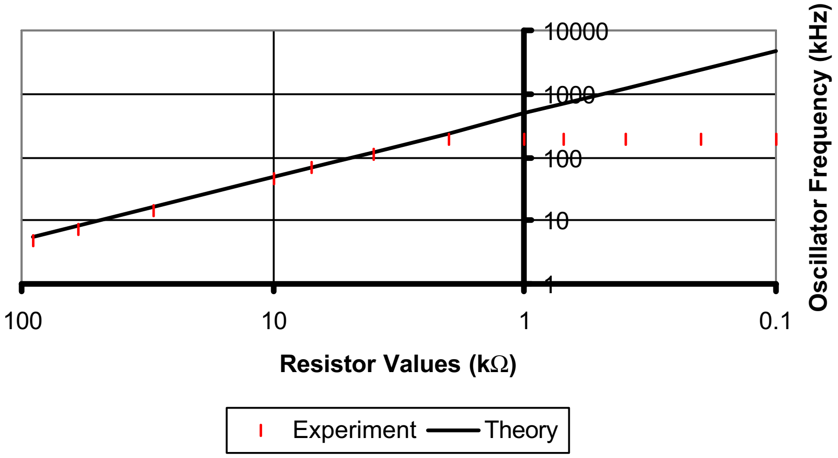

Fig 3.6 How changing the resistance of the RC component of the Wein-Bridge Oscillator changes its frequency, whilst the C Value is held constant at 330pF

The same pattern emerged where the experimental data followed that of theory until the oscillator reached 195kHz, which at this point decreasing the resistor values had no effect upon the oscillator frequency.

Both sets of experiments had a limiting value at which the circuit could oscillate at of 195kHz. This was independent of whether the resistor or capacitor values were changed. From this it must be concluded that this was a limiting factor of the chip. This didn't mean that higher frequencies could not be achieved, it was noted that changing the feedback to the oscillator not only changed the amplitude of the signal, but its frequency as well.

3.4 The Effect of Feedback Tuning

Regardless of which frequency of the oscillator ran at, the amount of feedback had to be tuned for each frequency. So far tuning involved altering the variable resistor shown in Fig 3.4 to the point where the signal was just saturated. Once the correct feedback was known for one frequency it could be reliably assembled with the same values and give the same waveform.

Using the feedback to increase the frequency of the signal was used to get over the limitation set by using the oscillators at their saturation point. The feedback was altered using the variable resistor to ground in Fig 3.4. The frequency and peak to peak voltage of the signal were then measured. The following graphs were obtained by using 330pF as the capacitance value and 1kΩ as the resistance value for the R component and the feedback resistor itself.

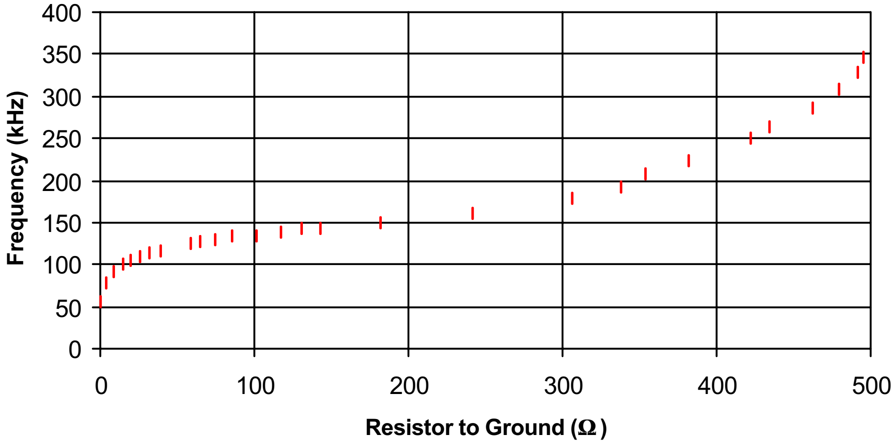

Fig 3.7 Changing the negative feedback by altering the resistor to ground affected the oscillator frequency, shown in this graph.

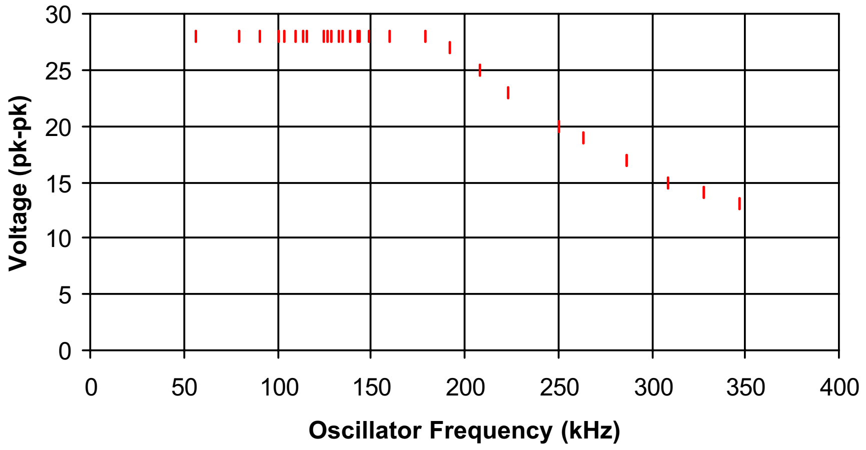

Fig 3.8 The signal voltage at each frequency determined by the alteration of the negative feedback.

Increasing the value of the resistor to ground past 500Ω killed the signal entirely. But at this point the signal had already passed the 195kHz barrier, to a maximum level of 347kHz. Making the RC component smaller, by using smaller capacitors and/or resistors was used to increase the frequency even further using this feedback technique.

3.5 Altering the Power Supply

Changing the power supply levels to the chips used in the circuit effected the frequency of the signal produced. The obvious effect was that an increased voltage, increased the pk-pk voltage of the signal, which was typically 2 volts below that of the voltage between the positive and negative power rails. An increased voltage also increased the frequency of signal, but the wave became more triangular and less like a sine wave.

All the above results taken with the Wein-Bridge Oscillator had the power rails at ±15V, which was the recommended voltage for the chip.

3.6 Accidental Construction of a Better Oscillator

While building oscillators at high frequencies, one was wired up the wrong way, the difference in circuit diagrams is given below,

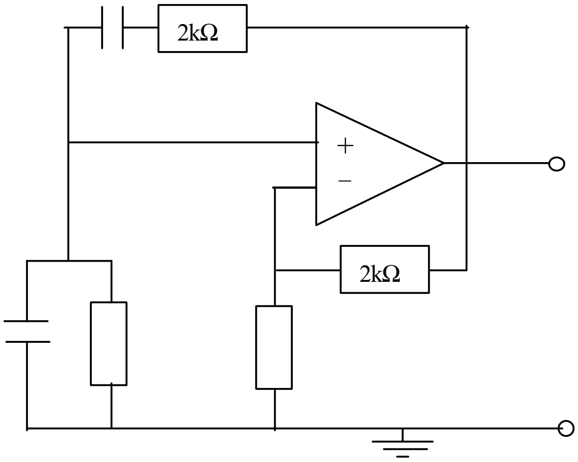

Fig 3.9a Wein-Bridge Oscillator

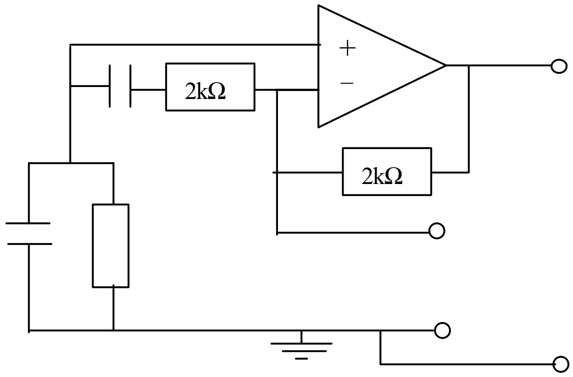

Fig 3.9b Wein-Bridge Oscillator Variant

They have a similar structure, the variant (fig 3.9b) still has the potential divider form of the Wein-Bridge feeding into the non-inverting input of the op-amp which is where the theory is all derived from. The diagram shows the difference is that the negative feedback comes from the output and top half of the potential divider. Looking at both circuits closer shows that this link is true also of the Wein-Bridge Oscillator, the top-half of the potential divider and the output contribute to the negative feedback.

The Wein-Bridge Variant has two sets of nodes where the output can be taken from. Taken from the output of the op-amp and ground the wave is a triangle wave. If the output is taken from the inverting input and the ground it takes the form of a sine wave with the same frequency as the triangle wave.

The first course of action was to identify its behaviour by changing its RC component.

3.6.1 Altering the Capacitance Values

In this experiment the resistor value was kept constant at 1Ω as the capacitor values were changed. Again, the readings were taken when the signal was just saturated.

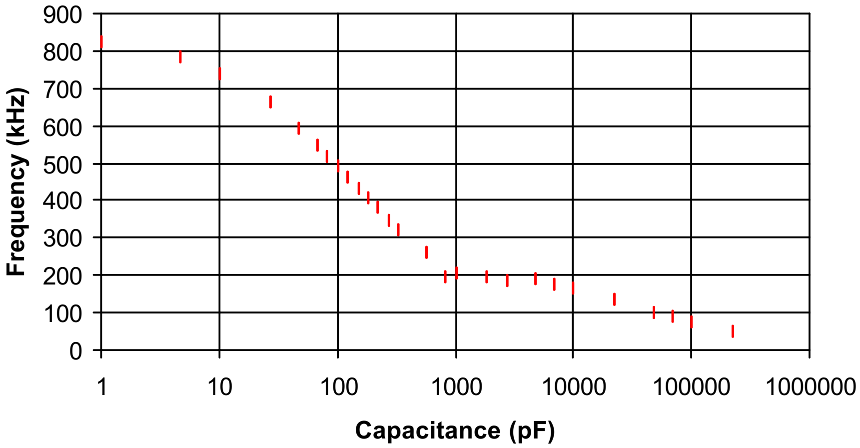

Fig 3.10 How changing the capacitance values effected the oscillator frequency

The first thing to note is that the oscillator demonstrated a trait of the Wein-Bridge oscillator, the frequency decreased with increasing capacitance values. But the theoretical frequency of the Wein-Bridge is massively different if the resistance and capacitance values for this experiment are used. The graph on the next page (Fig 3.11) shows how huge the difference is, by showing the ratio of the theoretical and experimental frequency results.

The graph's downward trend levels out quite abruptly around 200kHz, this is around the same frequency that the Wein-Bridge oscillator stopped following theory. This maybe coincidence, as any basis for this turning point seems unclear, but its was noted as interesting none the less.

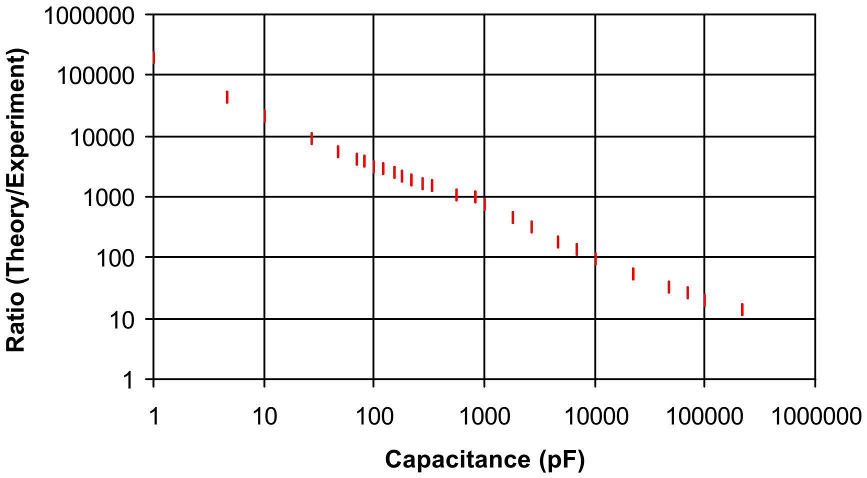

Fig 3.11 Graph showing the huge difference between the theoretical and experimental results.

The oscillator failed to oscillate when a capacitance value of 470nF was used. This may have been a limiting factor of the chip that was being used. To see if this was the case the resistance values were changed whilst the capacitance was held constant to see what effect it would have on the signal.

3.6.2 Altering the Resistance Values

In this case the capacitance value was kept at 330pF, while changing the resistance value.

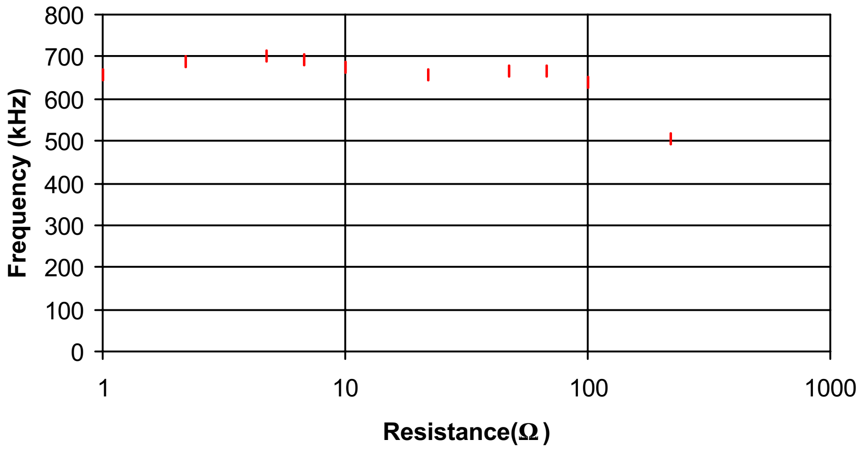

Fig 3.12 How changing the resistance value affected the oscillator frequency

A change in resistance of two orders of magnitude had little effect upon the frequency of the oscillator. The oscillator failed to generate a signal once the resistance value went above 220Ω.

This is a curious result, as some change would be expected from either the RC component changing or the feedback resistance altering due to the way the resistors in the circuit set up a potential divider around the inverting input node.

3.6.3 Altering the Power Supply

The same trend applied here as it did with the Wein-Bridge Oscillator. Increasing the voltage, increased the frequency and the amplitude of the signal while making the wave more triangular than sine wave shaped. All the results for the variant were taken using ±15V on the power rails.

4 Signal Mixing

The theory of signal mixing was tested out with signal generators provided in the lab, such that the best wave forms were mixed to get the best results before it was applied to the waveform the constructed oscillators produced.

Using the result that a movement of the hand above the aerial could produce a 2.5% change in frequency, the ideal oscillator frequency was calculated thus,

Good human hearing range 20Hz to 20,000Hz

Therefore frequency difference must be ~ 20,000Hz

So, $20{,}000 = f_2 - f_1$

And, $f_2 = 1.025f_1$

Therefore, $f_1 = 800\text{kHz}$

4.1 Experimental Set-up

One (fixed) signal generator ran at 800kHz and the other was varied above and below 800kHz, this was the variable oscillator. They were both connected as shown below in figure 4.1. The generators were actually connected using co-axial cables with and T-pieces splitting the signal out of the circuit.

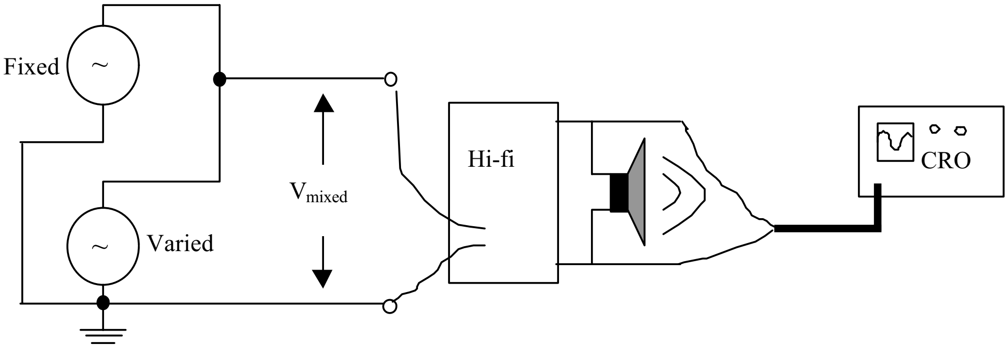

Fig 4.1 Set-up for the frequency generators for signal mixing.

The mixed signal was fed into the amplifier of a hi-fi via the microphone input. The input could be attenuated using a input level control on the hi-fi so one alter the strength of the microphone input. This was used as any input above 23mV caused the output signal of the hi-fi output signal to saturate and prior to mixing the signals were 2 Volts peak to peak.

The hi-fi output was split and fed into a speaker and an oscilloscope. The oscilloscope gave the frequency that the speaker was emitting, and the speaker itself gave an audible check as to the quality of the mixing and how much noise effected the signal. The signal V_{mixed} was also measured using an oscilloscope, to look at the envelope frequency before it entered into the hi-fi.

4.1.1 The Hi-Fi

The Hi-Fi was used as it was known to produce good quality sound. This meant that if there were a problem with the sound that the circuit produced, the likelihood of the amplifier producing the fault would be small.

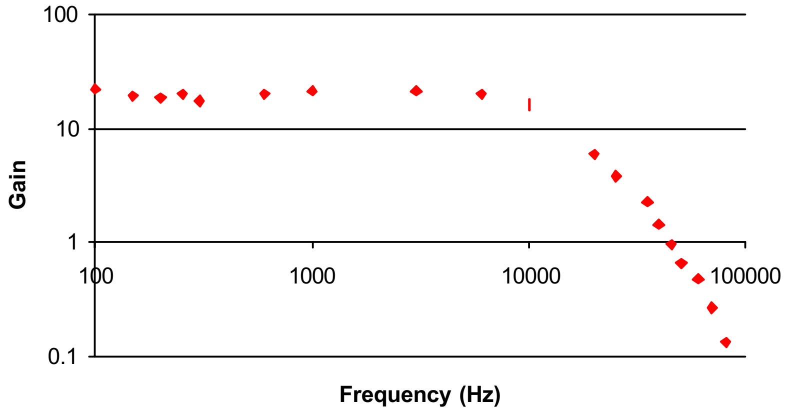

Fig 4.2 Bode plot of Gain vs. Frequency for the hi-fi used in the experiment.

A Bode plot above (figure 4.2) was taken form the hi-fi with the input signal at 23mV and the volume control set to half way, to check that it actually performed correctly within the regime that was used. The amplifier had a –3dB point around 15kHz.

4.1.2 Frequency Mixing Problems

The output from the hi-fi contained a large amount of 50Hz noise. It was possible to faintly hear a frequency change underneath the noise, but the oscilloscope readings taken from the speaker were impossible to read as they were swamped with the noise. A filter was incorporated into the design as to attenuate this noise, so the circuit was modified thus,

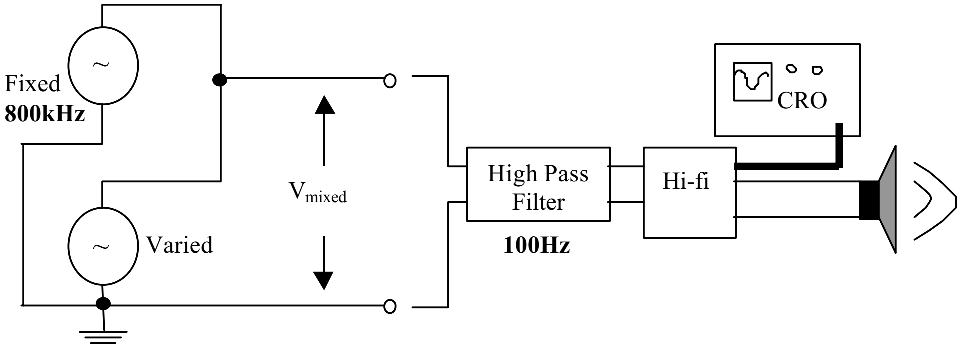

Fig 4.3 Modified Mixing Circuit with a High Pass Filter.

The high pass filter was one that was already constructed and in use in the lab, again so that any problems with the sound that the circuit produced was less likely to be the fault of the lab equipment. Nevertheless, the effect on a signal entering the filter was tested and it was found that the output of the filter was exactly the same pattern, except it was attenated by a factor of two. This wasn't a problem as the signal only saturated at 23mV, whereas the signal getting through was 2V pk-pk, which would be attenuated within the amplifier.

It was noted in the prior set-up that attaching the speaker in parallel with the oscilloscope caused a small change in the frequency displayed. To avoid this the left output channel from the hi-fi was used for the oscilloscope, whereas the right channel was used to power the speaker after it was verified that both channels produced the same frequency. With this set-up the following results were obtained.

4.1.3 Frequency Mixing Results

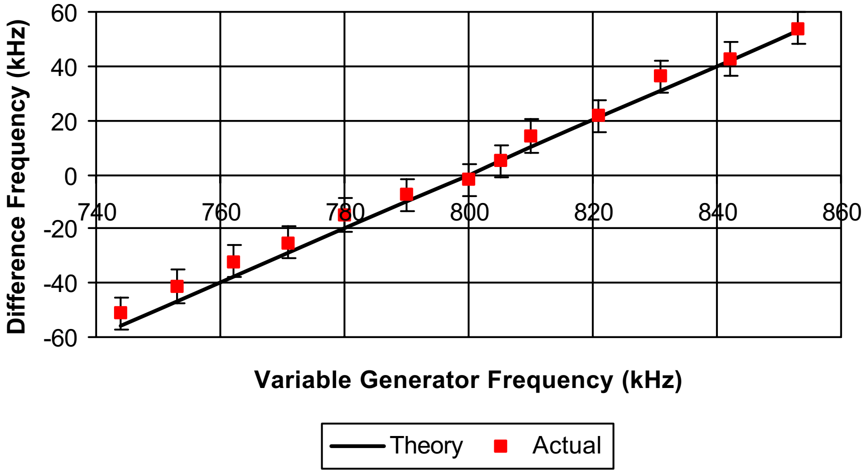

Fig 4.4 The theoretical and actual results from mixing signals of 744kHz to 853kHz with a fixed 800kHz signal. The negative difference frequency values are used to reflect the linear trend in the change of the variable frequency.

The first thing to note is that the trend follows the theoretical results. For example, a +21kHz shift in the variable oscillator from 800kHz, produces a 21kHz difference frequency.

The second thing to note about the results is that at 800kHz the difference frequnecy did not equal zero, but 2kHz. This was due to the fact that using an oscilloscope to determine the frequency could not get to the accuracy to the nearest 1kHz.

The method used on the oscilloscope to determine the frequency at 800kHz was to have 32 waves over 8 divisions, where each division was 5µs. Subsequent frequencies were determined by 32 waves every 0.1 of a division from 8 divisions (i.e. 7.8, 7.9, 8.0, 8.1, etc.). This lead to error of 0.05 divisions with each measurement, which in the worst case gives an error of 5kHz at 800kHz. This error was compunded at the highest frequency shown (lower periods), giving 6kHz error, but lessened the lowest frequency shown at 4kHz error. Most of the errors round to 5kHz and these are the values of the error bars shown in fig 4.4.

4.2 Mixing the Two Wein-Bridge Oscillators Together

The diagrams below shows the oscillators (fixed and variable) used in the initial mixing process.

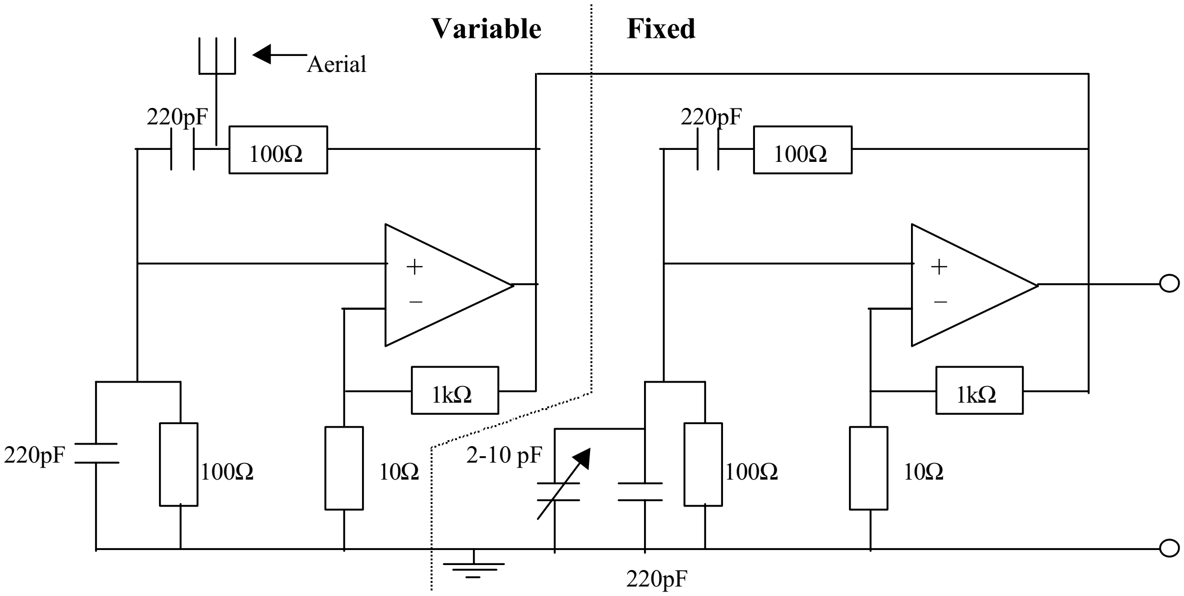

Fig 4.5 Circuit Diagram of the Wein-Bridge Oscillators mixed together

Both oscillators had RC components of 220pF and 100Ω. This gave a theoretical resonant frequency of 7.23MHz, but using feedback tuning the signal (resistor to ground was 10Ω) this frequency was taken up to 666kHz, much higher than the limitation in the previous experiments shown in sections 3.3.1 – 3.3.2. The left hand circuit is the variable oscillator as this is the one that changes with the movement of the hand over the aerial. The right hand circuit is the fixed oscillator, but can be tuned using the variable capacitor. So dispite it also being variable it is known as fixed because the other oscillator mixes relative to this one.

4.3 Mixing and Circuit Improvements

4.3.1 Noise Elimination

The pitch could be heard changing with hand movement over the aerial, but it was swamped with noise. The pitch underneath the noise could also be heard to change when anyone was near the power leads and the lead connecting the aerial to the circuit. From this it was obvious that the circuit was picking up fluctuations from the surrounding environment which was responsible for small capacitance values and which could have also picked up noise.

These problems were tackled by reducing the amount of wire used in the circuit. The circuit design itself was quite compact, but it was connected to the power supply by five leads, each of which roughly 50cm long. Instead of using these leads, the power supply was connected up using wires cut to length, with the circuit very close to the power supply. This cut out roughly 2 meters of wire reducing the amount of pick up in the circuit.

The lead to the aerial had to be long so movement near it would not effect the circuit. In this case the aerial lead which was roughly 2 metres long was replaced with co-axial cable, so the connection to the circuit would be through shielded wire.

4.3.2 Voltage Followers

While altering the circuit it was seen that movement near one oscillator and/or changing the RC value of that oscillator could effect the frequency of the other.

Voltage Followers (or buffers) are amplifiers with a gain of unity and is special case of a non-inverting amplifier.

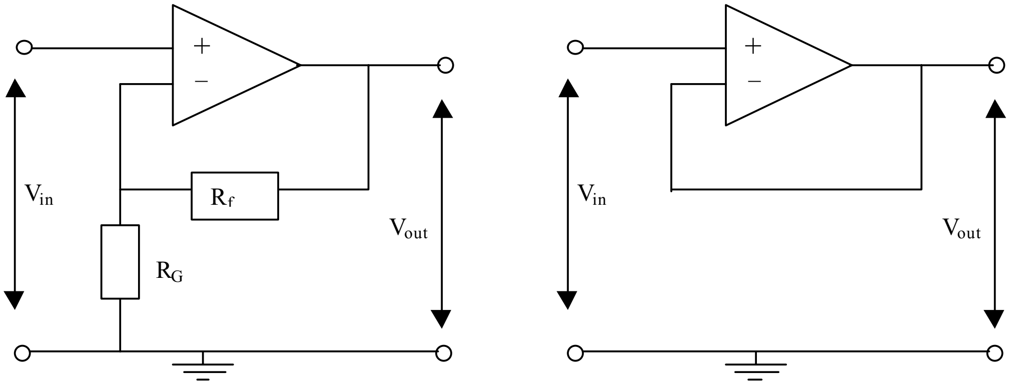

Fig 4.6 Left, a non-inverting operational amplifier, right a voltage follower

The gain of the amplifier is set by the values of the feedback resistance and the resistor to ground by the same relation as a potential divider.

$$v_{out} = v_{in} \frac{\left(R_f + R_G\right)}{R_G} \tag{4.1}$$

A voltage follower has the special case where $R_f = 0$ and $R_G = \infty$. For this case

$$v_{out} = v_{in}$$

By using a voltage follower the RC component before the operational amplifier can't become effected by RC components after it, the circuit prior to that is effectively screened.

4.3.3 The Operational Adder

It was realised that the way the signals had been mixed together was slightly more elegant than twisting two pieces of wire together, but only just. A better method of mixing was found in the operational adder.

An operational adder takes two voltages and adds them together. So inputting the signals from the frequency generators in effectively mixes them together.

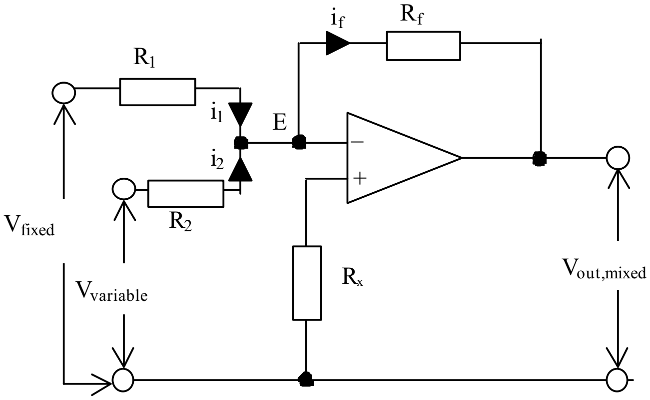

Fig 4.7 The Virtual Earth Adder that was used to mix the two signal together.

By equating currents around E, and assuming that the op-amp draws no current,

$$i_f = i_{fixed} + i_{variable}$$

The currents can be expressed in terms of signal voltages and resistor values thus:

$$\frac{-V_{mixed}}{R_f} = \frac{V_{fixed}}{R_1} + \frac{V_{variable}}{R_2}$$

$$V_{mixed} = -\left(\frac{R_f}{R_1}V_{fixed} + \frac{R_f}{R_2}V_{variable}\right)$$

If $R_f = R_1 = R_2$ then,

$$V_{mixed} = -(V_{fixed} + V_{variable})$$

In this case the signal is mixed and inverted.

4.3.4 Reducing the Power Rail Voltage

Previous experiment had shown that reducing the voltage supplied to the chips gave better wave structure, i.e. more like a sine wave, which is more pleasing to the ear.

4.4 Results after the Improvements.

- Noise Elimination - Shortening the power leads resulted in a cleaner signal and decreased the effect on the frequency due to proximity to the circuit. The shielding of the aerial lead also lead to decreased proximity effects.

- Voltage Followers – Also gave rise to a clearer signal when used as the only improvement measure.

- Operational Adder – When used it gave an increased sensitivity to movement over the aerial. But the tone was less pure than that of the ‘twisting wire’ approach.

- Reducing the Power Rail Voltage – The circuit became much more sensitive to hand movement over the aerial, and the signal became less noisy. Below 4 volts the circuit failed to oscillate. The best waveform results were when the power rails were set at ±5V

- Circuit Diagram after Improvements – The diagram on the next page shows the circuit diagram after the improvements.

With these improvements, the sensitivity could extend ~40cm above the aerial

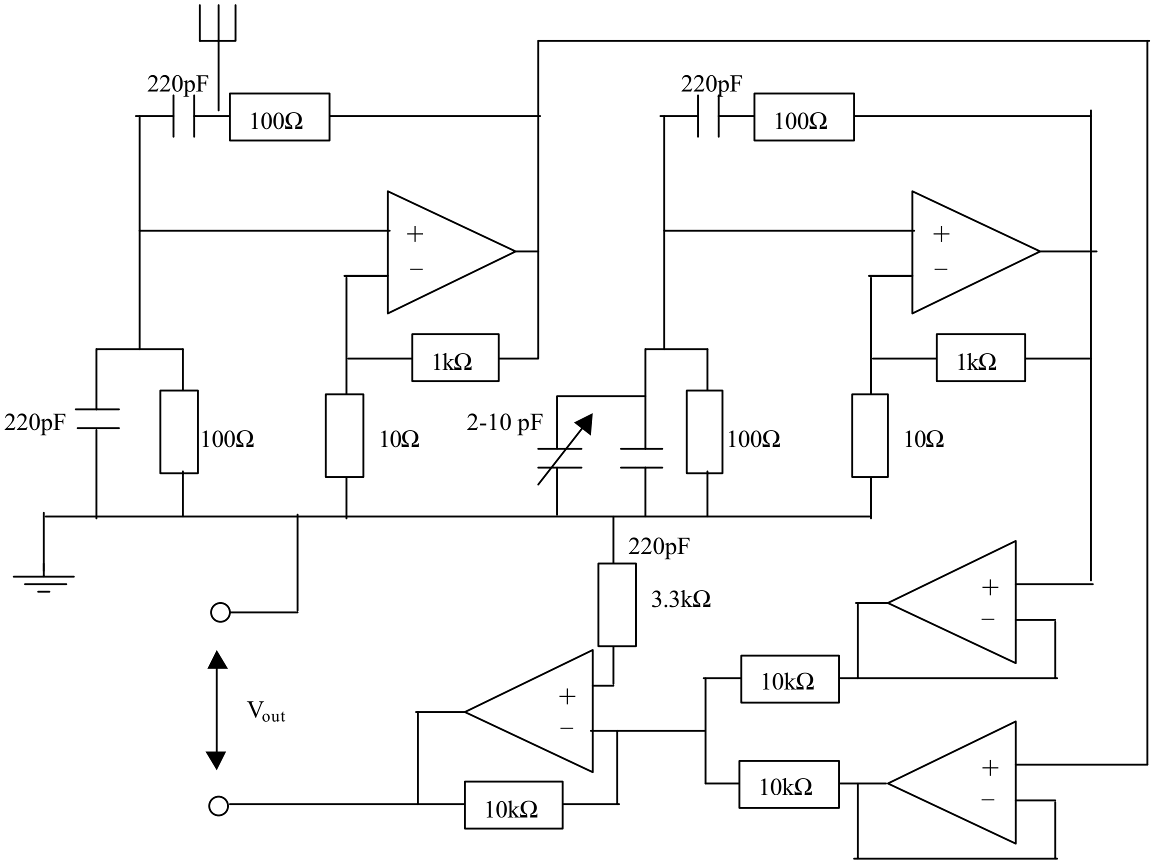

Fig 4.8 The Improved Wein-Bridge Oscillator Theremin

The output was fed into the amplifier via the microphone input, and the one speaker output was connected to the speakers and the other to an oscilloscope.

The hi-fi acted as a low pass filter, so the ultrasonic component of the signal was filtered out, giving rise to only the audible frequency on the oscilloscope.

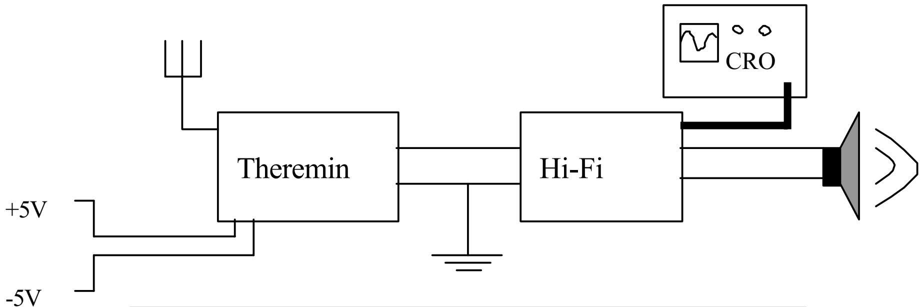

Fig 4.9 Diagrammatic Representation of the Theremin set-up

4.5 Constructing the Wein-Bridge Variant Theremin

Constructing a Theremin using the variant oscillators used the same lessons learnt when making the above circuit. The only difference in circuit design was that the oscillators where different, and the outputs were taken from the inverting inputs of the respective op-amps.

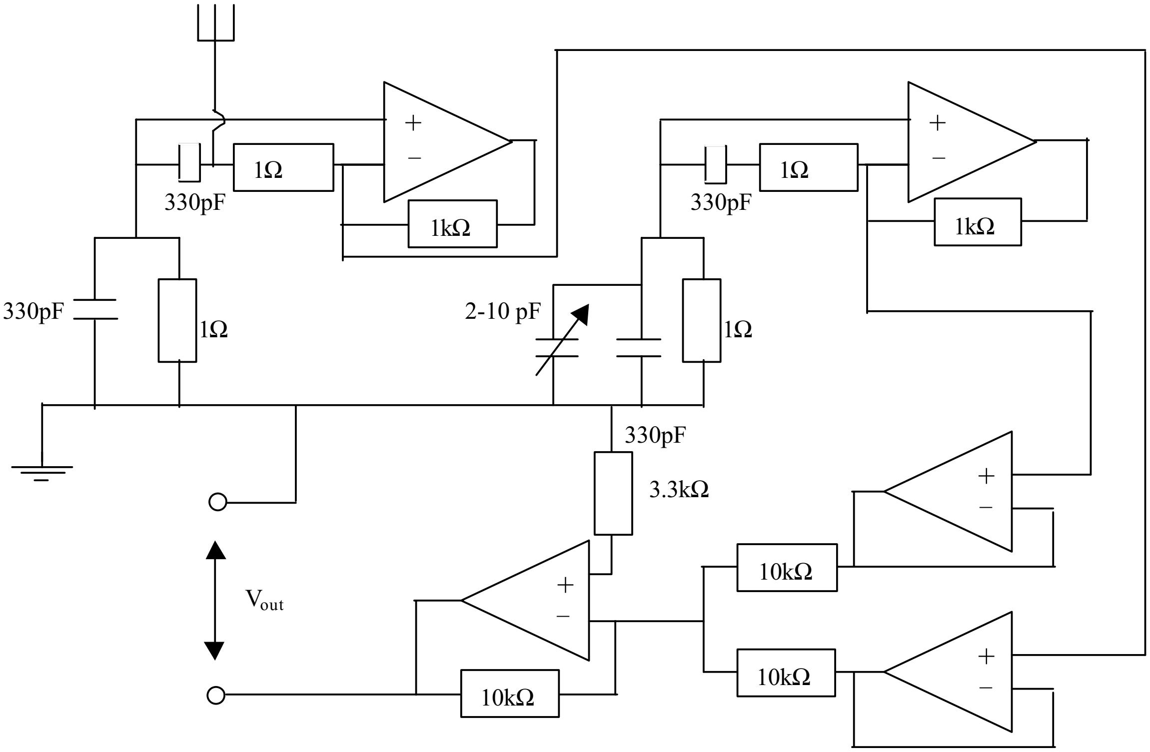

Fig 4.8 The Wein-Bridge Variant Oscillator Theremin

The variable oscillator had a range from 755kHz to 774kHz with close proximity to the aerial and not respectively. The fixed oscillator had a range of 766kHz to 798kHz by applying the tuning effect of the variable capacitor. These ranges overlap, which means in theory it is possible to tune it to a zero difference frequency.

4.6 Signal Mixing Saturation

It was noted that with the both designs the signal looked as though it was saturated at lower frequencies, some typical examples of the waveforms through the audible frequencies are given below.

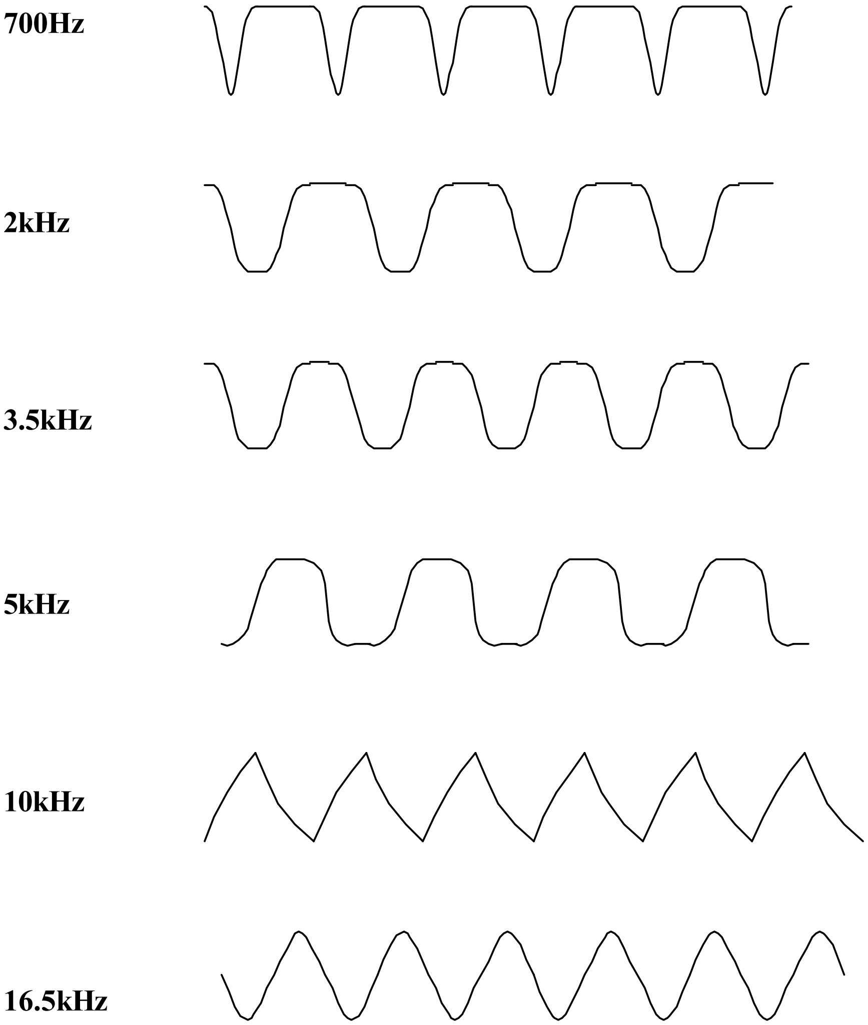

Fig 4.10 Output waveforms (taken from Variant Theremin) at different frequencies

The theremin didn't produce a clear signal below 700Hz

4.7 Increasing the Voltage to the Mixing Circuit

It was certainly clear that the lower frequencies were saturating. It was proposed that the signals from the oscillators were too big for the mixing circuit to handle without saturating.

Because the oscillators were running at their lowest possible voltage, then the voltage that powered the mixing circuit was increased to the maximum recommended for the chips at ±15V. In theory the oscillators could at produce a 10V pk-pk signal, and when added to another equally strong signal could produce a 20V pk-pk signal. The mixer chip powered by ±15V could produce a 30V pk-pk signal, which meant that the largest possible mixed signal was in no danger of saturation.

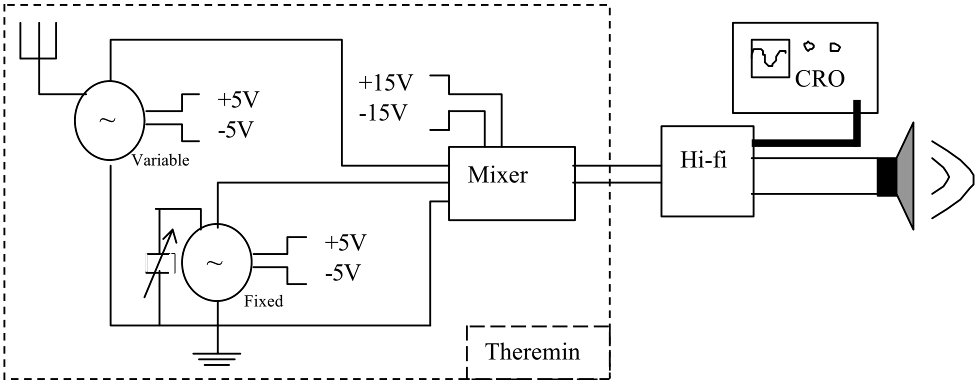

Fig 4.11 Diagrammatic representation of the Theremin with the increased mixer voltage

The waveforms produced by this set-up are shown below,

Fig 4.12 Waveforms from the variant oscillator theremin with the increased voltage mixer

The waveforms did not saturate in the set-up with the increased voltage mixer circuit. The waveform above 1.5kHz stayed at a constant shape, but above 22kHz the signal became far too noisy to read.

5 Playing the Theremins and the Sounds they Produced

5.1 Preparation

Before the theremin was played it had to be tuned, by use of the variable capacitor. The player stood away from the aerial and tuned the fixed oscillator so the theremin just stopped making any noise. In this case the player standing away from the instrument gave the theremin its ‘null frequency’, so the player standing away from the instrument is the ‘null position’ of the player in this set-up.

This procedure was slightly tricky, as the variable capacitor was tuned by rotating its plates by using a small screwdriver. As the screwdriver was made of metal, it would alter the capacitance of the circuit, so the sound heard would not be the same once the screwdriver was removed due to the changed RC component of the circuit. Using small adjustments, then taking the screwdriver away and listening for the response was the method used for tuning. But with practice it was possible to ‘develop an ear’ for how far to turn the screwdriver from the sound heard coming from the speaker.

5.2 Making a Sound

If the theremin is at its null frequency when the player is stood away from the instrument, the proximity of the player to the aerial increases the capacitance. This increases the RC component of the variable oscillator. This lowers the frequency relative to the fixed oscillator and causes the difference frequency to increase and is heard through the speaker. The closest proximity to the aerial resulted in the highest frequency due to this effect.

The theremin could be tuned such that when the player stood away from the instrument it would produce a high frequency. This meant the oscillators were unmatched. In this condition proximity to the aerial could cause the frequency to become ultrasonic or decrease to a lower pitch. The result depended on whether the fixed oscillator was running faster or slower than the variable oscillator respectively.

If the fixed oscillator were running faster than the variable oscillator, increasing the proximity to the aerial would decrease the variable oscillator frequency further, sending the signal ultrasonic. But if the fixed oscillator ran slower than the variable oscillator, then proximity to the aerial would bring the signal closer to the null frequency. Depending on how the oscillator was tuned, the null position could be when the player's hand was above the aerial. In this case the player could hold the null frequency and then increase the frequency by moving his or her hand closer to, or further from the aerial.

6 Limitations of the Theremins

6.1 Low Frequency Loss

Both Theremins had one big drawback, they couldn't produce low frequencies. The lowest frequency the Wein-Bridge Theremin could clearly produce was 700Hz, whereas the lowest frequency the variant theremin could produce was 200Hz.

At these frequencies the waveform wasn't as regular as a sine wave might have been, but more like the waveform at 200Hz shown in fig 4.12. These low frequency notes were very noisy and holding this low frequency resulted in a noise similar to the scratching sound on a vinyl record.

6.2 Possible Oscillator Locking via Power Source

The oscillators not being fully independent of each other may have caused this lack of the lower frequency. It was noted that when working on two oscillators that were only connected through the same power supply, changes in one could effect the others frequency response. From this it is proposed that one oscillator may have locked to the other when their theoretical frequencies were comparable, producing a near zero difference frequency.

This coupling via a power source had also been observed when two separate power supplies were used from separate plugs, along the same bench power supply.

The theremin seemed to broadcast noise to other experiments, much to their annoyance, and even broadcast it’s theremin sound to an AM radio (powered from the lab bench plugs) playing at the time. This meant that the theremin noise was either transmitted through the air to experiments and the radio in the lab, or through the power supply. The power supply seems more likely as this was observed on the circuit board. This transmission characteristic of the theremin was intermittent as observation through the power supplies and to the AM radio was never guaranteed.

Designs on the internet used capacitors from their power rails to ground to provide power supply decoupling. Due to time constraints this solution was never tried.

7 Field Potential Measurements

The sound the theremin made depended on the capacitance between the player's hand and the aerial plate. This means that where the frequency is the same the capacitance is the same.

Capacitance is defined as $C \equiv \frac{Q}{V}$

where Q is the charge on the capacitor and V is the potential difference between them.

If it is assumed that the charge on both the person and the plate remain constant, then plotting where the frequency is the same will plot where the potential difference is the same.

7.1 Measuring the Frequency Dependency on 'Hand' Position

A player's hand was considered too cumbersome for this experiment, as maintaining its position while measurements were made would be hard, and the resolution of measurements would suffer due to the hand's size compared to the aerial. Instead, a copper cylinder would act as a hand.

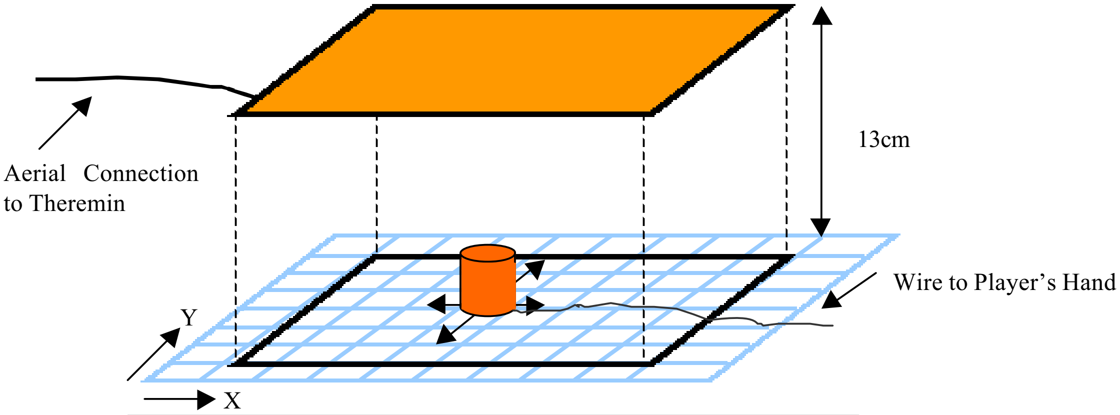

Fig 6.1 Set-up used to determine the Field Potentials of the Aerial

The cylinder was 2.5cm in diameter and 3.2cm in height. A thin wire was attached to the cylinder and held by a person so the block would have the same charge on it that a person would. The aerial was suspended 13cm above graph paper that would be used to record the cylinder's position.

The theremin was set-up such that closer proximity meant that the frequency increased. In this case the fixed oscillator ran faster than the variable oscillator. An increase in aerial capacitance lowered the variable oscillator's frequency, in turn widening the difference frequency. When the cylinder was not present the theremin output was at 4kHz

Sweeps were made along the x-direction in increments of 2cm whilst keeping the y value constant and vice- versa.

7.2 Field Potential Results

Due to time pressures, a complete set of measurements of the potentials for all points wasn't achieved.

A total of eight sweeps were conducted. Four sweeps covered the edge of the aerial, two went through the middle of the plate in the x and y direction and two went either side of the middle in the x direction.

The biggest problem with the experiment was frequency drift. This meant that each sweep wouldn't agree when they crossed the same point. The graph below was complied by assuming that the trend along the X = 16 line was accurate. The sweeps across the X = 16 line were then normalised such that their X = 16 value was the same as the X = 16 line. The trends of X = 0 and X = 30 lines were then applied between the y-direction sweeps, and normalised in the same way.

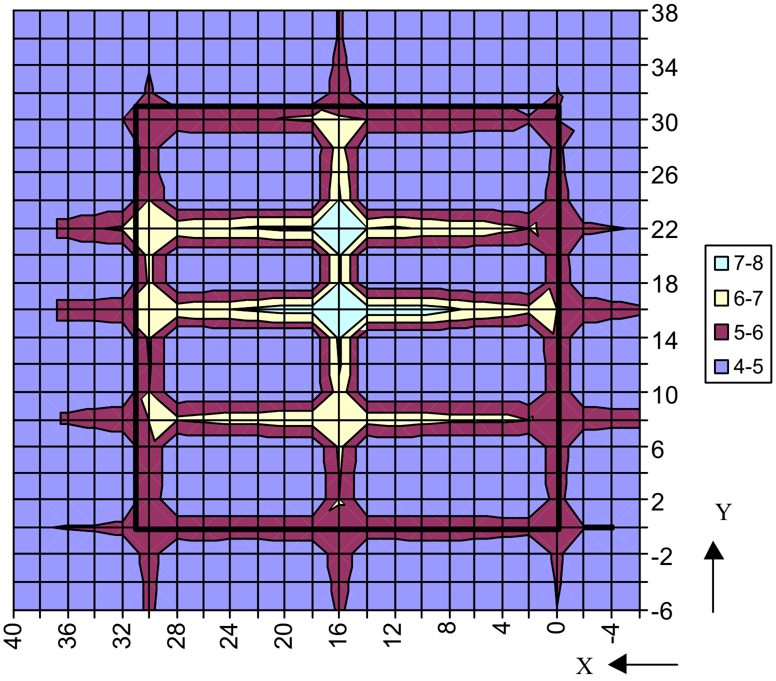

Fig 6.2 Plot of the frequency in response to the position of the 'Hand' used in the experiment. The plate position is indicated by the thick black outline and the legend shows the frequency response of the theremin in kilohertz. In this case 4-5kHz measurements correspond to co-ordinates were there were no measurements

Although this doesn't lead to accurate results, it does imply the field potential trend below the plate (and by symmetry above it). The graph above is represented in the two 3D graphs below.

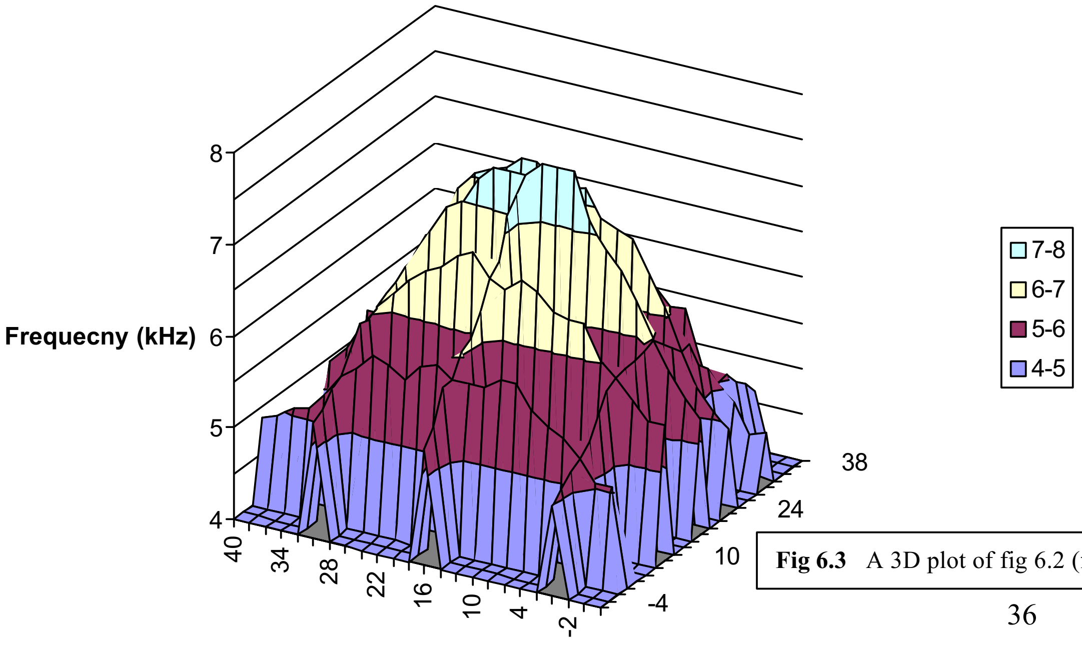

Fig 6.3 A 3D plot of fig 6.2 (front)

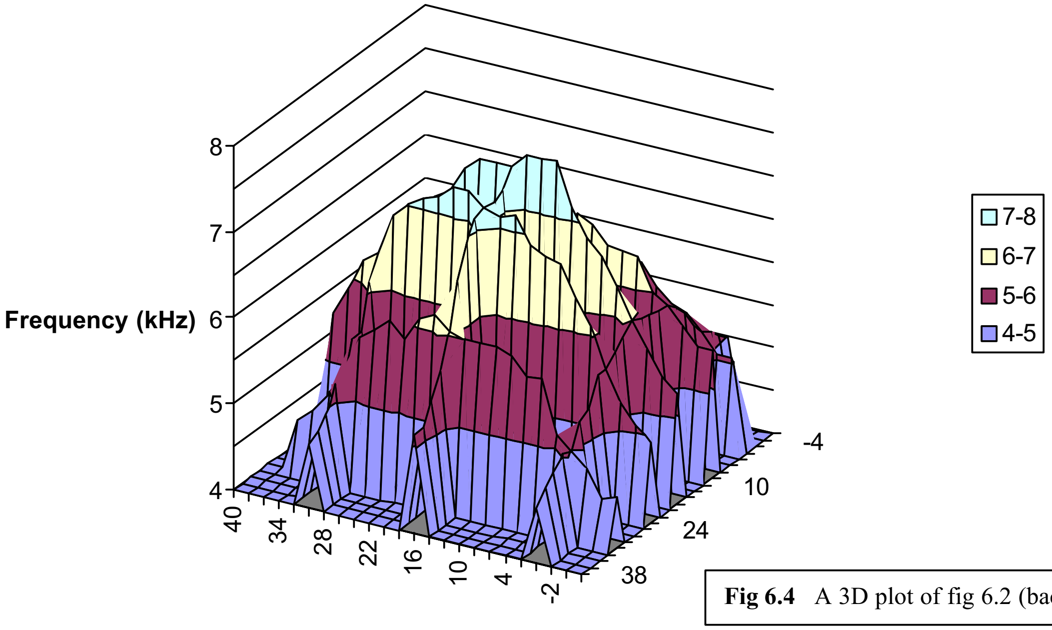

Fig 6.4 A 3D plot of fig 6.2 (back)

The graphs show that the frequency decreases towards the sides of the plate and increases towards the centre of the plate. This shows the trend that the capacitance offered by the 'hand' decreases the further it was from the centre.

From this trend it would be expected that the distribution would be symmetrical. But point 16,22 in fig 6.2 shows that the frequency doesn't change symmetrically. This may have been due to the fact that the laboratory contained large sources of metal that may have effected the potential in the field. The benches also had large metal poles underneath them for support. Much care was taken when placing the experiment to avoid these poles and other large metal objects. But there was no-where in which the experiment was not 10cm away from something that was large and metal.

8 Other uses for Theremins

8.1 Movement Sensors

Passers by, including myself were often shocked when walking past the aerial to the theremin when it had been left on tuning to its null position, as it would make a noise at the passer-by. Due to it's sensitivity it could be used instead of pressure based movement systems for valuable objects. The problem of frequency drift in the oscillators would have to addressed to avoid accidental alarms being set off.

8.2 The Grid?

Recent developments have suggested the use of transmitting the web and other information along power lines to avoid duplicating the amount of wire used to get information around. The theremin that was produced interfered with another theremin using the same power source, and alteration of one theremin changed the frequency of the other. Whether this alteration was equivalent of sending information down a power line could not be proven as it was an intermittent effect, but it was interesting to note none the less.

9 References

(1) M H Jones (1995) A Practical Introduction to Electronic Circuits 3rd Ed.

(2) Art's Theremin Page - http://home.att.net/~theremin1/index.htm

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(4) J S Rigden (1985) Physics and the Sound of Music 2nd Ed.