Imperial College London

Analog Music Synthesiser Project

ELEC40006-Electronic Design Project

Husna Fathiah, 01754444
Jing Lin Loh 01718534
Yuhan Diao, 01711760

Mrs Esther Perea

Dr. Edward Stott

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1.0 ABSTRACT

Analogue music synthesiser remains a prominent part of music production due to its unique range of sounds even after the emergence of digitalised musical instruments. The principal of a synthesiser is generating sounds through the manipulation of voltages supplied to them. As the main aim of the team is to build a working monophonic synthesiser, we have focused on developing one that comprises a voltage-controlled oscillator (VCO), voltage-controlled frequency (VCF), voltage-controlled amplitude (VCA) and envelope detector (ADSR) to produce the intended notes. To further extend the capabilities of an analog synthesiser, tremolo and vibrato circuits were added so the synthesiser provides practical features. In the pursuit of a better sound quality, lecturers and instructors are consulted through emails and interviews. Through a series of research and testing that led to multiple designs, we have constructed the synthesiser. The use of MATLAB and other graphing tools was utilised accordingly to prove that the result achieved was explained completely from different perspectives. The elimination of sound in the final product was a contributing factor to our final design. After thorough deliberation and mitigation, the components that produced the best notes are chosen and altered to fit the full schematic.

2.0 INTRODUCTION

The acoustic aspects of analogue music synthesisers has led to its resurgence in the world of synthesisers. For the Year 1 Electronics Design Project, we have decided to build a monophonic analogue music synthesiser that is able to output 7 notes in the C major scale in the 4th octave. The goal of this project is to put together the knowledge gained throughout the first year and apply it to a practical problem. This project also aims to expose us to the dynamics of team working and management. Each component is designed based on an existing design but includes modifications or improvements of our own. This project is made to be a good starting point for future analogue synthesiser designs.

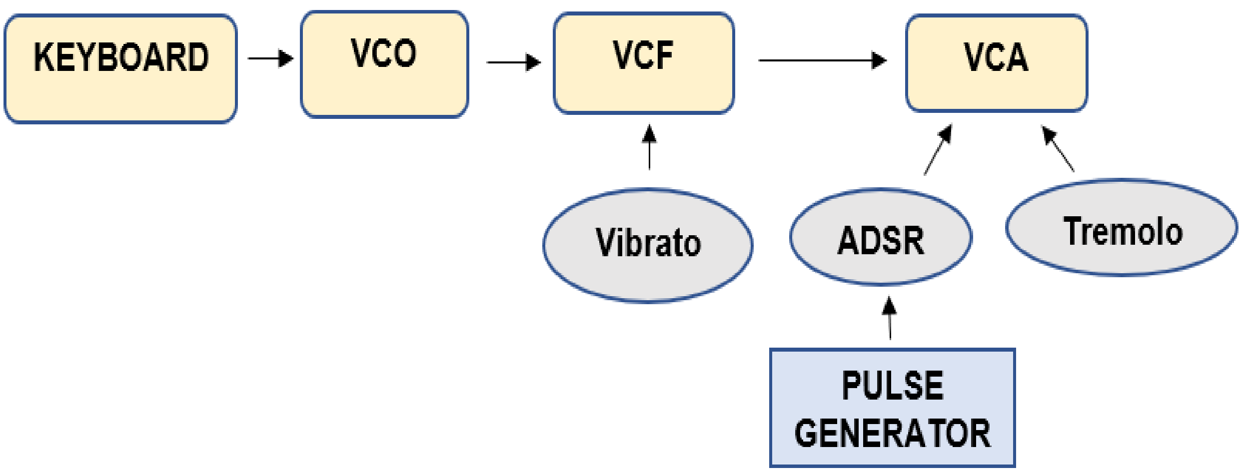


Figure 1: Block Diagram

The design is broken down into 8 sub-circuits as shown in Figure 1. Each circuit is built and tested in LTSpiceIV. All the components used model real world components. The final signal is used to drive a loudspeaker of 8Ω impedance. The detailed explanation of each circuit is provided in section 3.

3.0 COMPONENTS

3.1 Keyboard

Introduction:

Keyboard is the most important aspect to generate the voltage required to produce the required notes on the analog music synthesiser. As the keyboard is connected to the voltage-controlled oscillator, it is important for the keyboard to be able to generate the right voltage to be fed to the input of the VCO.

Design specifications:

The input to the synthesiser should be 7 voltage sources, each representing one key of a keyboard. 5V represents a pressed key and 0V a released key. Use the PWL source type for the keyboard inputs because this will allow you to simulate a sequence of key presses over time.

Process:

As the design of the final voltage-controlled oscillator (VCO) is the exponential converter with VCO, this gives 60 keys to be possibly generated [1]. The keys and voltage required are given in [1] and are included in Appendix [iii]. It follows an exponential response as seen below [1, Figure 2].

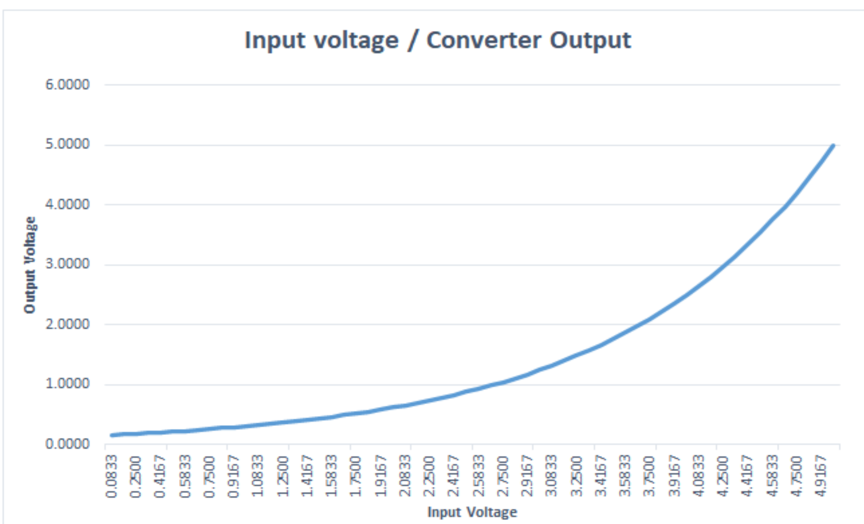


Figure 2

In order to generate the voltages, it was necessary to build a 1V/octave keyboard in the range of 0V to 5V. In constructing the keyboard, source [2] is consulted. However, the schematic was unsuitable for our VCO because of there was too extensive for our functions and the numerous materials include in it that could drive up our cost. As a result, the schematic built was changed and constructed based on the principle of voltage division technique.

To generate 60 notes, the idea was to use the voltage division formula

*Equation 1: Voltage out= (R*voltage in)/ (R+ fixed R)*

where fixed R is the resistance that is already fixed, and R is the resistance to be calculated. Initially, the circuit's idea is as below (Figure 3). R1 is the fixed R and R2 is R.

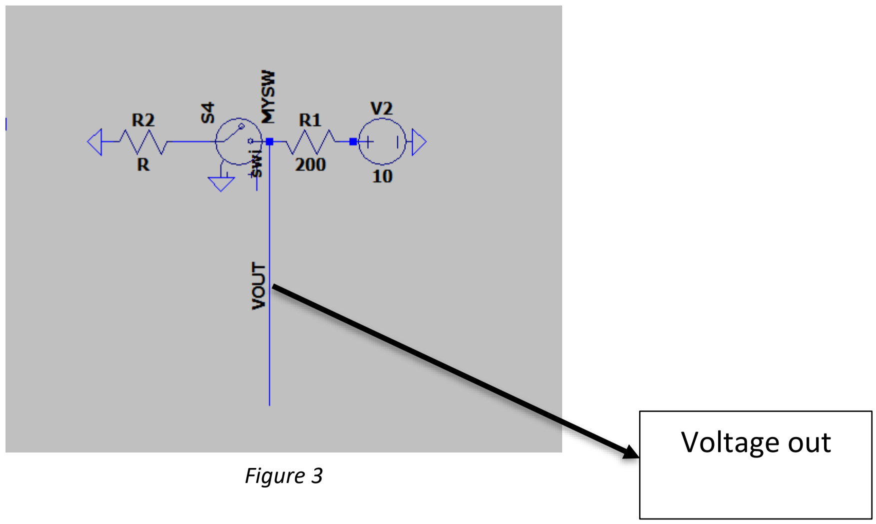


Figure 3

The other resistors will be connected in parallel with the first resistor (Figure 4).

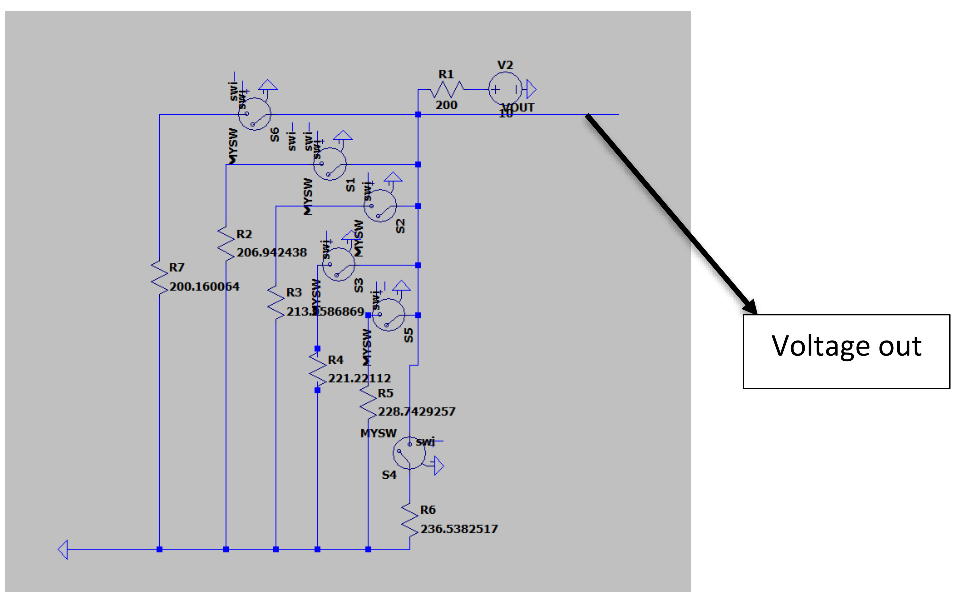


Figure 4: One 'group' with one power source

The 60 notes are divided into several 'groups' with separate power sources for each group (Figure 4). As the design is monophonic, if the key is not available in one group, the voltage output of that group should be near to 0. However, with the design in Figure 4, if there are no suitable keys in the group, the voltage output will be 10V. This makes the voltages produced wrong.

Hence, the design is changed (Figure 5) so that if no key in the 'groups' are pressed, the voltage output would be 0. This is made by changing the placement of the voltage source.

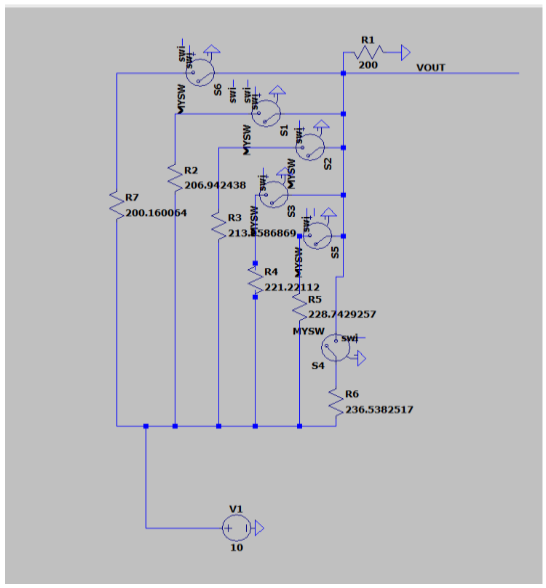


Figure 5

To determine the value of R suitable for the keys, the potential divider formula was used but the R fixed and R are interchanged from (1). Therefore, the formula becomes:

*Equation 2: Voltage out=Voltage in*R fixed/(Rfixed+ R)*

The R value for each key, the voltage in and the R fixed are given in the Appendix [iv]. The whole group of resistors are formed (Figure 6).

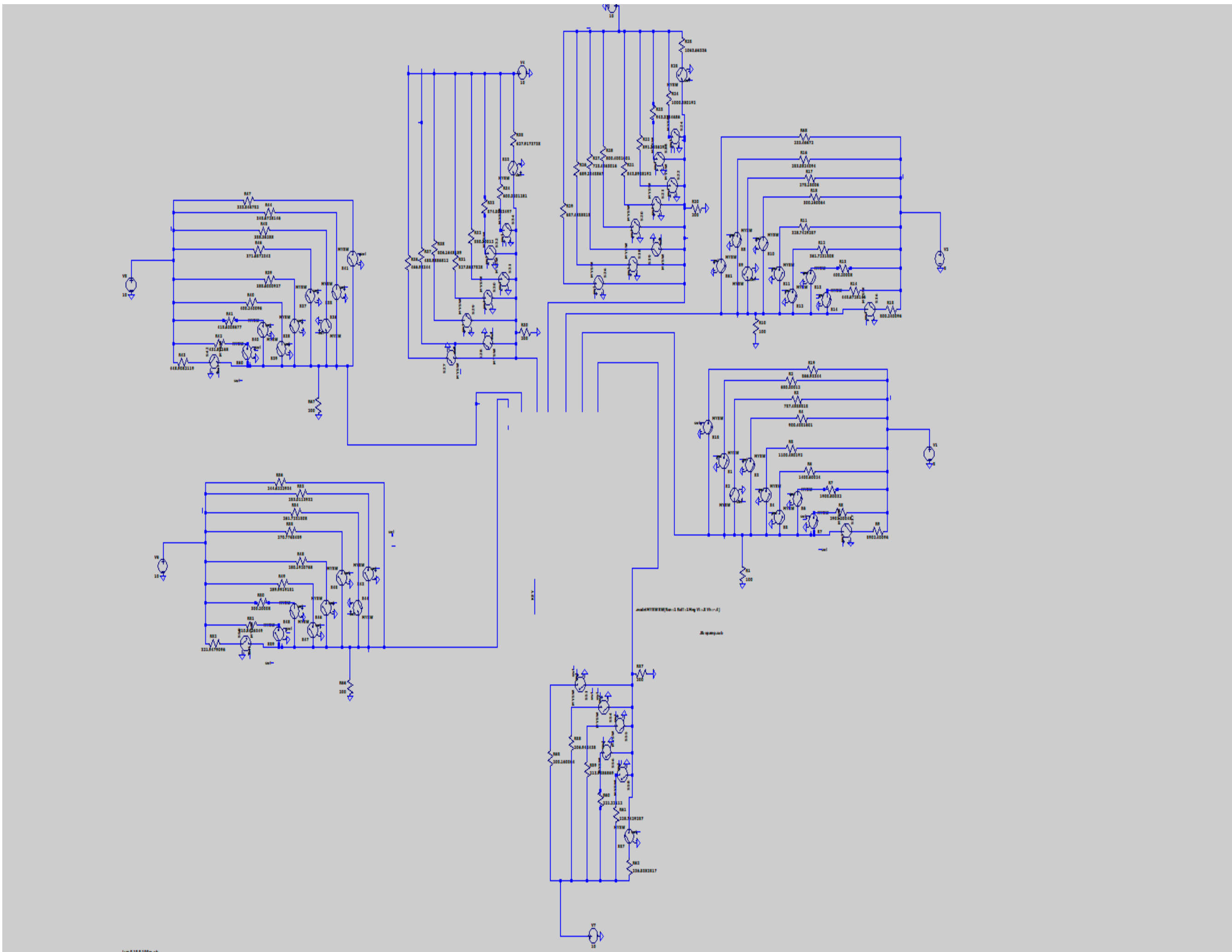


Figure 6

However, as there are multiple outputs, it is necessary to use summing amplifiers for the right voltage output to come out. To perfect the design, an inverting amplifier with negative feedback is constructed at the output, for the keys to be played correctly. This is as below in the red (Figure 7).

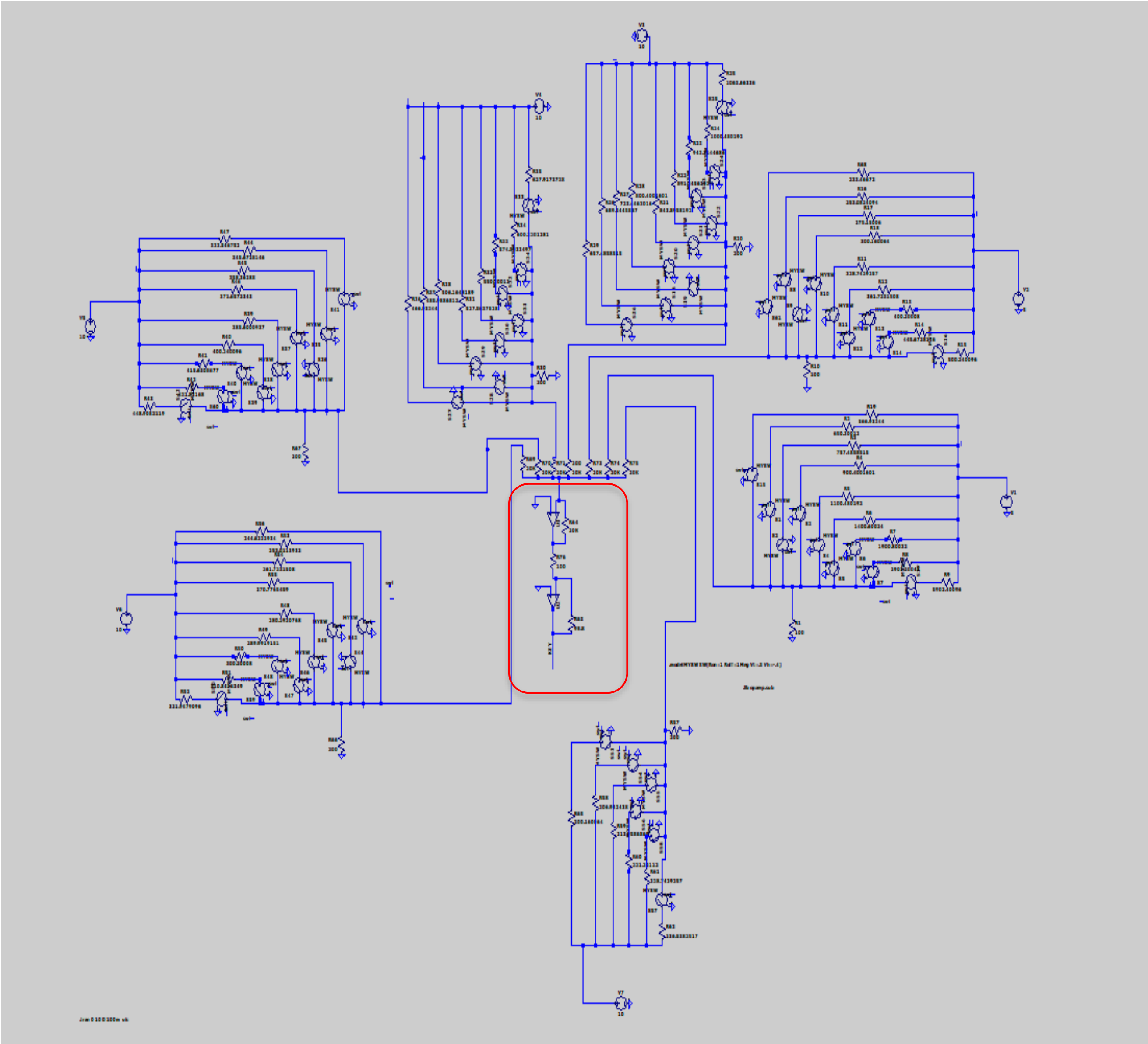


Figure 7: Summing amplifier and inverting amplifier inserted

The result is close to the real value of the voltage (Figure 8).

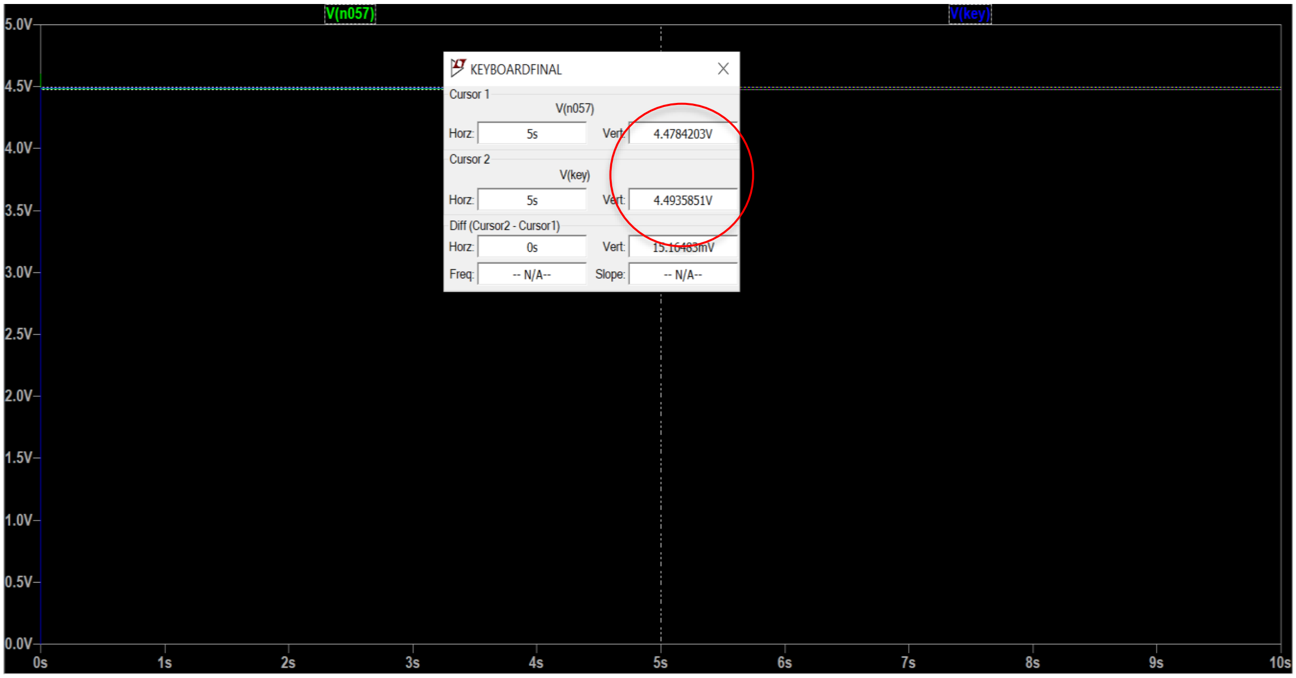


Figure 8: The voltage output is almost similar

After discussion with Dr. Steve Wright, he proposed to calculate the value of impedance of the op amp to compensate for the voltage drop across it as the op amp is not ideal. The problem with the design is that to execute the VCO, there are a lot of resistors needed, hence increasing the cost.

Final design:

For the analog music perfectly, the 7 notes are picked [1, Table 1] among the other 60 notes as the notes produced are the clearest notes produced. A keyboard to accommodate from the note C4 to B4 is produced by using the voltage varying measures.

*Equation 3: Voltage exponential=5/32*2^vin*

*Equation 4: Frequency= voltage exponential*395.1149425*

Notes	Voltage out	Exponential Voltage	Frequency
C4	2.0833	0.6622	261.6311
D4	2.25	0.7433	293.6709
E4	2.4167	0.8343	329.6345
F4	2.5	0.8839	349.2356
G4	2.6667	0.9921	392.0037
A4	2.8333	1.1136	440.0092
B4	3	1.25	493.8937

Table 1

7 voltage sources are set as shown in Figure 9 with a pwl text file. The voltages are programmed to be stable for 5 seconds each to show the effect as if a note is being pressed during simulation. Switches are connected to the VCO at the key.

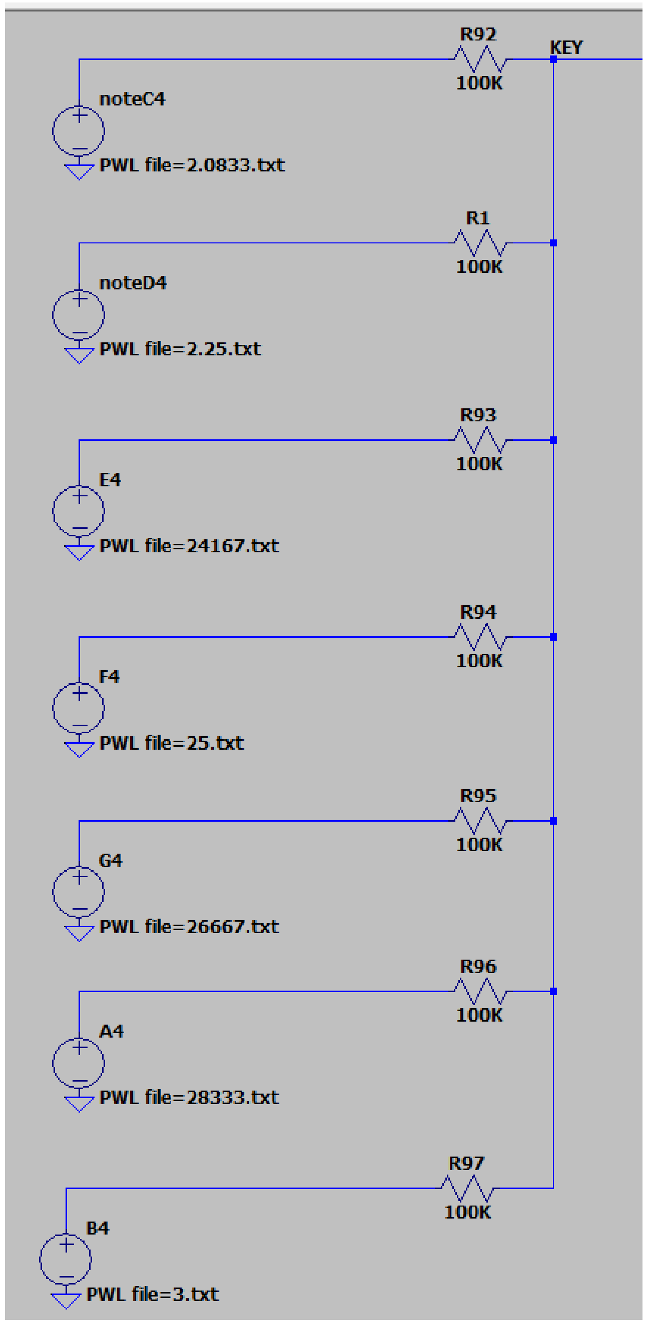


Figure 9

In the pwl file, each voltage source is programmed to be on for 5 seconds each, amounting to 35 seconds for the whole circuit. This will make the circuit produce continuous notes consisting of C4, D4, E4, F4, G4, A4 and B4 for 35 seconds.

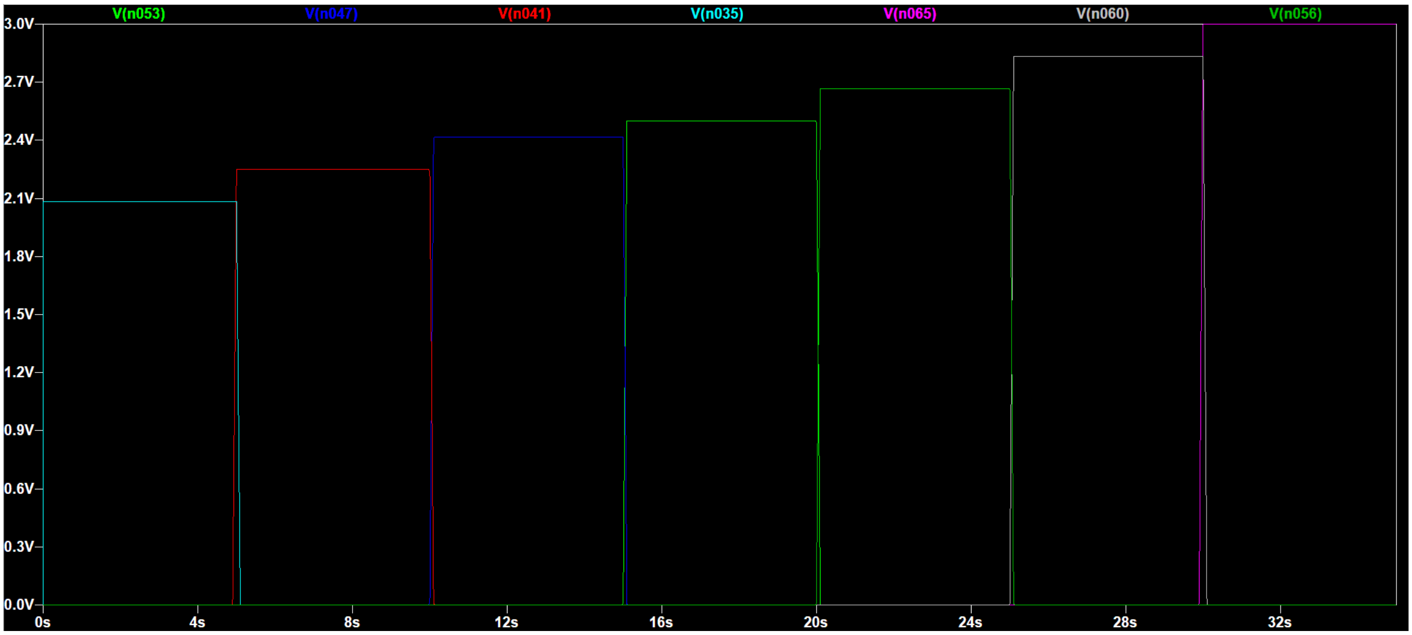


Figure 10: The output waveform of switches

3.2 Voltage Controlled Oscillator (VCO)

Introduction:

A voltage-controlled oscillator is a component that its frequency is controlled by the DC input signal it received. The VCO will generate different waveforms depending on the circuit configuration. Each of these waveforms has its own distinct sound [3]. In this particular experiment, square wave is used for testing the output of the whole analogue synthesiser as to tell the extent to which the various frequencies are amplified or distorted using a waveform analyzer, oscilloscope, or our own ears [4].

Design specifications:

The synthesiser must generate audio frequency tones for the 7 notes in the C major scale in an octave of your choosing.

Process:

In the earlier stages, the basic working of the VCO was referred, to establish the basic understanding of the VCO. The first design is consulted from [5], this design uses a 555 timer. It consists of several components such as comparators, pre-settable flip-flop and a discharge transistor. This design also uses the marvel of the inverting Schmitt trigger, it is practiced by connecting the trigger to the threshold pin. When the voltage at the trigger and threshold goes lower than 2*Vs/3, the output will go high. On the contrary, when the voltage at trigger and threshold goes higher than 2*Vs/3, the output will go low.

As the capacitor in NE555 [6] will be charged and discharged continuously but not linearly, it is important to have a constant and linear current and voltage. The current mirrors are used to generate a bidirectional current source to the 555 timers. A bidirectional current source is to make sure when the 555 output is high, the current is flowed into the capacitor and when it is low, current will be sank from the capacitor.

The current in the current mirrors is varied by varying the voltage across the current setting resistor. The two transistors between the current mirrors function to vary the current and switch the direction of flow and current. If the top current mirror is on, current is sourced and if the bottom is on, current sank. The sinking and sourcing charges the capacitor with constant current linearly due to the current mirrors' properties. This current depends on the current going through resistors R1 and R2.

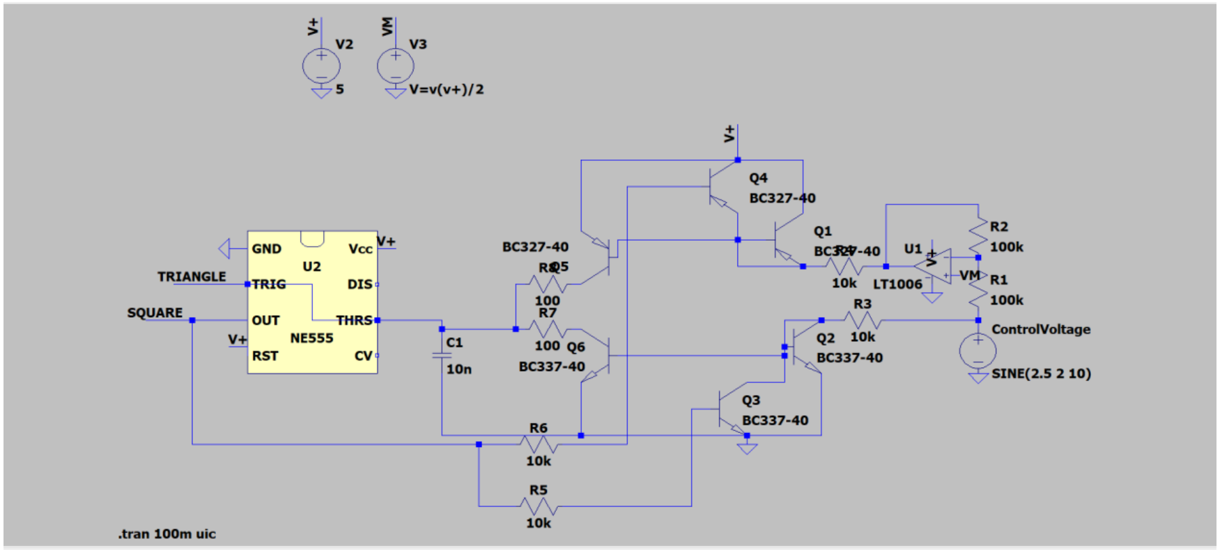


Figure 11

The emitter degeneration resistors are included to help with balancing any issues caused by the non-matching transistors [5].

To improve this design, it is a good idea to replace the NE555 timer [7]. This is because it consumes a higher voltage than the latest designs. As example, replacing it with Exar's XR-2206 [8] function generator that generates sine, triangular, sawtooth waves and square waves. Furthermore, it can be amplitude or frequency modulated.

Figure 12 and Figure 13 displays the outputs:

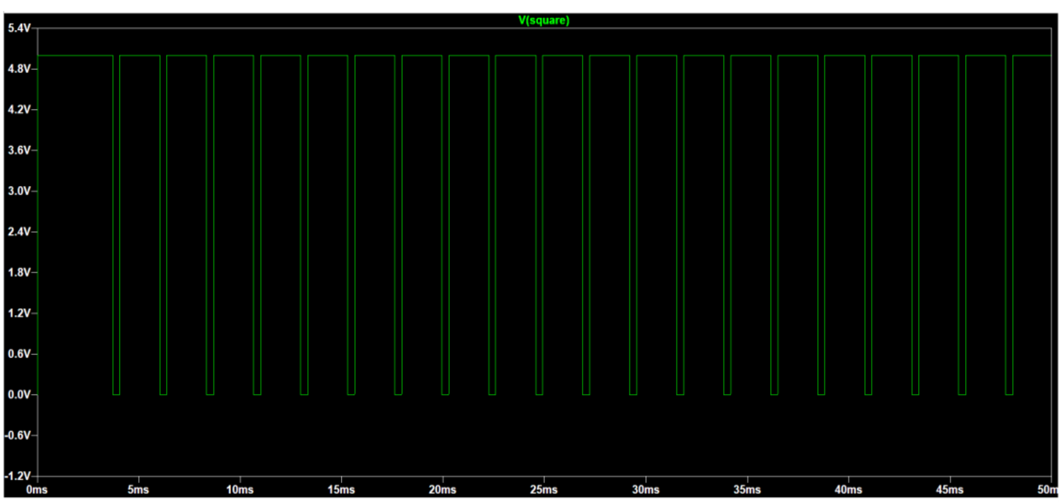


Figure 12: Square wave

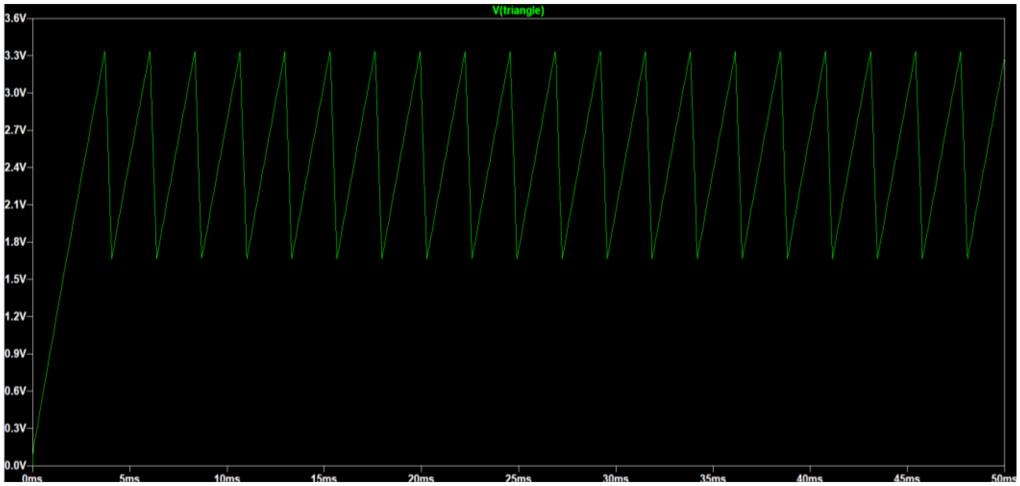


Figure 13:Triangle wave

The problem with this configuration is that there is only one input allowed which is a sine wave to generate a square and triangle wave and this will not abide the requirement. It will be complicated to build a sine wave generator that converts the voltage input to a sine wave input. Also, the current sinks and sources will not be perfect at low voltages resulting at low frequencies, the output will not be perfectly linear. This is shown in Figure 14.

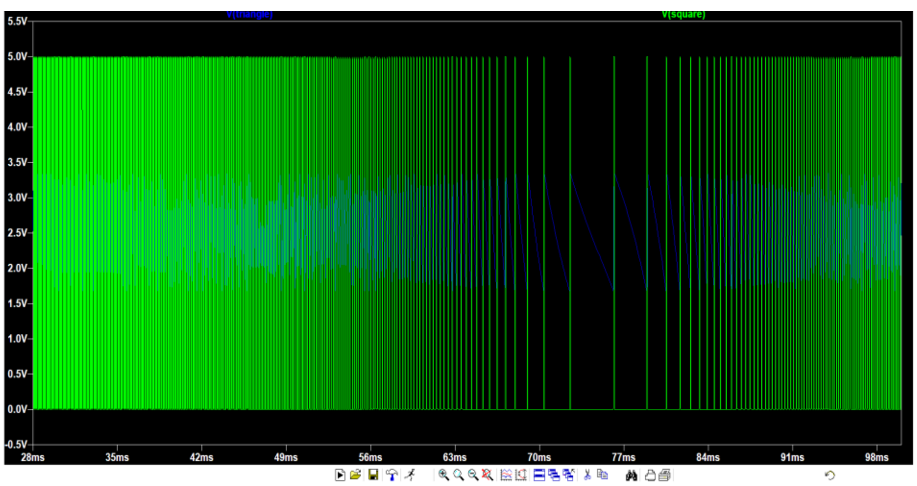


Figure 14

Final Design:

A 1V/octave synthesizer was built that will result in any 1V increase of input, there will be a rise of 1 octave of frequency in the output [1]. The synthesiser will be able to generate 60 keys in 5 octaves, all of it depending on the input voltage that is supplied from the keyboard. An exponential converter is effective in converting a 1V to 5V voltage input to an exponential current. The conversion allows waves that are linearly proportional to input current to be generated. As the voltage increases, the input current and tone frequency increase exponentially [1, Fig 15].

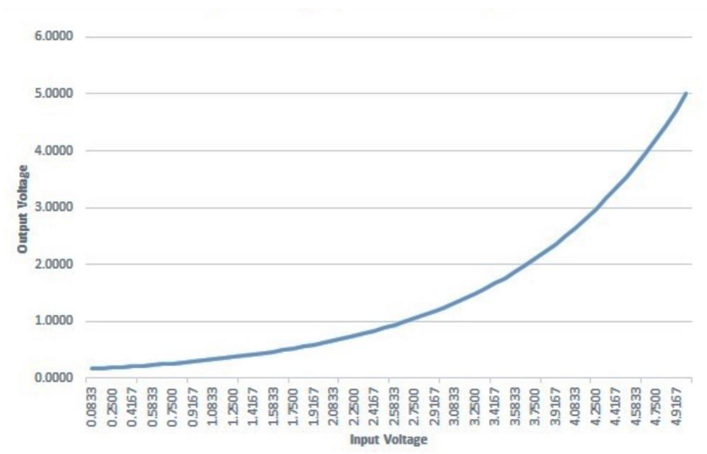


Figure 15

In the circuit, there is an input adjust, linear to exponential converter and the actual VCO [1]. In this experiment, LM358 amplifiers [9] and the NPN transistors, BC548 [10] are used [1, Fig. 16].

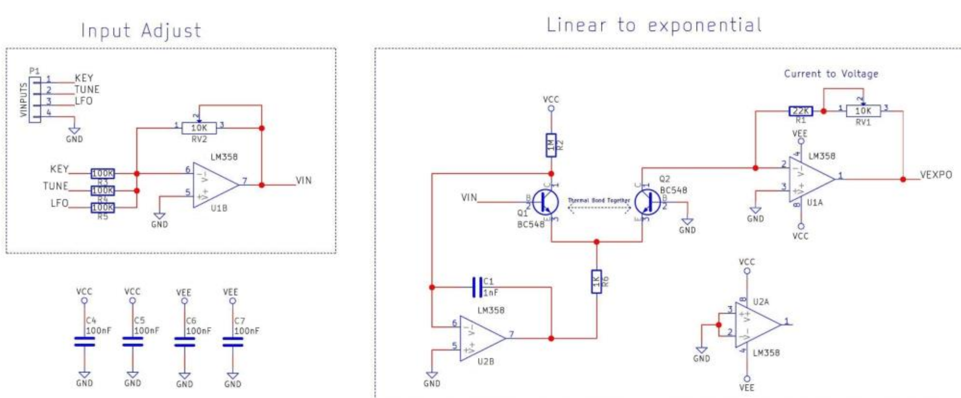


Figure 16

The input adjustment consists of key, tune and low frequency oscillator (LFO). The key is obtained from the input of the keyboard that has to be constructed. The tune comes from a trimmer. The LFO is used for effects. The key, tune and LFO will be summed using a summing amplifier that is responsible for producing an -18mv output for 1v inputs.

In the voltage to exponential converter stage [11], the Vin will enter a differential pair, Q1 and Q2. The current in Q1 is kept constant by amplifier U2B. If there is a change in Q1 base voltage, there will be a corresponding change in Q2's base-emitter voltage. As in Equation 5, the change in the base-emitter voltage causes an exponential change in collector current

Equation 5:Ic=Isexp (Vbe/Vt)

The similar high hfe (Hybrid parameter forward current gain) of Q1 and Q2 will cause a high DC gain [12]. R1 and Rv1 are chosen to give a unity gain to the input voltage. The output voltage from U1A gives the exponential voltage.

In the actual VCO, there are integrator (U3A), Schmitt trigger (U3B) and reset circuit (Q3) (1, Fig. 17).

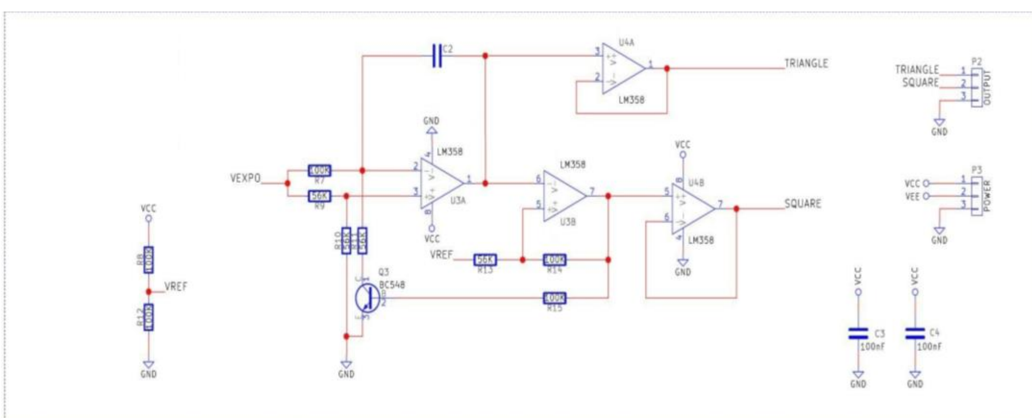


Figure 17

The integrator's output depends on Q3(BC548 NPN transistor) and the presence of input voltage at VEXPO (the input from the exponential converter). If Q3 is off, capacitor C2 charges and the integrator output would decrease. C2 discharges and integrator output will increase if Q3 is on. C2, R7, R9, R10, R11 and the exponential input determine the rate of rising or falling of output. The VEXPO determines the rate of charging of the capacitor C2.

U3B is the Schmitt trigger. The reset circuit (Q3) is dependent on the output of the Schmitt trigger based on. If the trigger output is high, Q3 will be on and inversely, if it is low, then Q3 will turn off.

So, as a whole, the circuit works by the functions of all three components. Say, initially, Q3 is on, the U3A output will increase. It the output will eventually passes the U3B's upper threshold and this will result the Schmitt's trigger operation to happen. The output of the U3B will be 0v and cause the Q3 turns off. Hence, the output of U3A will fall causing U3B to produce 5v. The process will repeat continuously causing the oscillation of circuit that depends on the voltage. Hence, the operation of the VCO will be complete.

There was initially a buffer in the original schematic however it was removed as it did not affect the operation of the circuit.

The circuit is constructed as below [1, Fig.18]:

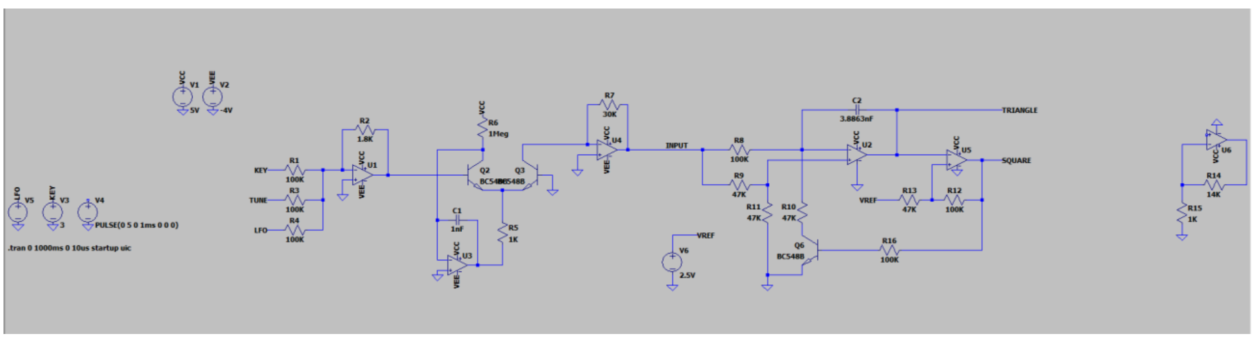


Figure 18

Below are the outputs of this circuit:

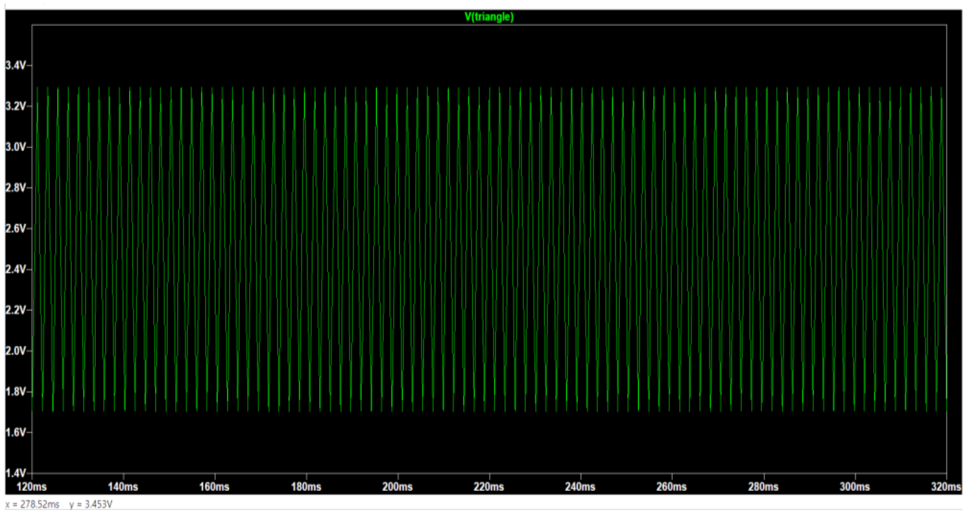


Figure 19: Triangle wave

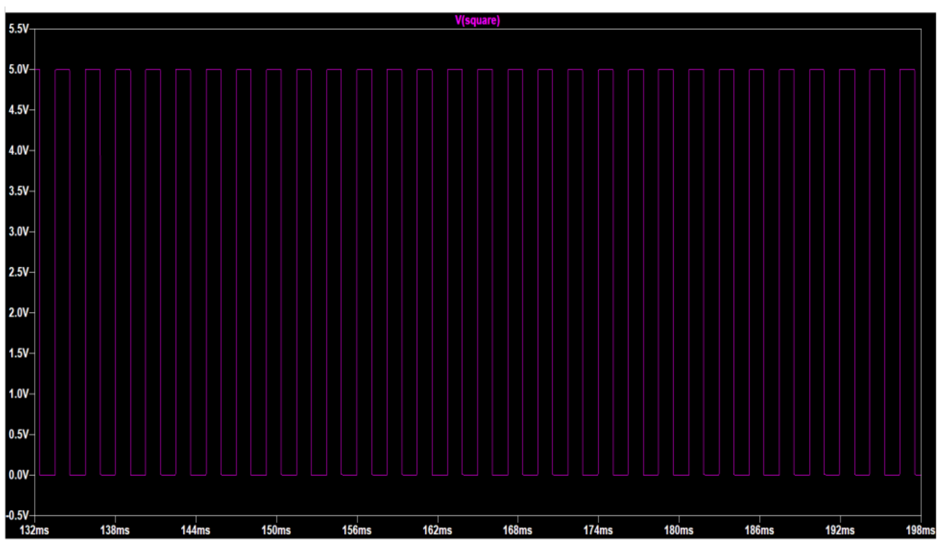


Figure 20: Square wave

The weakness of this design is that because of the exponential converting process, the output tends to be off when it goes to a higher frequency or a lower one. As an example, going to lower keys or higher results a couple of semitones off. This causes the output to be inaccurate and we resorted to use only 7 notes in the 4th octave to produce the perfect design.

3.3 Voltage Controlled Filter (VCF)

Introduction:

A voltage-controlled filter (VCF) is one of the major blocks of an analogue music synthesiser. It is responsible for shaping the desired tones and it gives each synth its own character and unique sound. It achieves these functions by having different filter types such as low pass, high pass, band pass and all pass [13]. The amount of filter applied can be controlled by using control voltages.

Design specifications:

Able to accommodate frequency range for 7 notes in the C major scale in the 4th octave.

Process:

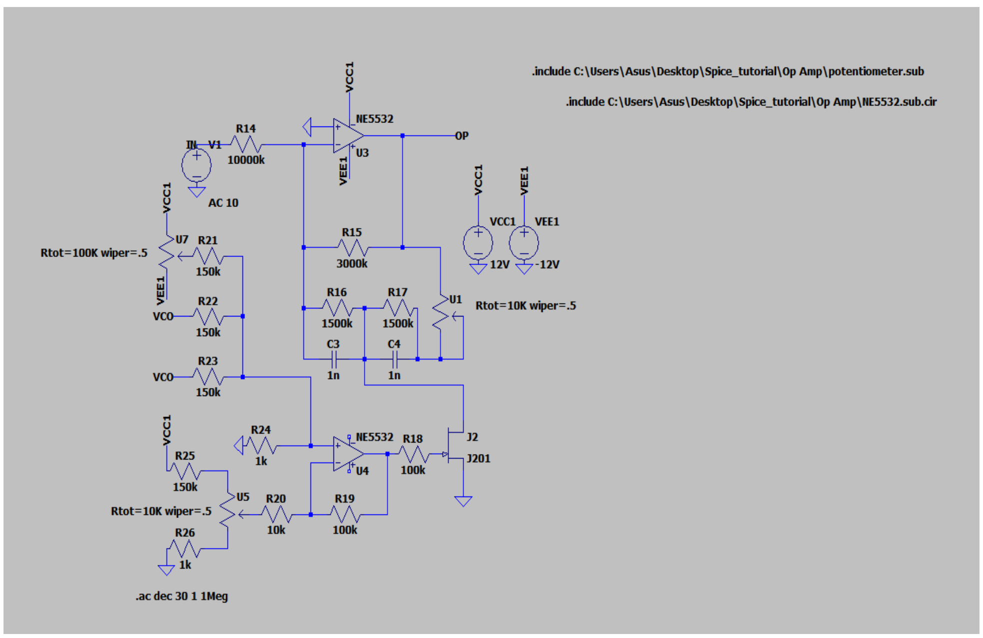


Figure 21

[14, Figure 21] is based on Ray Wilson's design. It is chosen due to its simplicity, but its downside is that it only works as a low pass filter, thus limiting the flexibility of the overall synthesiser.

AC analysis of the design (Figure 22) shows the low pass filter will allow frequency of up to about a 50kHz, which is way above our requirement, which only require a frequency range of 261Hz to 494Hz.

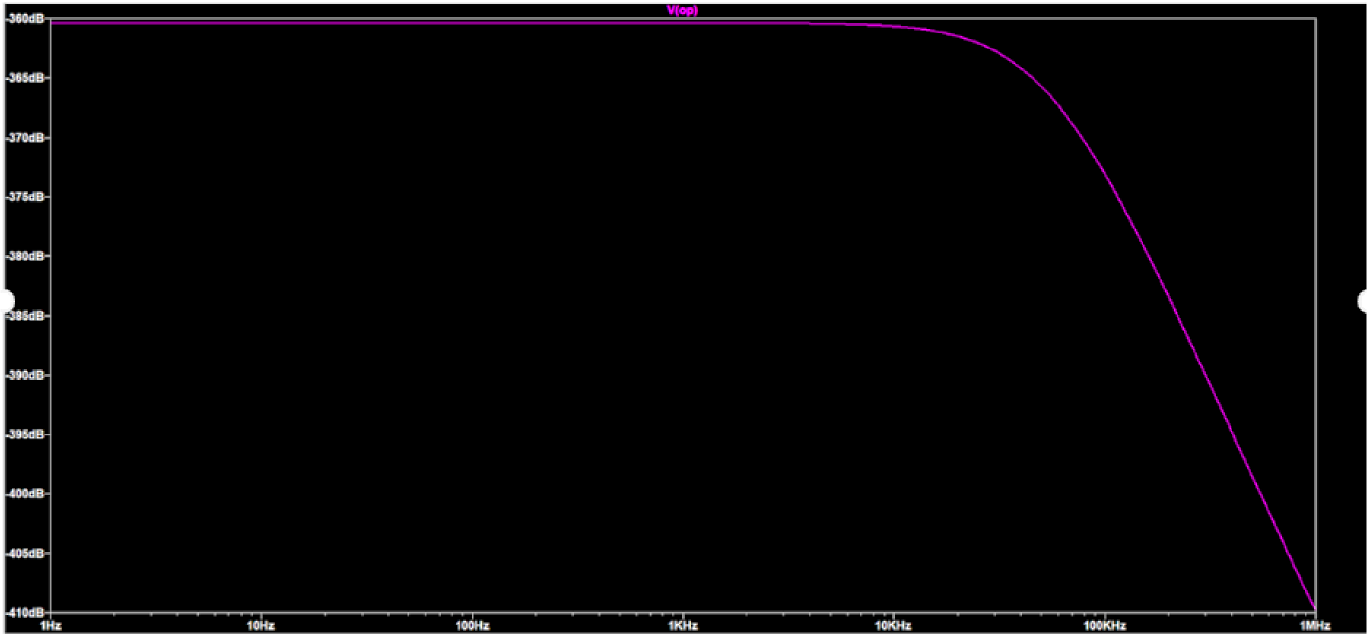


Figure 22

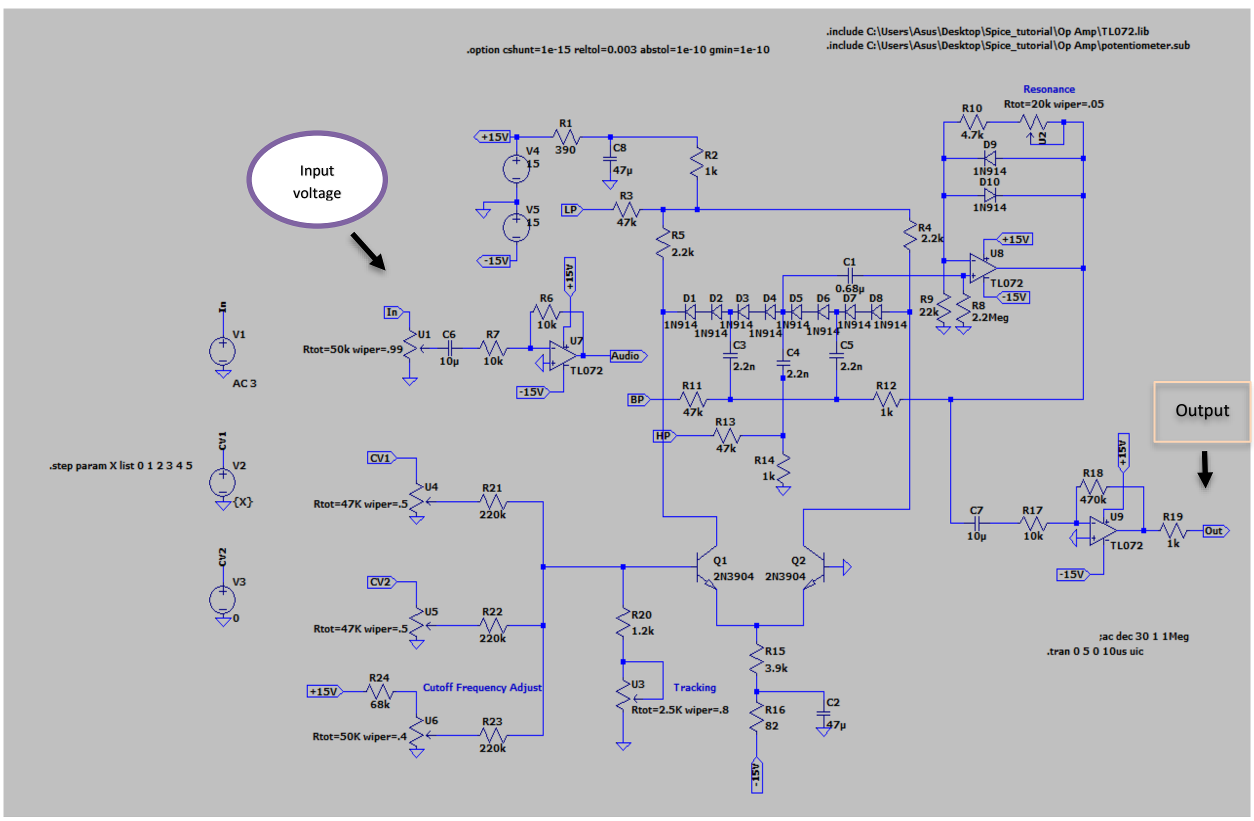


Figure 23

After discussion, it is decided that we will build a VCF that allows switching between low pass, high pass, band pass and all pass. Figure 23 is based on the famous Steiner-Parker Synthacon design [15]. It is a multimode filter which allows users to switch between low pass, high pass and band pass. One of the main advantages of this circuit is its ability to tune across the whole audio spectrum, 20Hz to 20kHz, without the need for range switching. As the original design is rather complicated for our synthesiser, our final design incorporates the main functionality of the original design but tones down some of the more complex functions.

Circuit explanation:

"In" which is the input of the VCF will be connected to the output of the VCO. The level of the input is set by the potentiometer U1, which is then buffered by the TL072 [16] op amp. Diode string D1 to D8 acts as voltage-controlled resistors. Diodes 9 and 10 are introduced as an improvement on the original design to limit the amplitude of the oscillation of the filter at maximum resonance [17]. According to the needs of the user,

"Audio" is then connected to "LP", "BP", "HP" or "AP", "AP" being achieved by connecting "Audio" to "LP" and "HP" simultaneously. Moving down to the circuit, Q1 and Q2 generates different voltages, thus providing a differential voltage for the diodes, causing the DC current to flow through them.

The control voltages of the VCF are provided by U4, U5 and U6. The level of cutoff frequency is adjusted by trimming U6. U3 is used to calibrate the VCF to ensure that the control voltage tracks with the filter cutoff. CV1 and CV2 are summed and fed into the base of Q1, which will then exponentially convert the voltage. C1 couples the RC filter output into U8 where control of resonance can be achieved by trimming U2. The output of U8 is then positively fed back into the RC filter output through R12. Resonance feedback is provided by R12, C3 and C5. Before generating the final output, the signal is fed through U9 to be amplified and buffered.

Simulation outputs:
Settings:

1. Control voltage 1 is stepped from 0V to 5V, increasing by 1V at a time.
2. Resonance set to maximum (0.95) or minimum (0.05) or 0.5.
3. Cutoff frequency set to default (0.4).
4. Calibration/tracking set to 0.8.
5. Input signal set to 0.99.
6. CV1 and CV2 set to 0.5.

Test 1: Low pass filter

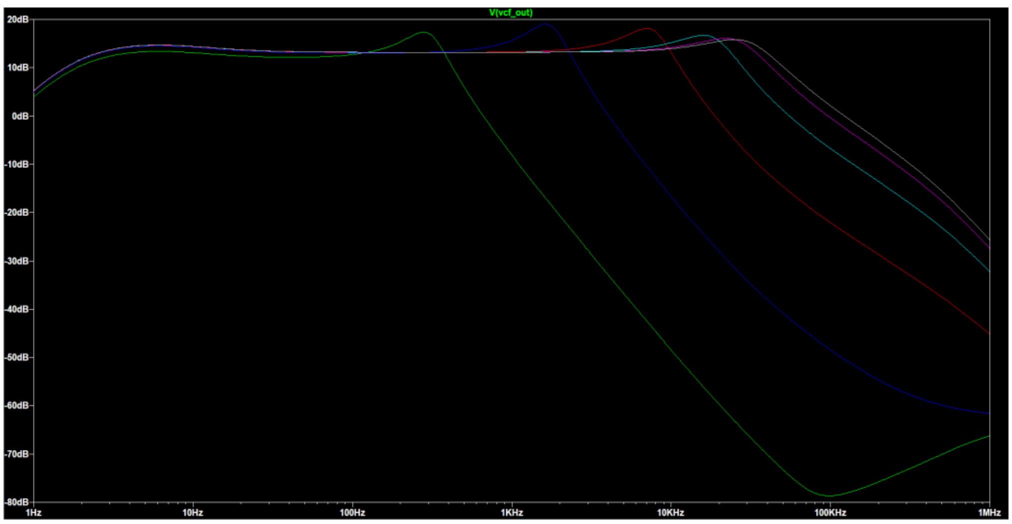


Figure 24

The first test uses a standard setting with resonance set to 0.5. CV1 increases 1V at a time, starting from 0V, showing from green to grey. Slight peaks are seen due to resonance, but simulation shows that the circuit is performing as expected of a low pass filter. As the control voltage increases, the frequency range of the low pass filter increases. For a control voltage (CV1) of 5V, the frequency range can go up to approximately 50kHz, which is way above the audio range of a human.

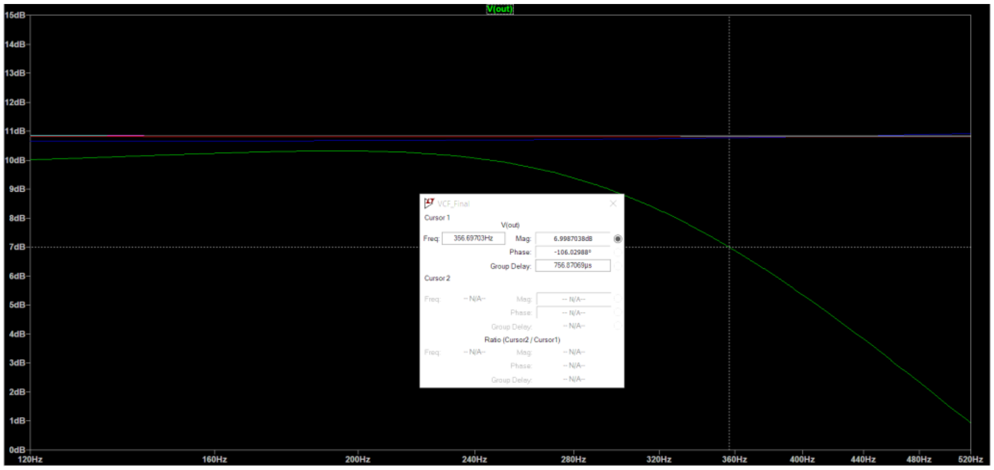


Figure 25

CV1 = 0V, cutoff frequency is around 356.7Hz.

CV1 = 5V, cutoff frequency is around 6kHz.

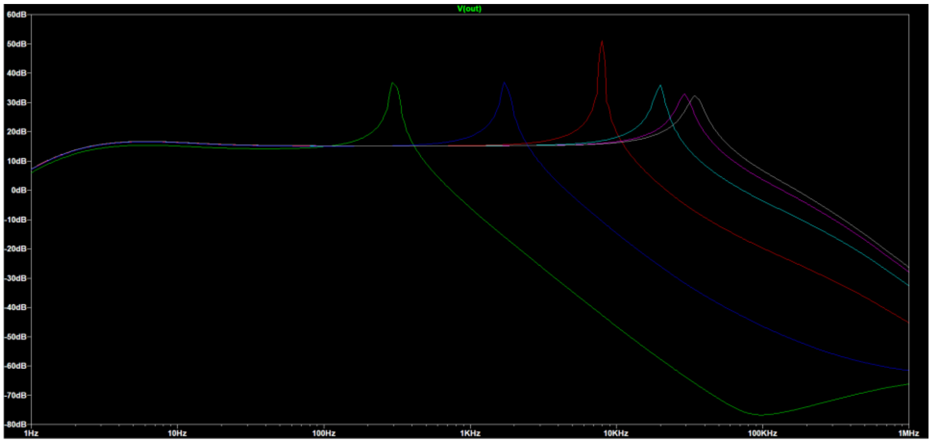


Figure 26

Figure 26 used the standard settings with a maximum resonance. Higher peaks are seen and in the actual circuit, oscillations might be seen. Frequency range is still suitable for a music synthesiser.

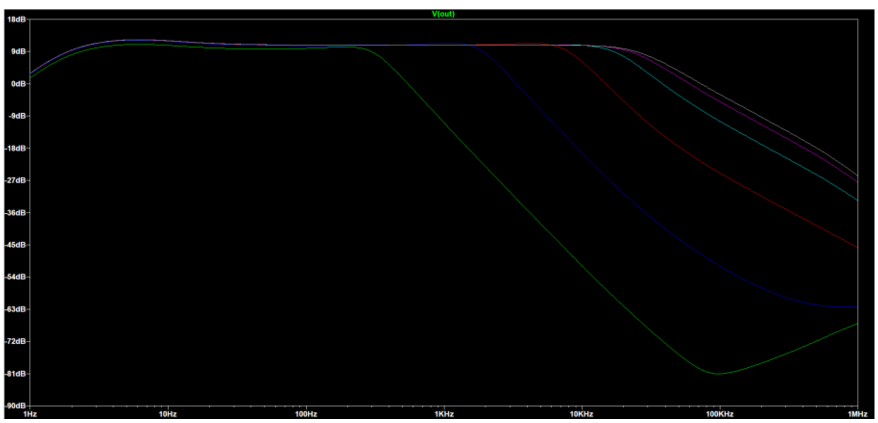


Figure 27

Figure 27 used standard settings with resonance set to minimum. No peaks are visible.

Test 2: High pass filter

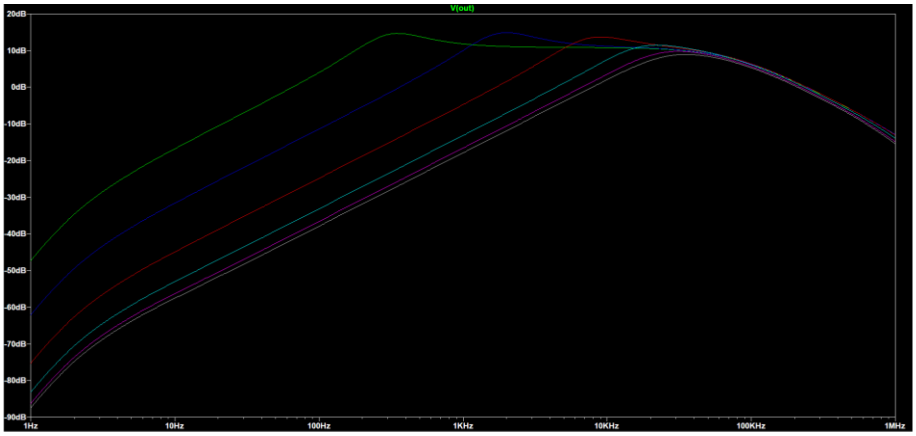


Figure 28

Figure 28 used the standard settings with minimum resonance. There is slight peaking at the cutoff frequency, which is about 10kHz.

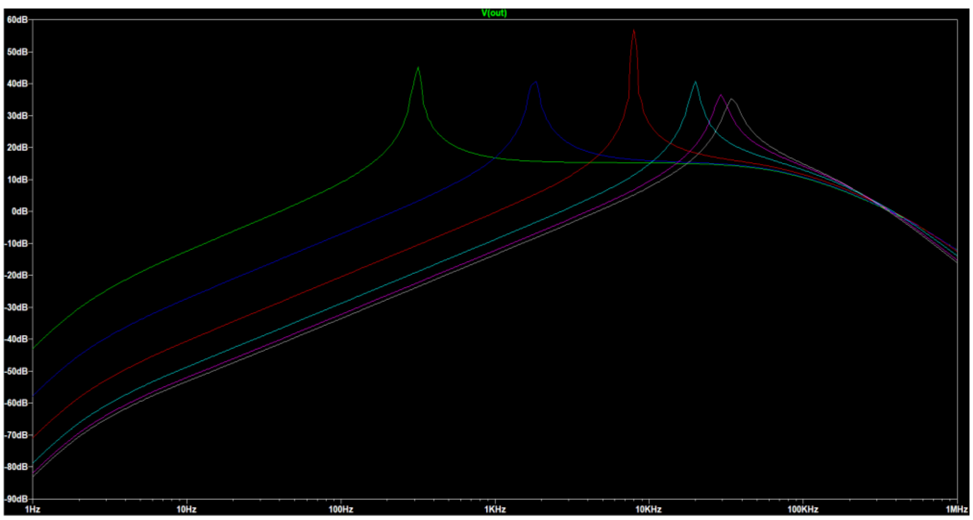


Figure 29:Simulation with maximum resonance

Test 3: Band pass filter

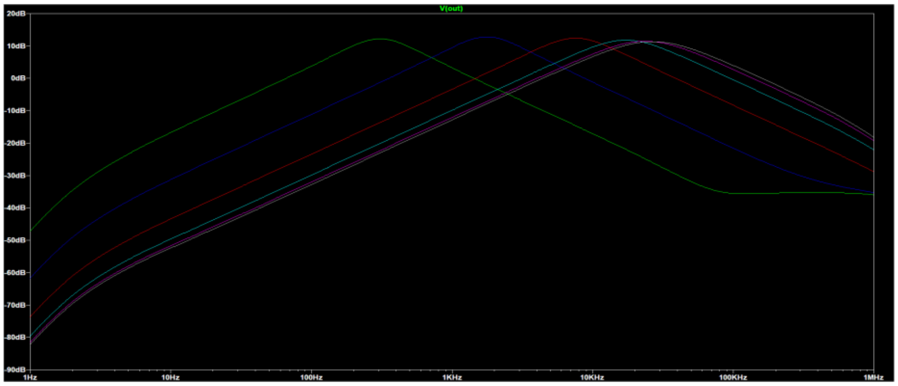


Figure 30

Figure 30 is achieved using minimum resonance control. This feature can be controlled to achieve a certain band of frequencies.

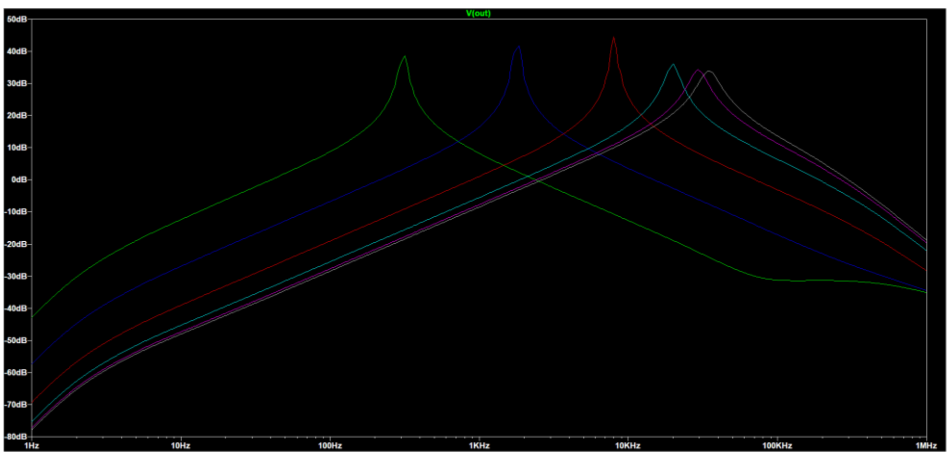


Figure 31:Simulation using maximum resonant control

Test 4: All pass filter

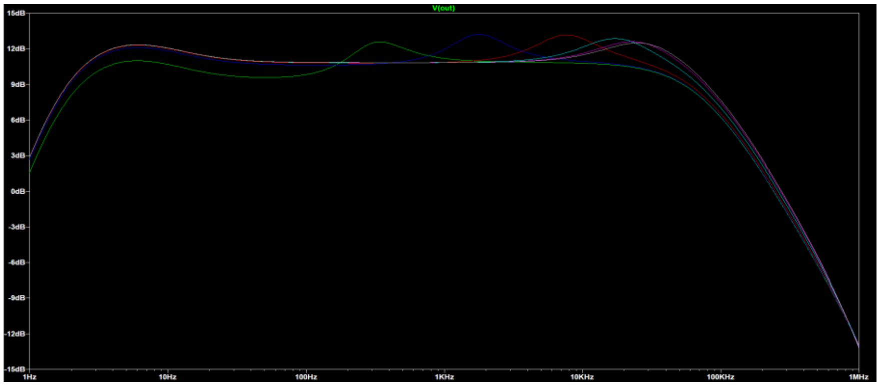


Figure 32

Figure 32 used the standard settings and resonance control set at 0.5.

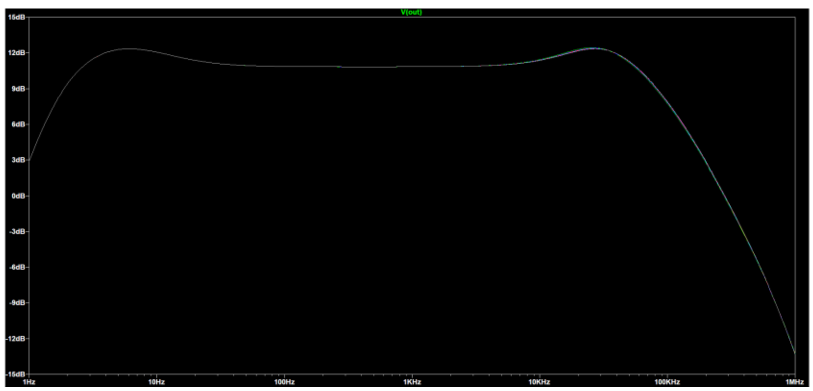


Figure 33

Cutoff frequency setting set to 0.9 with minimum resonance.

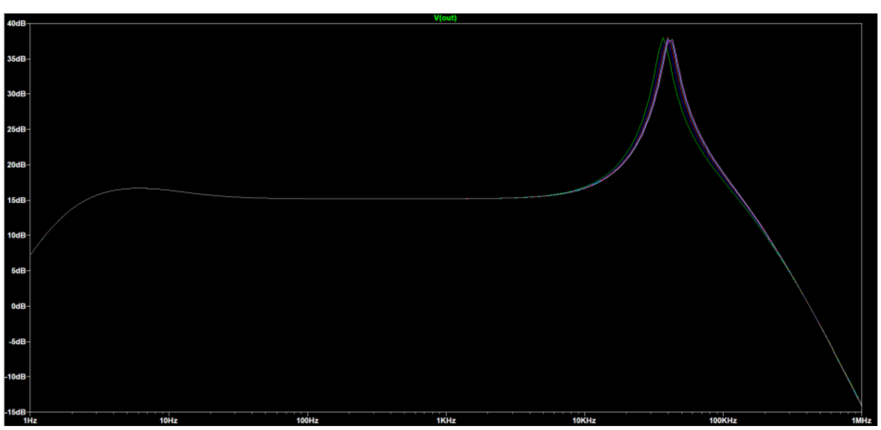


Figure 34

Cutoff frequency setting set to 0.9 with maximum resonance.

Final design:

As the VCO that was built could handle 60 notes and they are within the frequency range of 261.6311Hz to 493.8937Hz, we decided to build a VCF based on the Steiner-Parker VCF. Based on the specifications of our synthesiser, we decided to use a band pass filter that has a bandwidth of the required frequency.

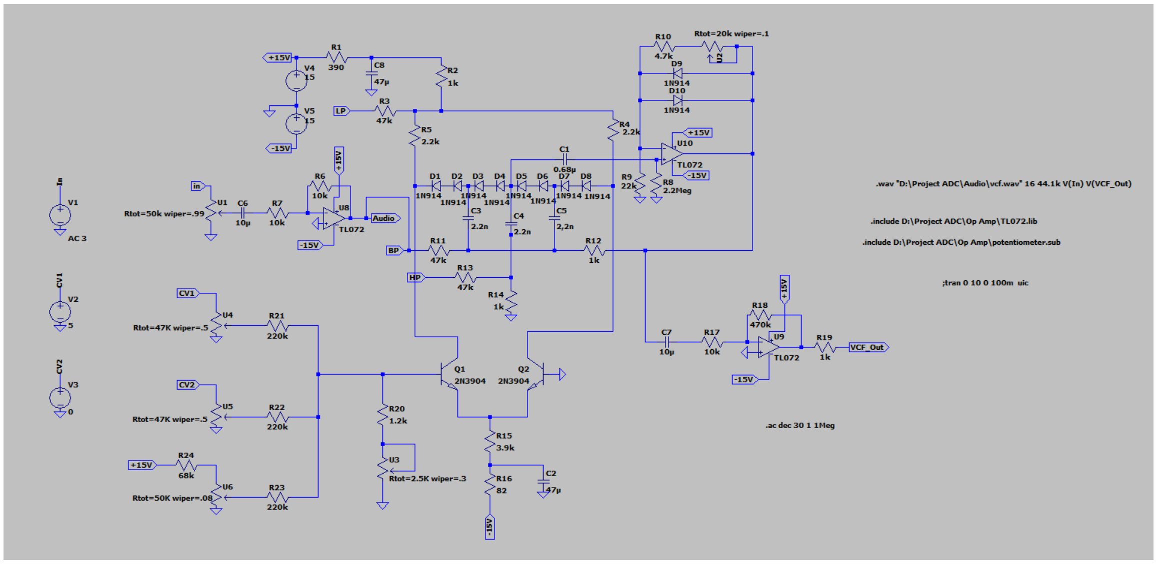


Figure 35

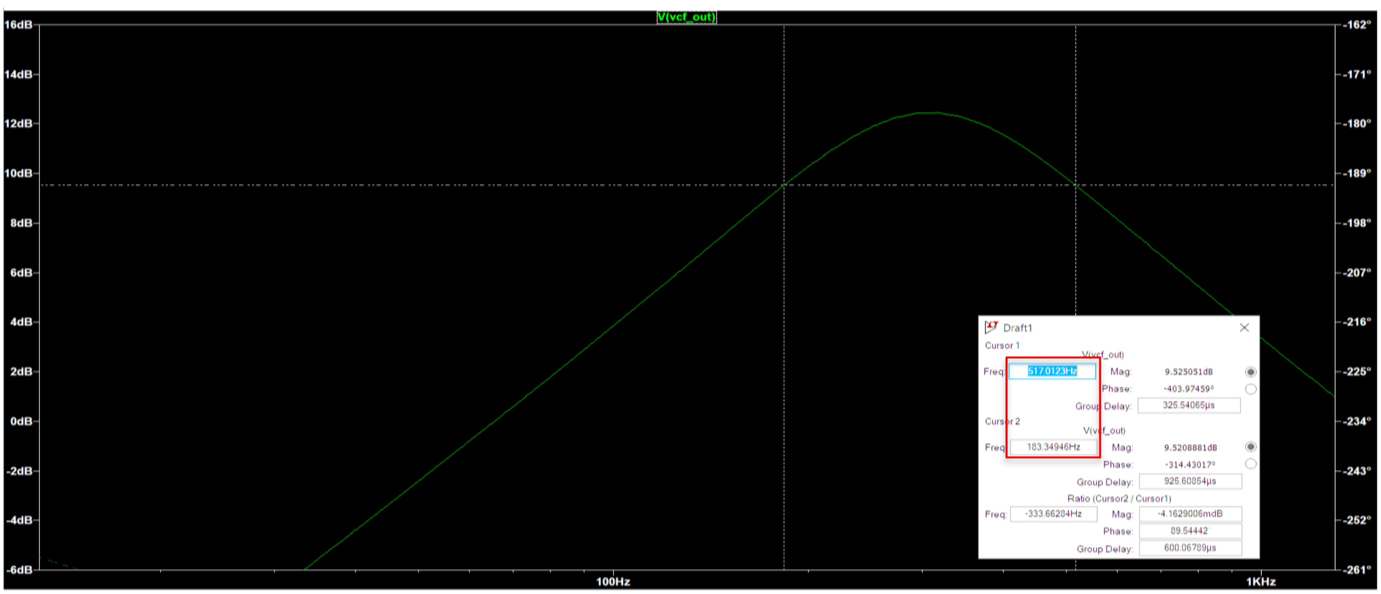


Figure 36

Frequency range of the band pass filter is from 183.3Hz to 517Hz, which satisfies the frequency range of the 4th octave. Q factor of the filter is

Equation 6: $Q = 307.42/333.7=0.921$.

Hence, this shows that the band pass filter is relatively selective.

3.4 Voltage Controlled Amplifier (VCA)

Introduction:

A voltage-controlled amplifier (VCA) is used to control the level of amplification of a signal. Amplitude modulation is typically achieved by connecting an envelope generator and/or the output of tremolo to the control inputs of the VCA [18]. The output of the VCA is then the instantaneous product of the two signals.

Process:

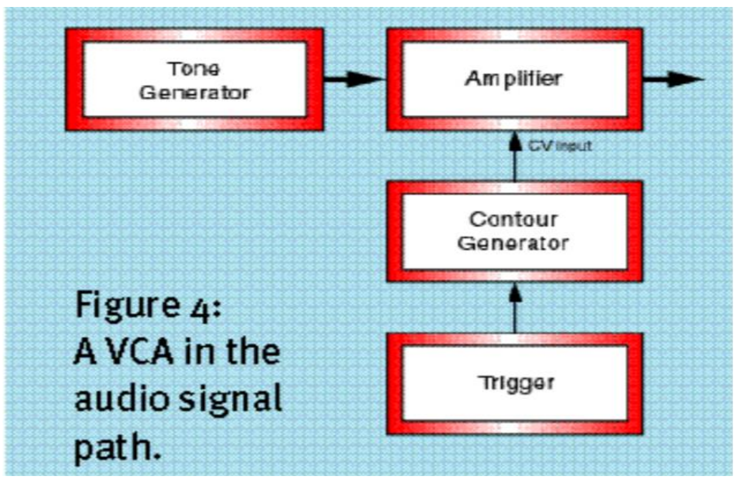


Figure 37

Our VCA design follows the basic outline of the image from [19, Fig. 37]. As differential amplifiers are one of the best building blocks for amplification, we decided to implement the long-tailed pair differential amplifier as the core of our VCA. To improve the performance of the VCA, it is noted that adding an emitter degeneration resistor in the differential amplifier would make the VCA more linear, although its downside is that it would decrease the differential gain [20]. To control the tail current, we decided to review [21]'s design.

Voltage controlled amplifier

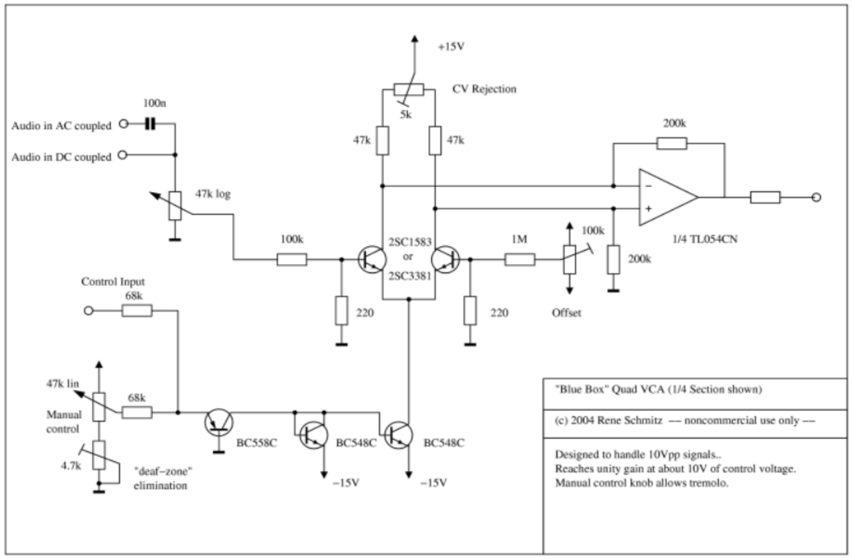


Figure 38

[21, Fig 38] uses 1 PNP and 2 NPN transistors to generate the tail current of the differential amplifier.

Final Design:

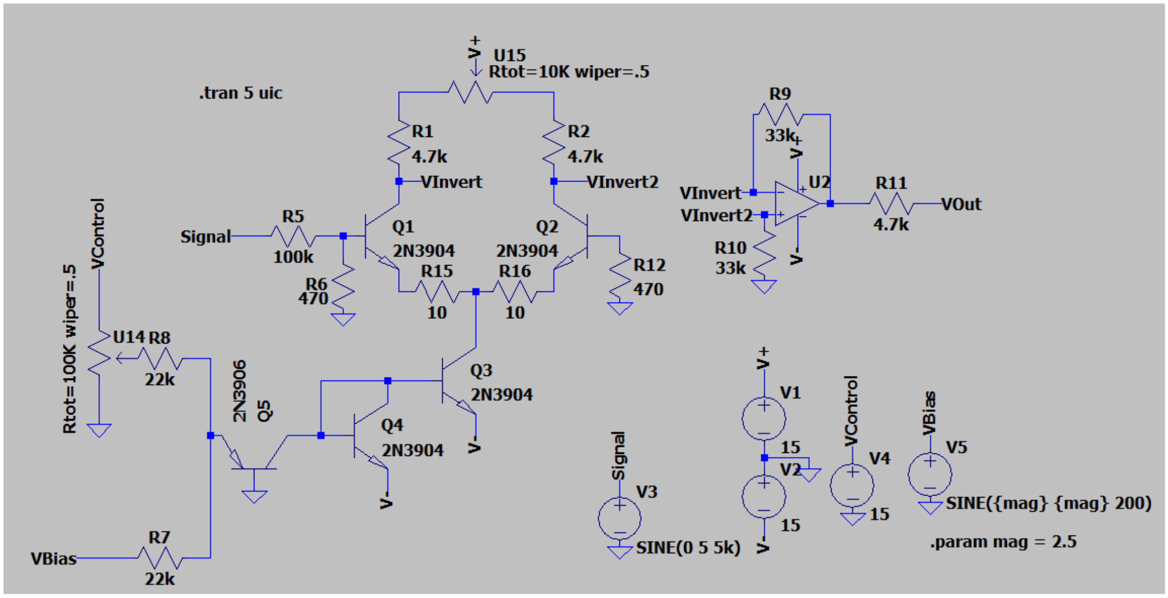


Figure 39

Circuit explanation:

The obtain a small signal, the original signal is multiplied by factor R6/R5 and fed into the base of Q1. To reduce power supply noise rejection, Q1 and Q2 are chosen to be matched transistors. R15 and R16 are added on top of [21]'s design to make the VCA more linear. The gain of the circuit is set by R1, R2 and the bias current.

The tail current of the differential amplifier is set by the collector of Q3. Standing DC bias of Q5 is set by U14, R8 and R7. Q5 acts as a common base amplifier with a small gain. As the base and collector of Q4 is connected, Q4 essentially acts as a diode. When an input is applied to VControl, +dv and -dv will be added to the original -14.4V at the base of Q3. Thus, by changing the amount of control, the tail current can be changed. VBias is a sine wave which is applied to shape the signal, its magnitude trimmed by U14. VControl controls the amount of amplification applied to the signal.

The output from the long-tailed pair differential amplifier is fed into another differential amplifier to remove the common mode between VInvert and VInvert2. It also aims to condition the correct voltage for the overall circuit.

This final design will be incorporated with the ADSR circuit and the tremolo circuit. Both of the components will be connected at the control input of the VCA.

Simulations:

An input signal of 5Vpp is applied.

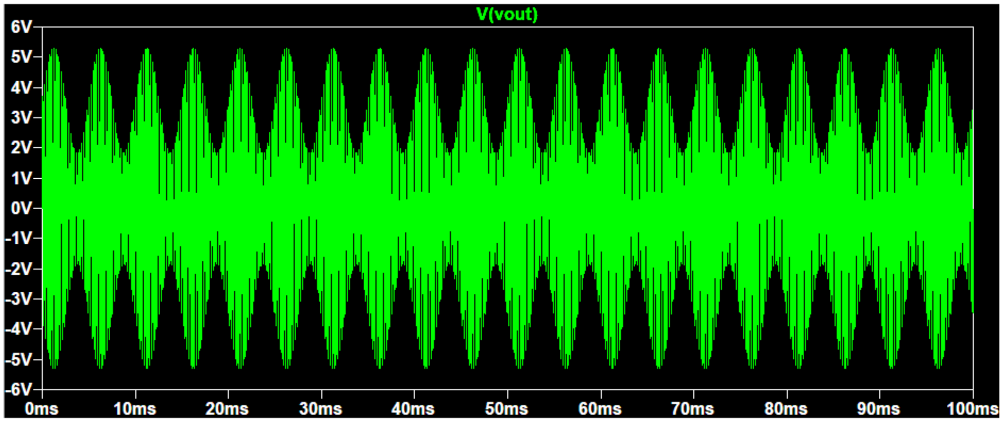


Figure 40

VControl is set to 0.5, where no amplification is needed. Gain is 1.

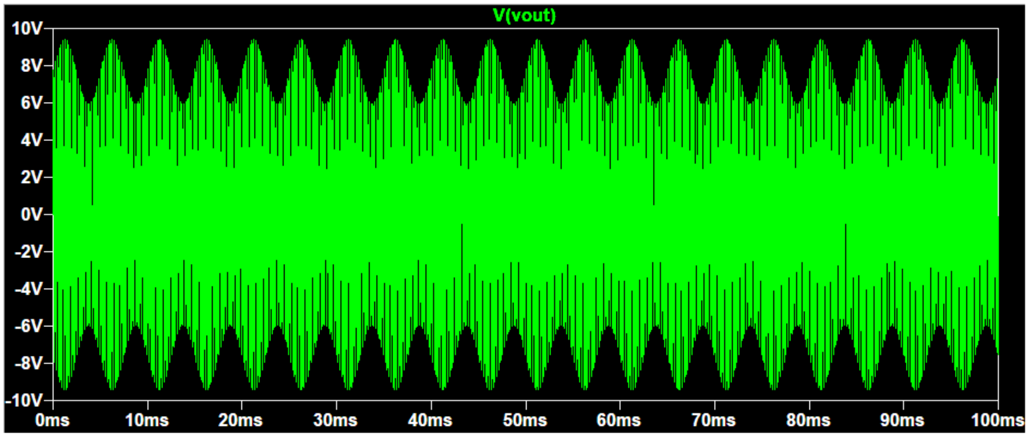


Figure 41

VControl is set to 0.1, where amplification is needed. Gain is about 1.9.

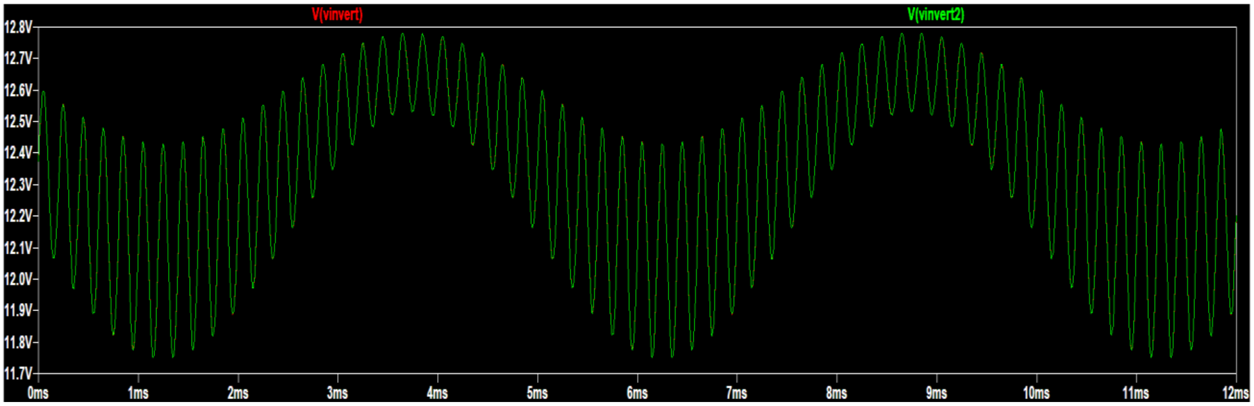


Figure 42

Voltages at the non-inverting and inverting output of the long-tailed pair differential amplifier shows that they have matching amplitudes, hence it can be concluded that there is no error at the outputs of the differential amplifier.

Reflections:

Overall, our VCA works relatively well and uses simple and easily accessible components. Future designs may include another sink transistor beside Q3 to increase the tail current. Another improvement is that a buffer can be added before feeding the input signal into the differential amplifier.

3.5 Envelope Generator

Introduction:

An envelope generator generates a signal that mimics the note dynamics of various instruments. The signal is then typically used as the control voltage of a voltage-controlled amplifier (VCA) [22]. The complexity of an envelope generator varies depending on the desired outcome of a synthesiser. The simplest design is known as the Attack-Release (AR) envelope generator and it is used to produce a simple non-sustaining percussion sound. More sophisticated designs such as the Attack-Decay-Sustain-Release (ADSR) circuit which allows the user to choose how loud the synthesiser is as time goes on. It can be broken down into four components:

1. "Attack" determines how long it takes for the synthesiser to reach its full volume.
2. "Decay" determines how long it takes for the synthesiser to decrease to its secondary volume.
3. "Sustain" determines how long the synthesiser stays at the secondary volume.
4. "Release" determines how long it takes for the synthesiser to completely fade out.

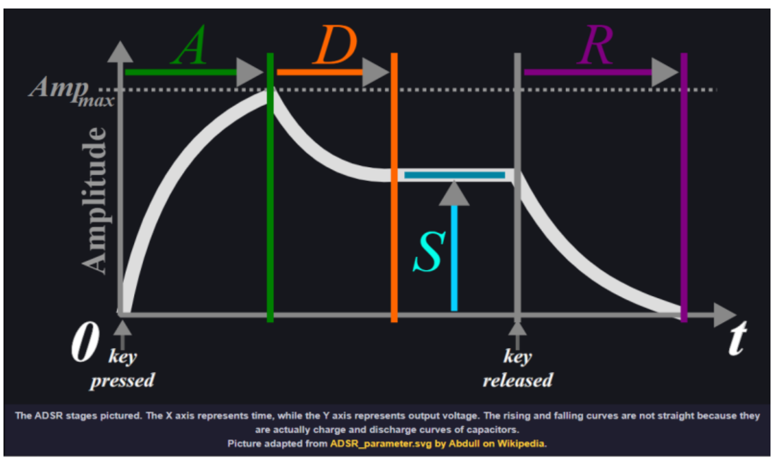


Figure 43

For more details, the reader is referred to [23, Fig 43]

Process:

a)

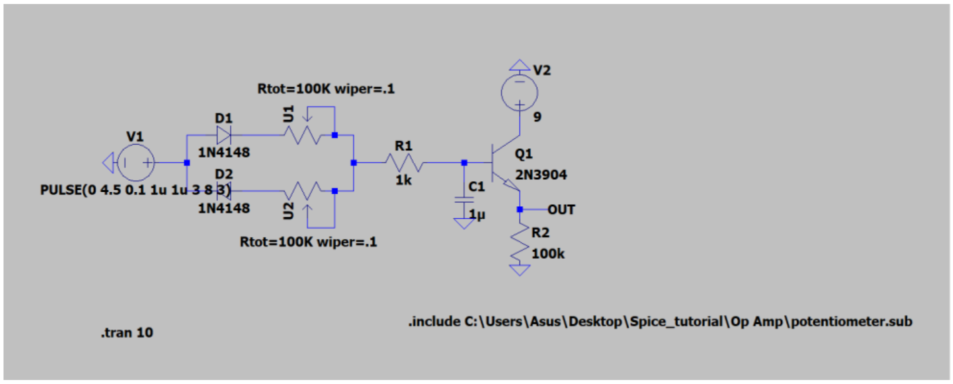


Figure 44

Figure 44's design is adapted from [24].

Circuit explanation:

Capacitor C10 acts as a separate charge and discharge path. When Gate goes high, D4 acts as a forward diode and allows C10 to be charged. The time constant is

$$\textit{Equation 7}\ \tau = (RV3 + R17)(1uF) = 1ms(min)\ or\ 100ms(max)$$

When Gate goes low, C10 discharges through D5, RV4 and R17. The time constant remains unchanged.

Simulation:

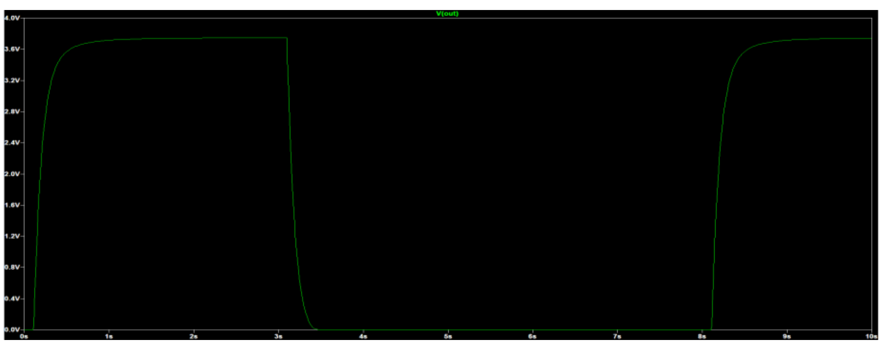


Figure 45

The above simulation is achieved by setting the potentiometer to minimum (0.1). Von = 4.5V.

b)

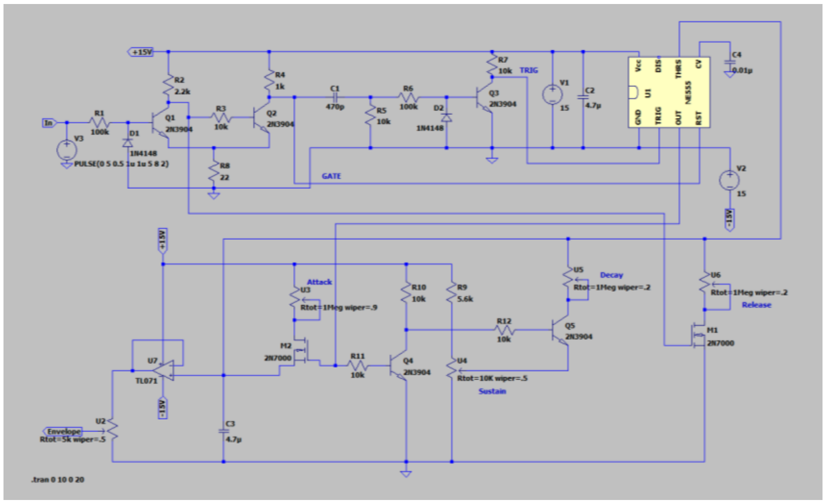


Figure 46

Figure 46 is adapted from [25], an improvement from the Thomas Henry design [5]. is an improvement from the Thomas Henry design [26].

Circuit explanation:

An input signal, “In”, of either 0V or 5V is used to initiate the ADSR. Q1 and Q2 form a discrete Schmitt trigger, turning any input signal into a gate with sharp edges between 0V and 15V. C1 and R6 turn the sharp edge into a short pulse of a few of 10s of microseconds, which is then buffered and inverted by Q3. Hence, the TRIG signal is theoretically at 15V and makes a short pulse at 0V at the start of each GATE.

These signals are used to initiate the NE555 timer. When OUT goes high, the DISCHARGE pin will be floating. C3 will start charging through M1 and R11. The ATTACK potentiometer can be adjusted to control the time for the signal to reach the full volume. The voltage over C3 is buffered through U2, and the enveloped output can again be adjusted using U3.

The output is fed into THRESHOLD. When this pin reaches ⅔ Vcc, 10V, the timer will switch off. OUT goes low and C3 stops charging. At the same time, DISCHARGE will be connected to ground. U5 now defines the sustain voltage between 0V and 10V. The output level will remain at the sustain level until the gate signal ends. When GATE turns 0, discharge through U7 RELEASE potentiometer will occur until reaching the 0V output.

Simulation:

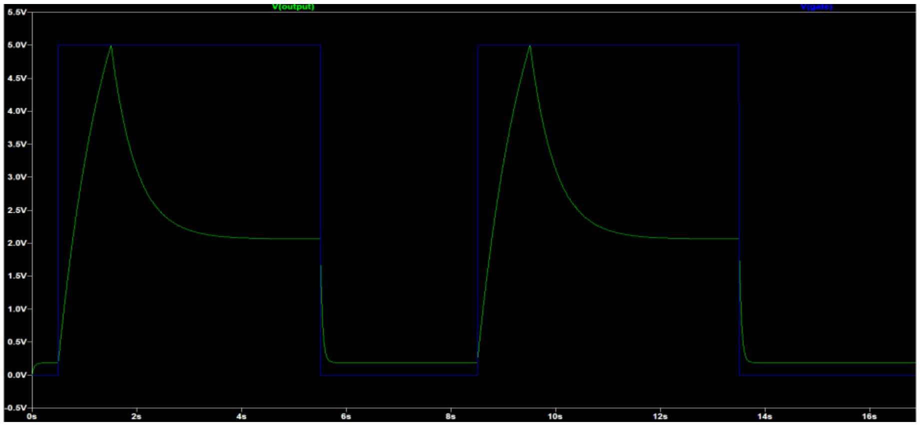


Figure 47

It can be seen from Figure 47 that the output of the enveloped output never quite reaches the 0V level, although a longer sustain time would change that.

ATTACK is stepped through 0.1, 0.5 and 0.8. (left to right):

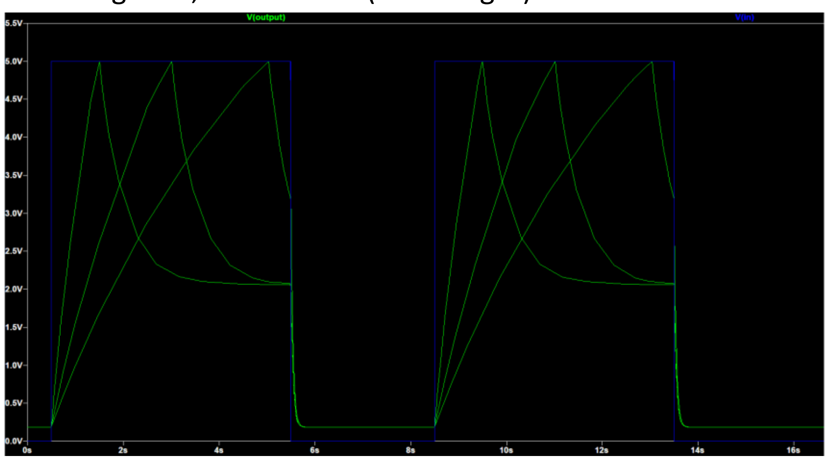


Figure 48

SUSTAIN is stepped through 0.1, 0.5 and 0.8:

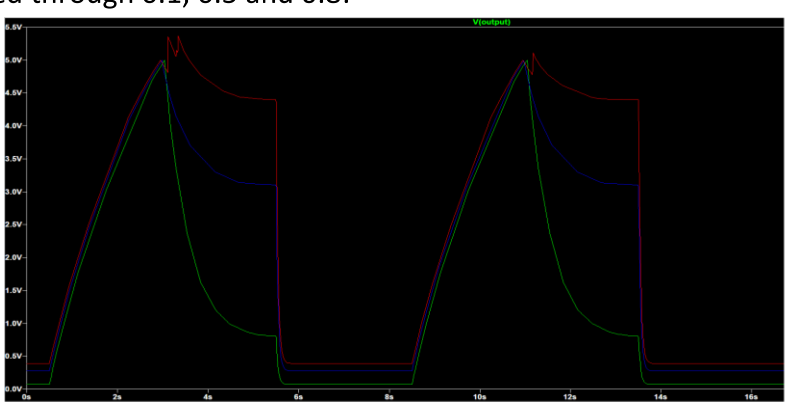


Figure 49

DECAY is stepped through 0.1, 0.5 and 0.8:

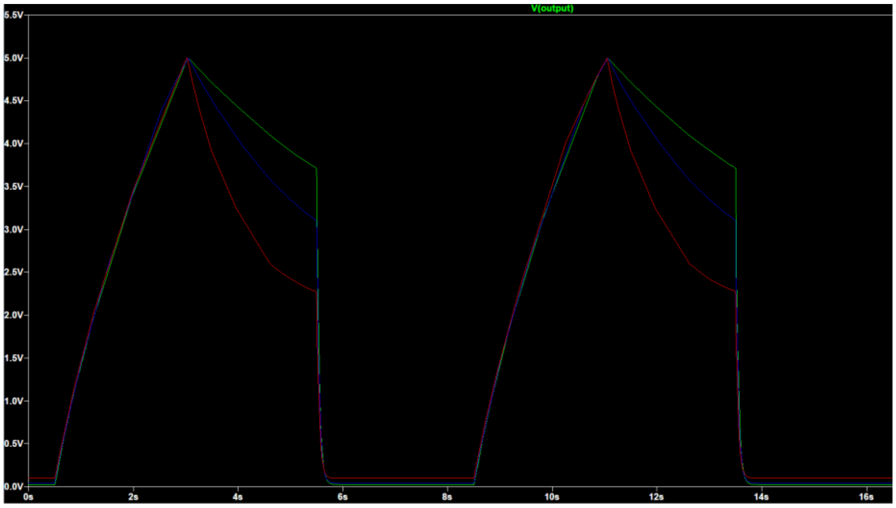


Figure 50

RELEASE is stepped through 0.1, 0.5 and 0.8:

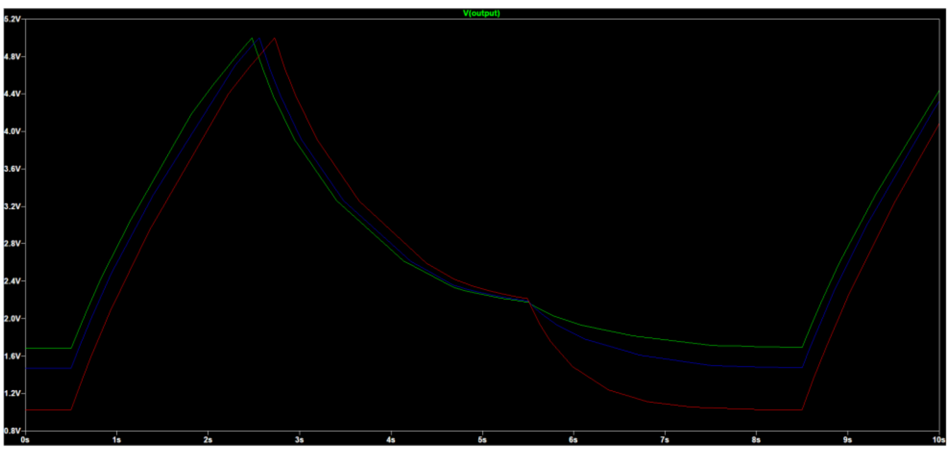


Figure 51

Final Design:

After discussing and researching, it is decided that the ADSR circuit will be more crucial in generating a better sounding synthesiser.

3.6 Frequency Modulation (Vibrato)

Introduction:
Frequency Modulation (FM) uses one wave (modulator) to change the frequency of another wave (carrier), then a new frequency wave will be created. The effect can be shown as a graph below [27, Fig. 52]:

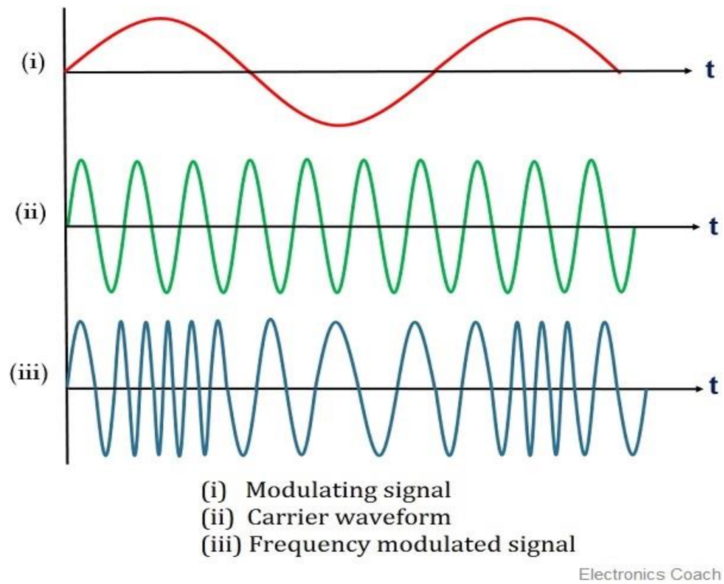


Figure 52

Vibrato is a type of frequency modulation, quoted from [28] “It is a pulsating tone that wavers from slightly above to slightly below the actual musical pitch.”

Process:

Schematic refererred from [29], (Fig.53):

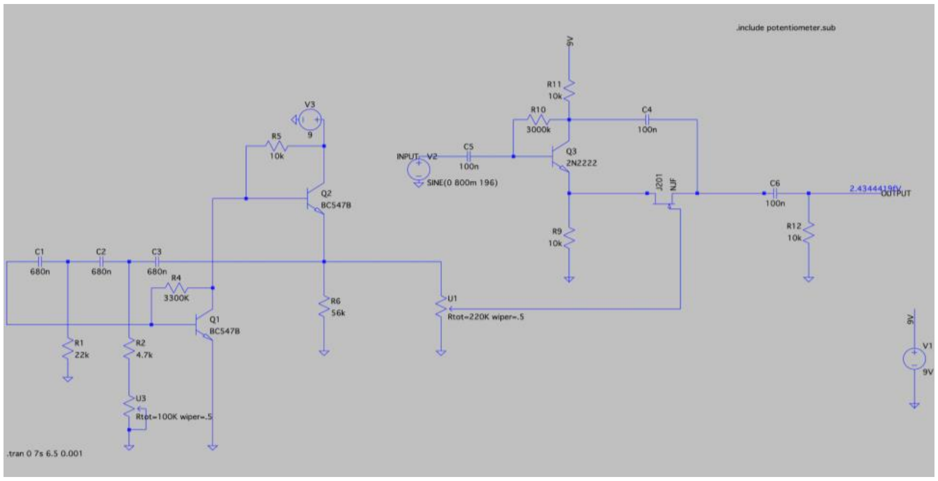


Figure 53

Circuit Explanation:

This circuit contains an LFO itself which is formed by the Q1 BC547B[30] transistor. Capacitors C1, C2, C3 and resistors R1, R2 can be used to set the default frequency. The potentiometer U3 is used to set the speed of vibrato and U1 is to set the depth of vibrato.

As the input signal comes in the capacitor C5 is used to filter out any DC signal comes into the circuit, the Q3 2N2222[31] transistor and resistors R9, R10, R11 form an emitter bias circuit [32, Fig.54]. The emitter bias configuration gives stability regardless of beta value.

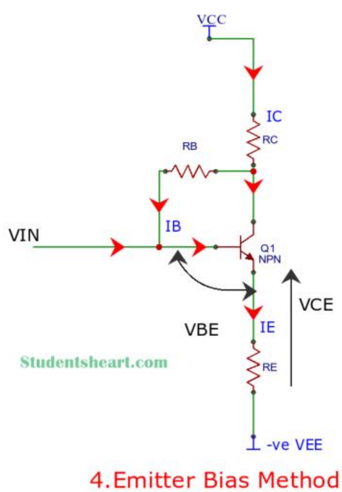


Figure 54

Then the J201 field-effect transistor works as a variable resistor here, the carrier signal mixes with the modulation signal and we will get the frequency modulated signal.

Simulations:
For this simulation, we use transient analysis to start from 6s and end in 7s with a 0.001 step.

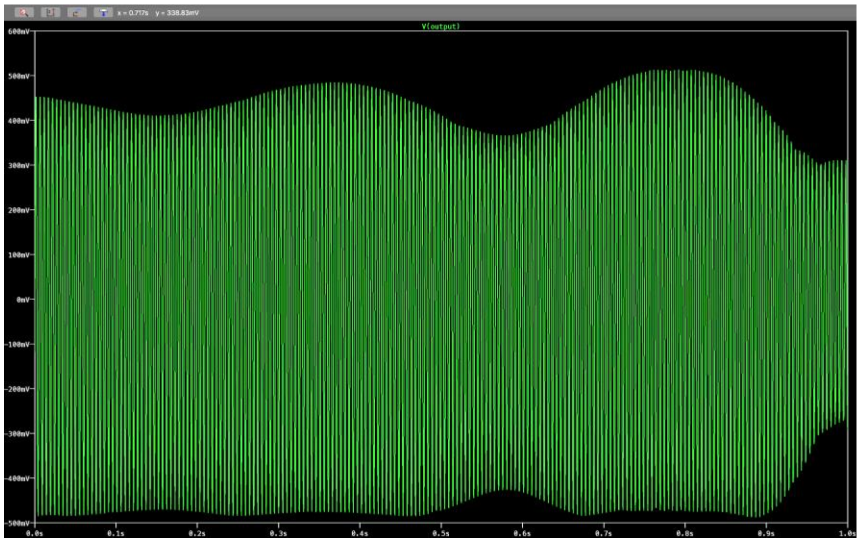


Figure 55

Initially, we thought it was not correct due to the fact that it doesn't follow the typical frequency modulation graph as shown in [27]. However, after a bit research, [33, Fig.56]:

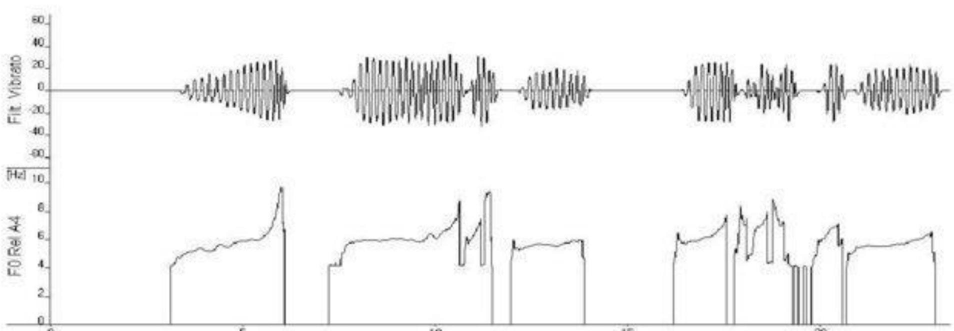


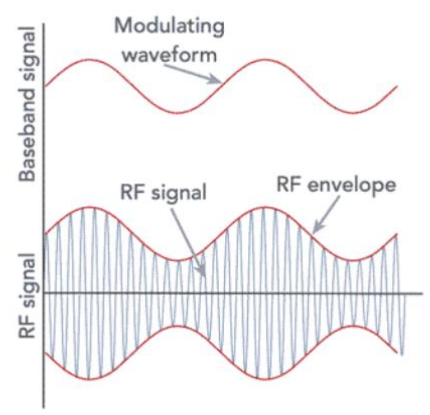
Figure 56

The waveform abides the frequency modulation graph hence, it can be concluded to be true

3.7 Amplitude Modulation (Tremolo)

Introduction:

Modulation is a process where the sinusoidal carrier's parameters such as amplitude, frequency and phase are varied according to the baseband signal [34]. In amplitude modulation, the amplitude is varied linearly [34] with the baseband signal as [35, Fig.57].



Amplitude Modulation, AM

Figure 57

Quoted from [36] "Tremolo is a modulation effect that rhythmically changes the volume of your signal". For tremolo, it is actually an amplitude modulation with a very low frequency modulator [37].

Final design [38]

The two essentials for amplitude modulation are the carrier signal and low frequency oscillator [39]. Phase shift oscillators are oscillators that produce sinusoidal output leading the input [40]. The circuit contains amplifier units such as amplifiers or transistors. The degree of leading of output depends on the feedback components (resistors and capacitors) values [40].

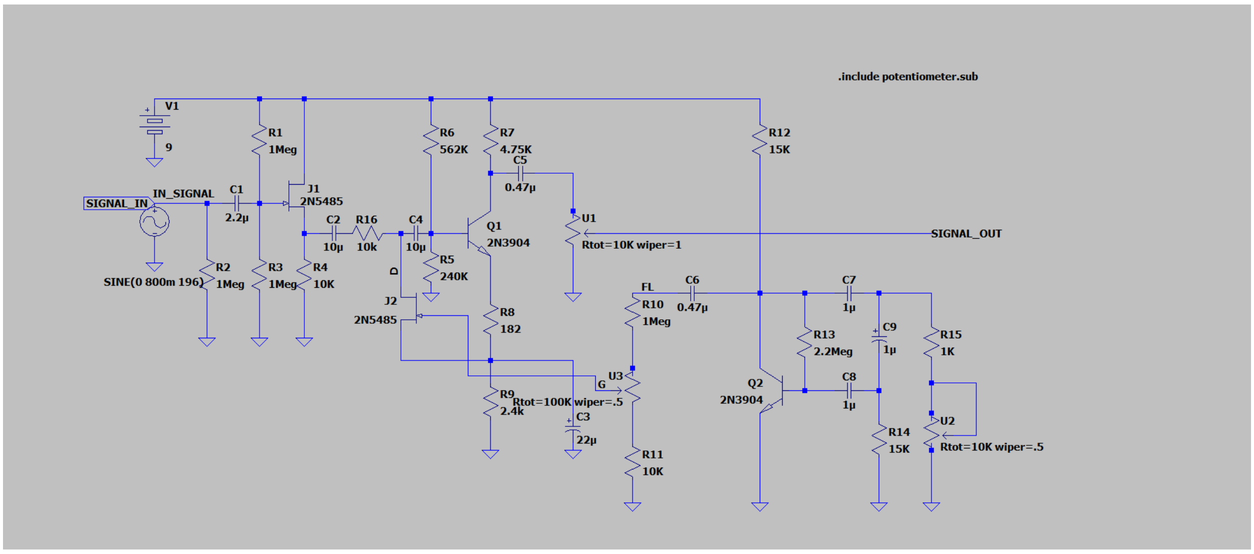


Figure 58

In the first part of the circuit where the initial amplification takes place, output supplied has an amplitude of 0.76V centred around 6.08V.

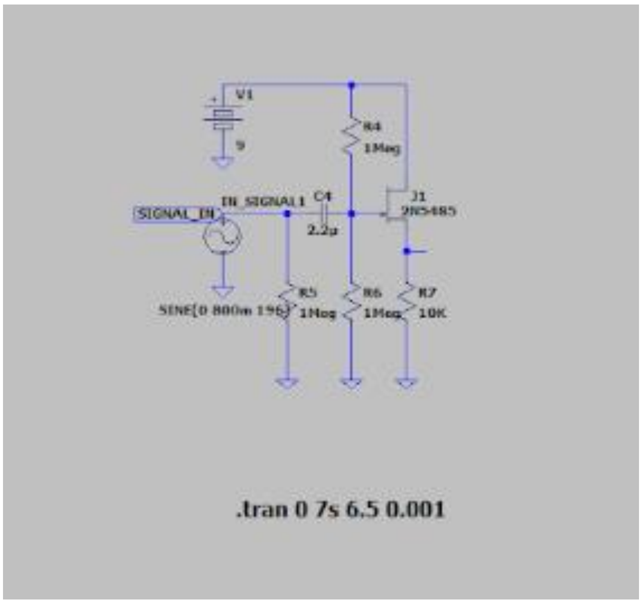


Figure 59

After passing C2 and R16, the output becomes centred around a lower voltage and low frequency oscillation starts to take place. C4 gives a distinct low frequency oscillation to the current and provide small current to the base of the transistor.

The use of R5 and R6 is to give a more distinct low frequency oscillator shape and give a lower base voltage to Q1, and a higher Vout.

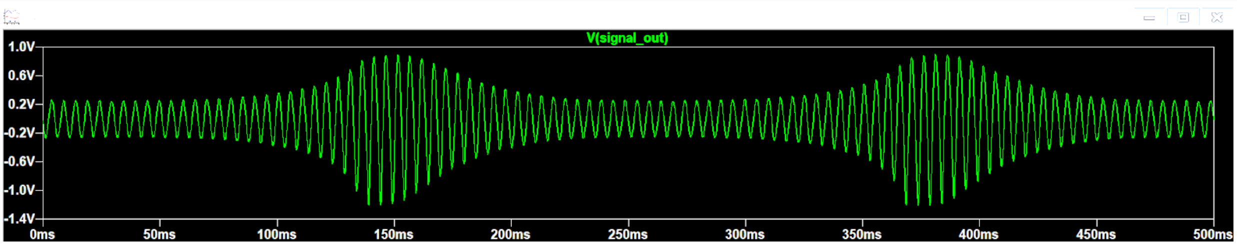


Figure 60: Simulation with R5 and R6

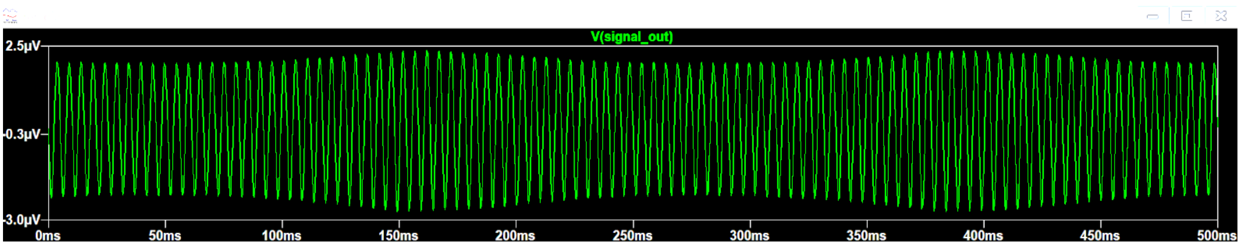


Figure 61: Simulation without R5 and R6

The mosfet, J2 is essential for low frequency oscillation to take place.

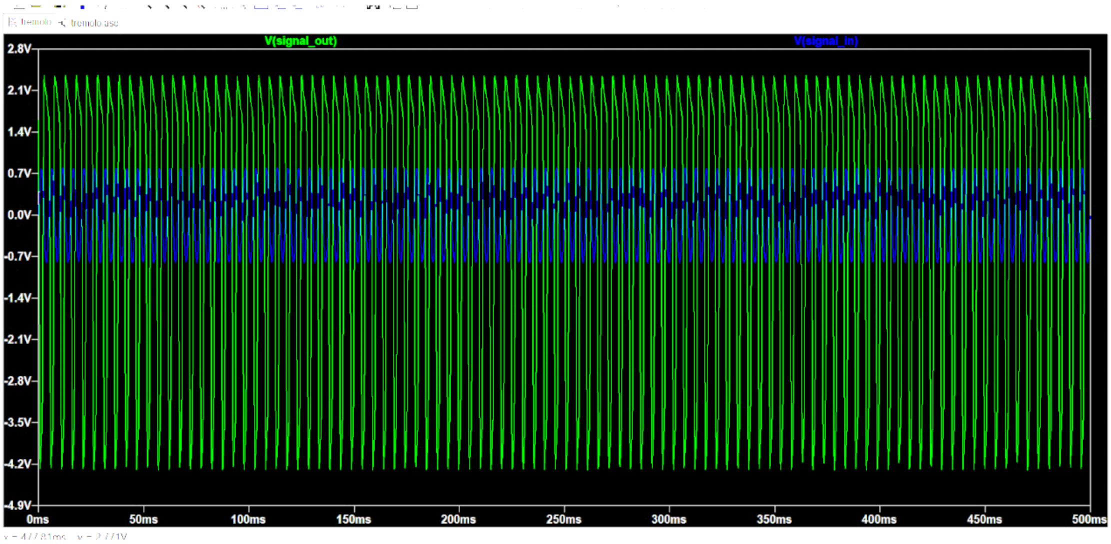


Figure 62: Simulation without J2

Without J2, the output will not be tremolo.

There is a phase shift oscillator around Q2. Around Q2, it can be seen that it is a common RC phase shift oscillator with a transistor functioning as an active component as an example.

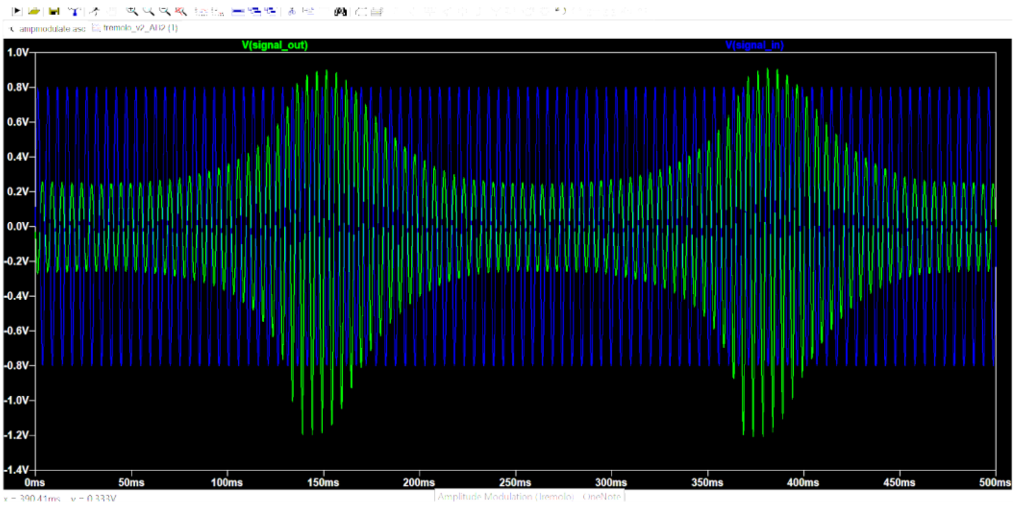


Figure 63: Output

After consultation, we decided to further reduce the number of components by eliminating the first part of tremolo. This is because the only use of the first part is just for amplification and this can be made by the VCA.

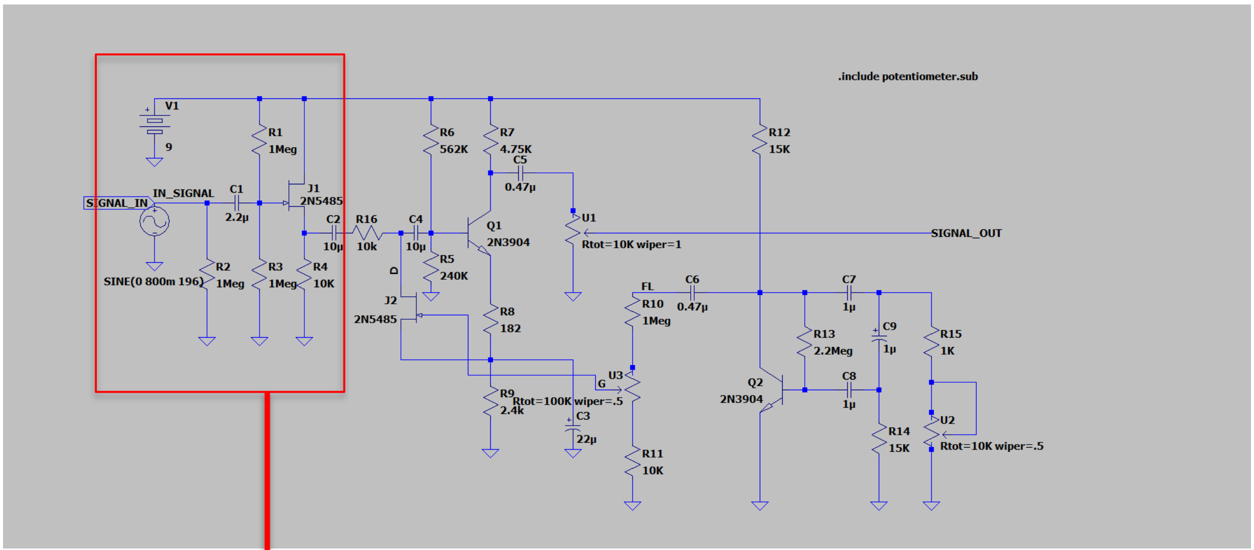


Figure 64

Eliminate this part

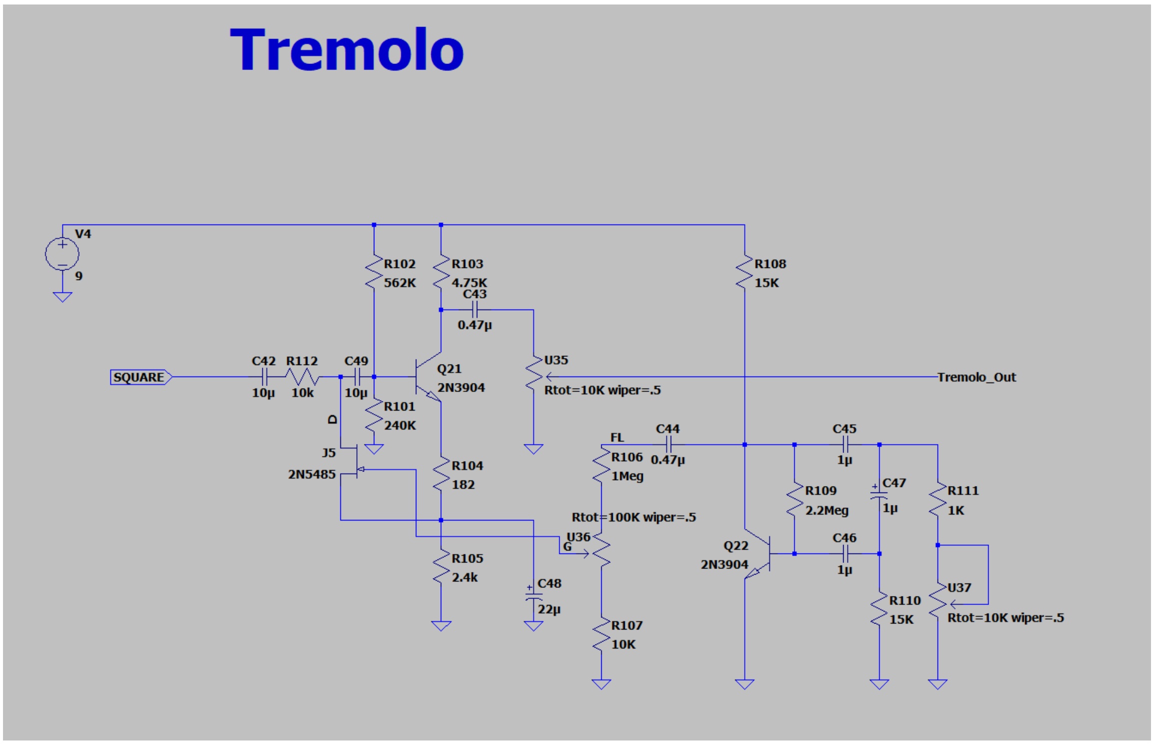


Figure 65: Final circuit after elimination

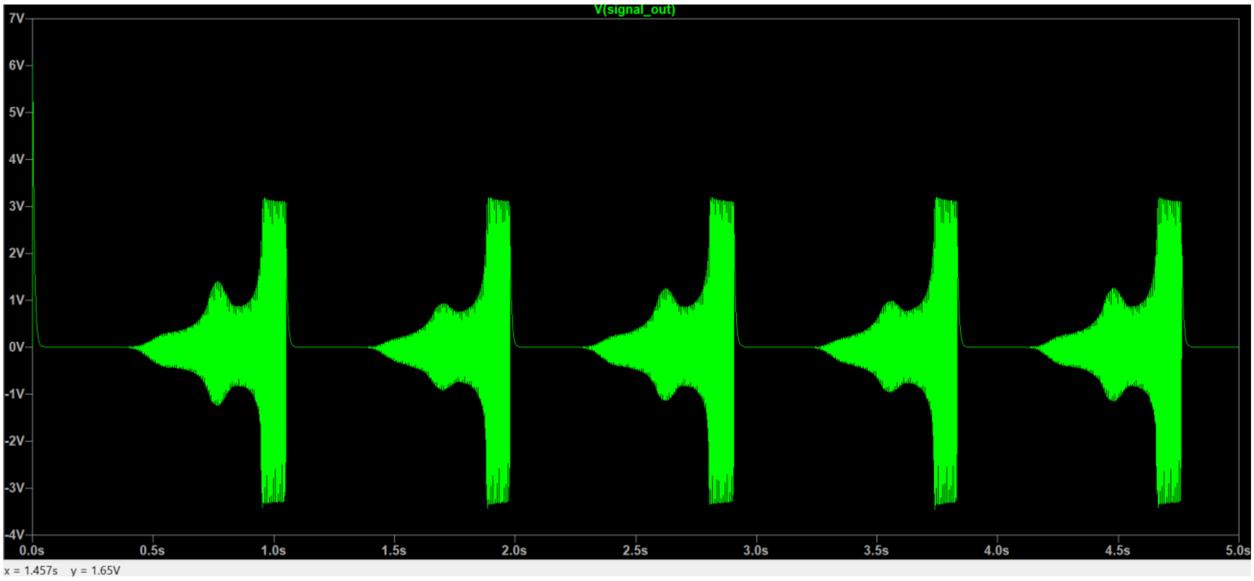


Figure 66: Waveform of output of tremolo before elimination of components

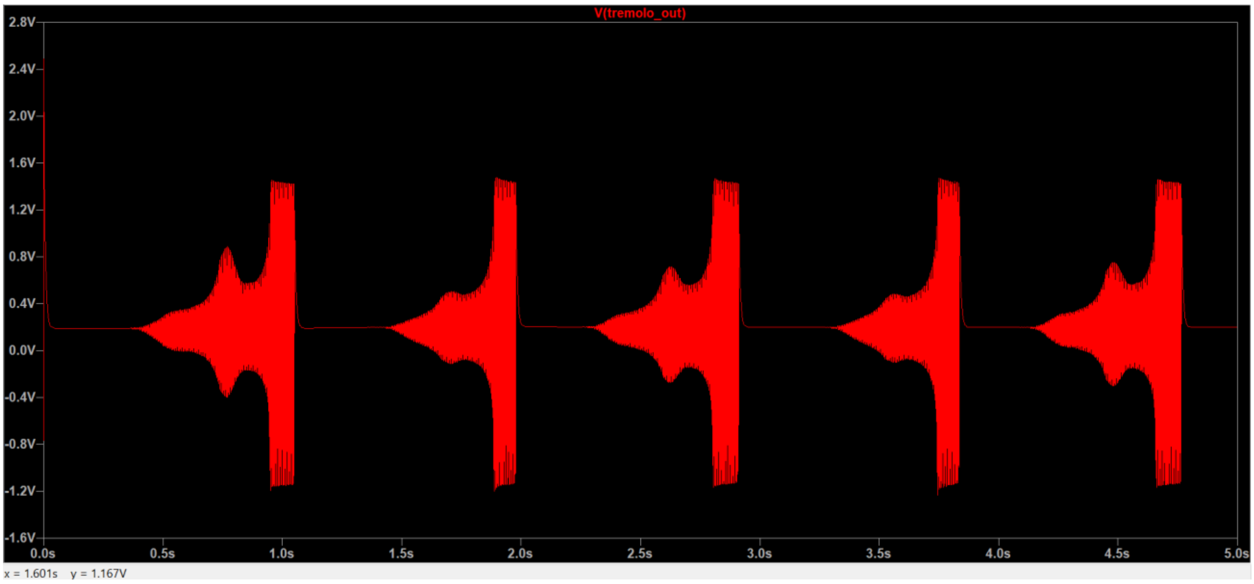


Figure 67: Waveform of output of tremolo after elimination of components

3.8 Pulse Generator

Introduction:

Pulse generators are mainly used in electronic circuits to generate rectangular pulses. The pulses generated can be used to initiate logic functions or sub-circuits such as an envelope generator [41].

Process:

As no behavioral components are allowed in the final design of the synthesiser, we had to replace the voltage source that generates pulses in our ADSR design. And since a keyboard that produces gate and trigger inputs is very complicated to build, we decided to build a pulse generator that will be connected to the ADSR.

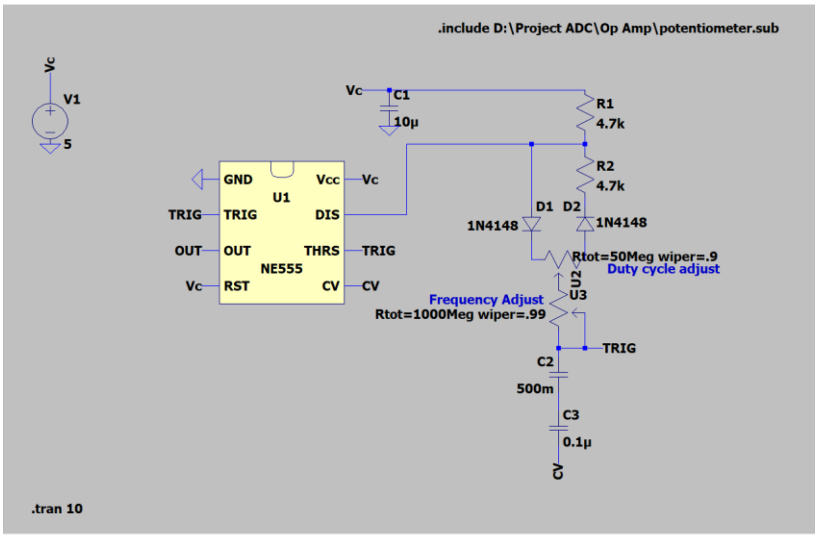


Figure 68: 555 pulse generators

Circuit explanation [42, Fig. 68]:

The charging time of C2 is determined by diodes D1 and D2. The duty cycle is adjustable by trimming U2. The frequency of the rectangular pulses can be set by trimming U3. The duty cycle (d) can be calculated from U2 and U3:

Equation 8: d=1+U2/U3

The frequency, f, can be calculated using:

Equation 9: $f = 0.69/(2 * U3 + U2 + 4.7k) * C2$

Simulation:

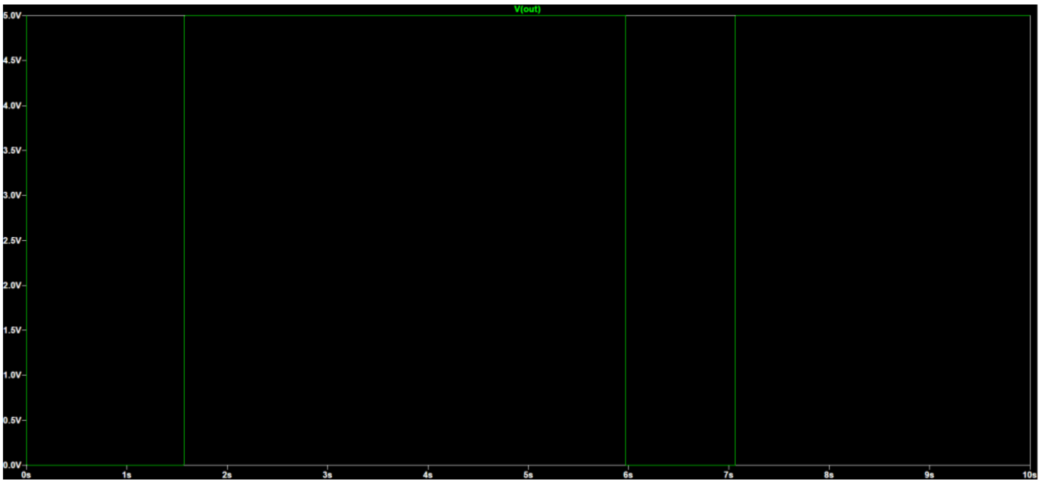


Figure 69

From the simulation, the duty cycle is approximately 73.2%. Frequency of the rectangular pulse is 182.5mHz.

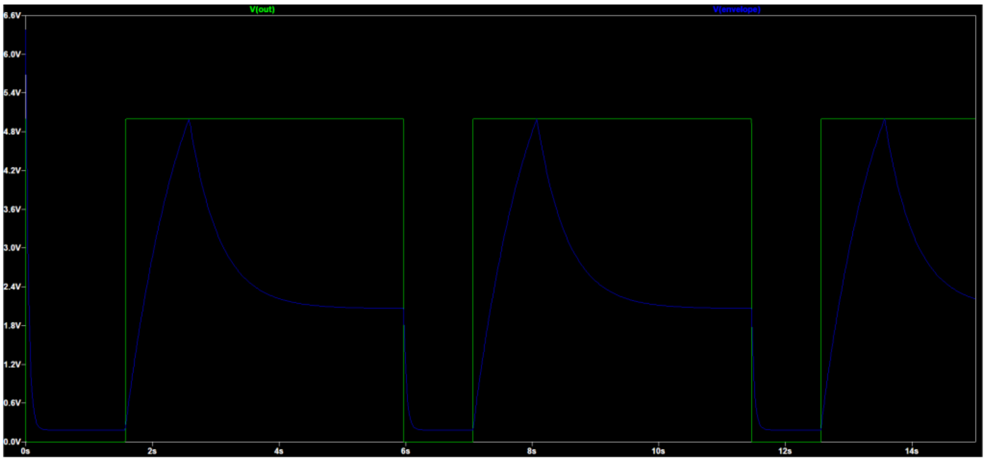


Figure 70: Waveform of ADSR(Blue)when connected to pulse generator

Reflection:

If we have more time, it would be more practical to build a keyboard that is able to produce gate and trigger inputs for the ADSR. With our design, the user has to manually adjust the frequency of the pulse generator to produce envelopes that follow the length of a note played.

4.0 TROUBLESHOOT

Keyboard:

1. There was a 0.2mV uncertainty in the voltage output.
   Solution: Build a simpler keyboard that only uses only 7 voltage sources and 7 resistors. Uncertainty is negligible. This method also reduces cost.

VCO:

1. First VCO built could only accommodate one input that is a sine wave whereas we are required to have 7 inputs.
   Solution: Increased functionality by building a VCO that has an input adjust and exponential converter.
2. VCO built does not have a perfectly linear output.
   Solution: Build a VCO that does not use components that performs imperfectly at low voltages.
3. Noisy output
   Solution: Added capacitors parallel to voltage sources.

VCF:

1. VCF output sounded very noisy
   Solution: Fine tune the frequency range of the VCF so that only the fundamental frequency can pass through the band pass filter.
2. Traces of transient voltage at the start of the waveform.
   Solution: Added a pull-down resistor, Added a buffer between output of VCO and input of VCF. However, spikes only reduced slightly with only a little improvement on the audio, hence the buffer and resistor are removed after cost-benefit analysis.

VCA:

1. Output of VCA was not linear
   Solution: Added two emitter resistors in the long-tailed pair differential amplifier to improve linearity.

5.0 FINAL CONNECTION AND RESULT

For the final connection, we decided to connect the vibrato to the voltage-controlled filter as it functions as to modulate the frequency of the note produced. The tremolo is connected to the voltage-controlled amplifier as it is functioning as an amplitude modulator. The ADSR is connected to the VCA to envelope the signal and dictate the overall duration of attack, sustain, decay and release. For the ADSR, to reduce the need of a signal generator as stated in the requirement, a pulse generator is connected to the input of the ADSR. In general, the connection should start from the keyboard to the VCO. Then, the VCO's output is connected to the input of the VCF. And lastly, the VCA is connected to the output of the VCF. The whole schematic is as below in Figure 71.

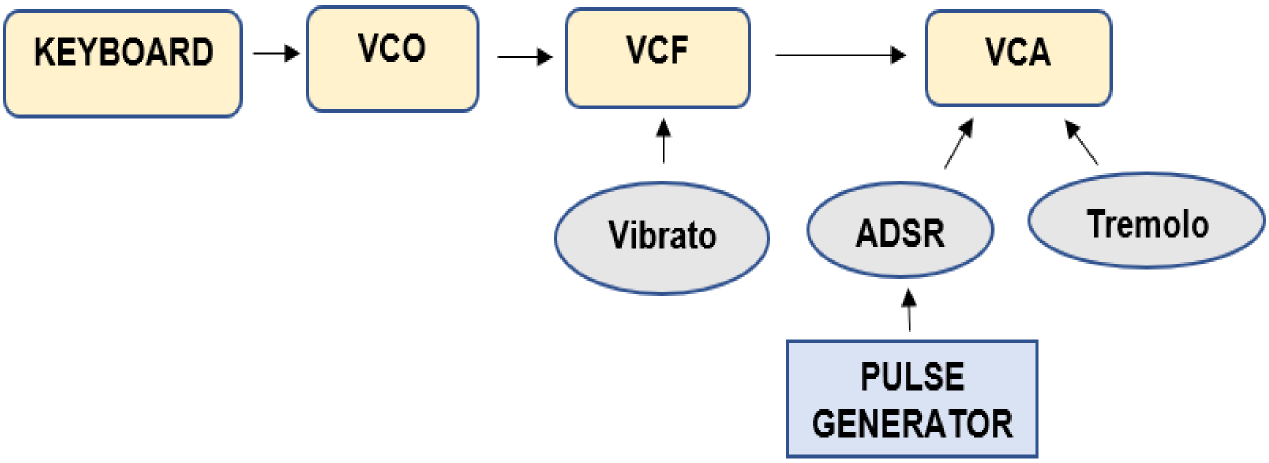


Figure 71

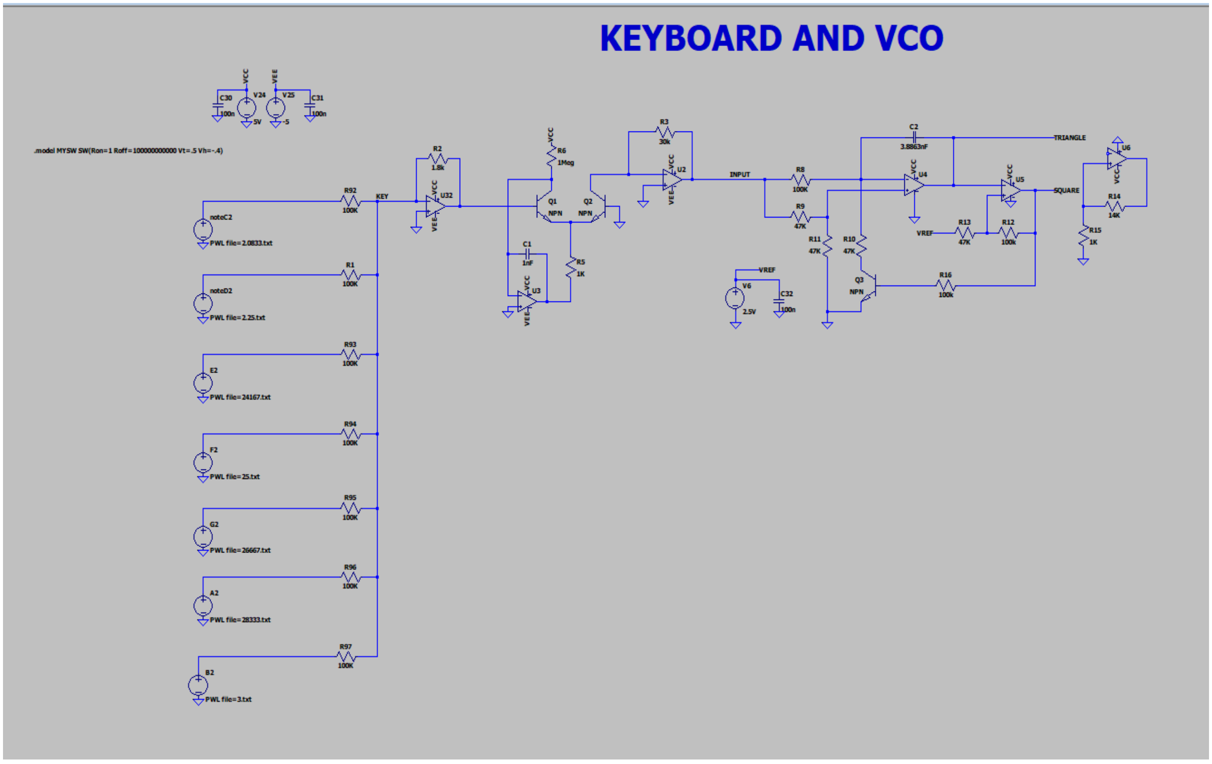


Figure 72: Keyboard and VCO

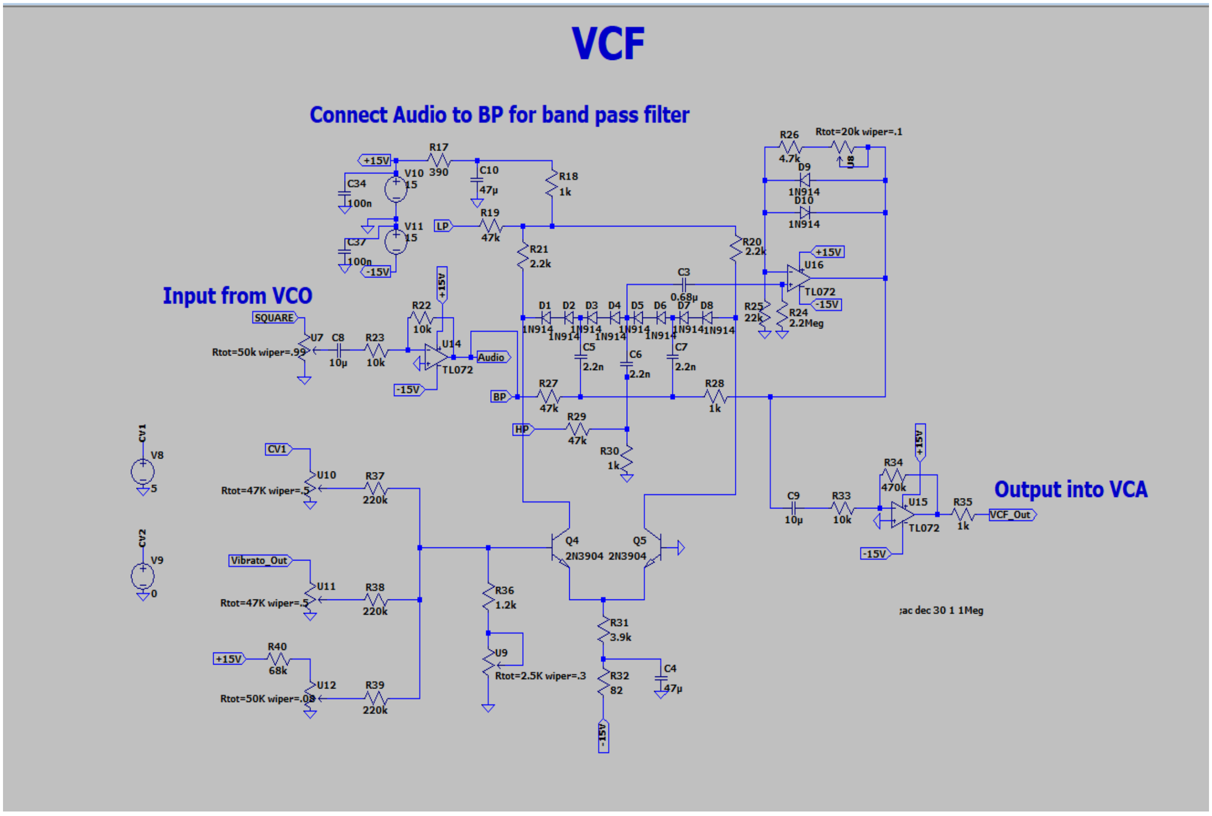


Figure 73: VCF

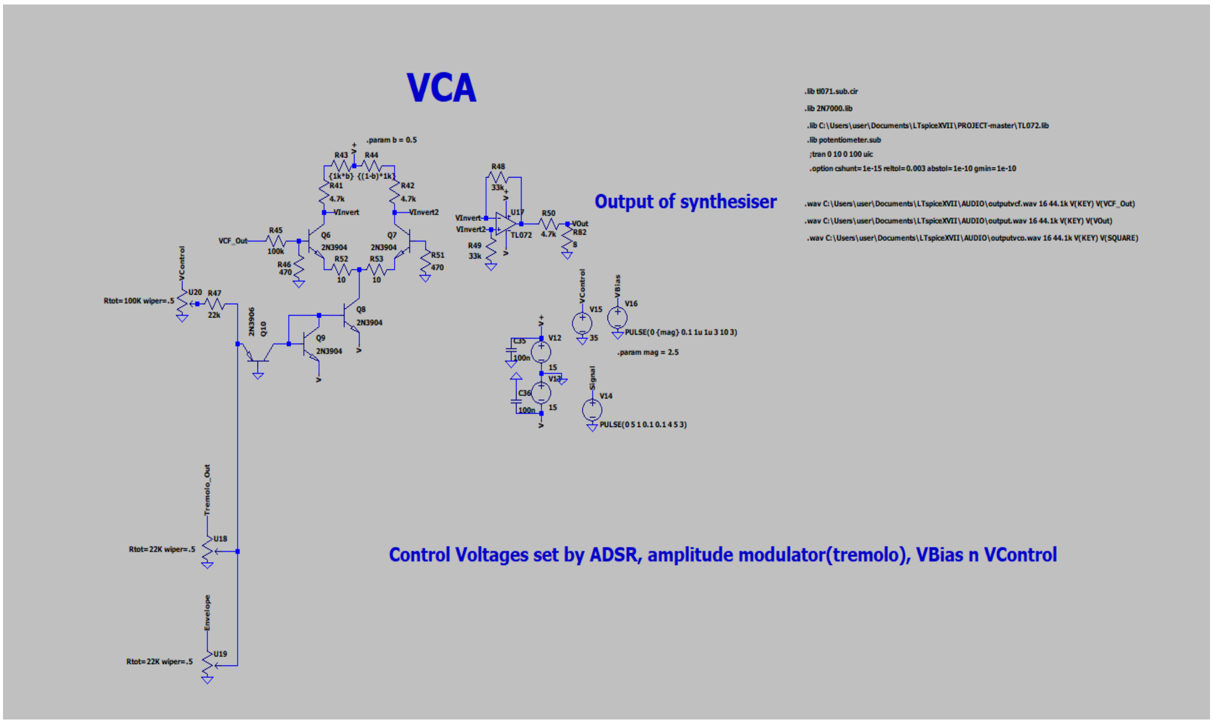


Figure 74:VCA

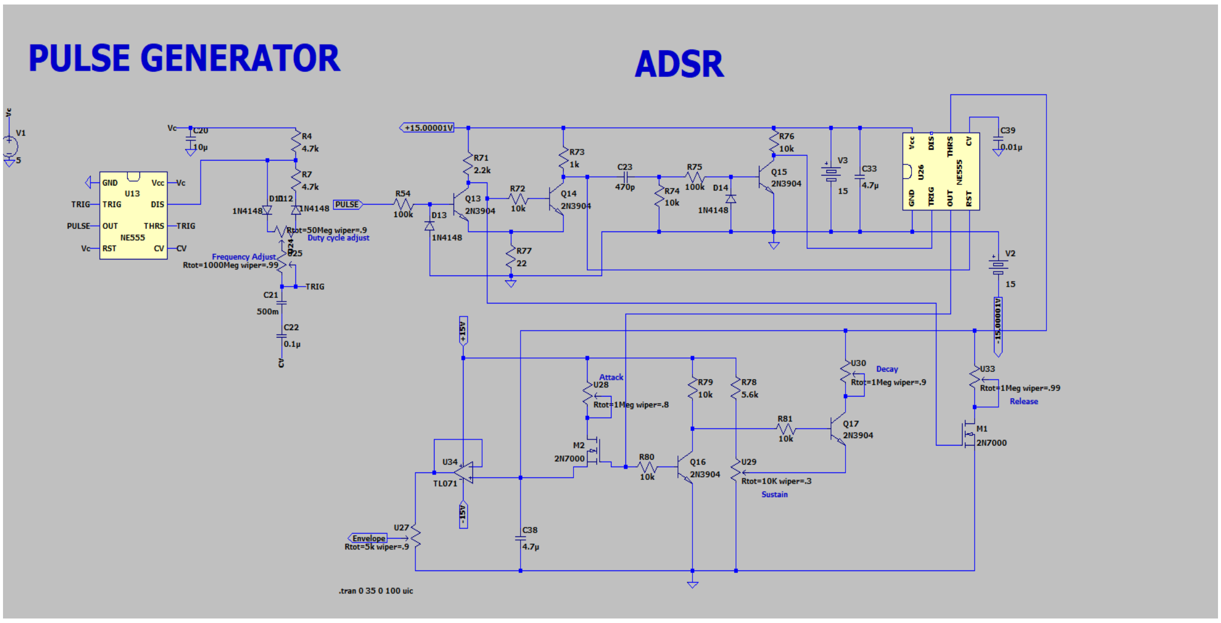


Figure 75: Pulse Generator and ADSR

To solve parallel voltage sources error in LTSpice, the voltage sources in ADSR have been temporarily replaced by batteries. Tests have shown that they produce the same results.

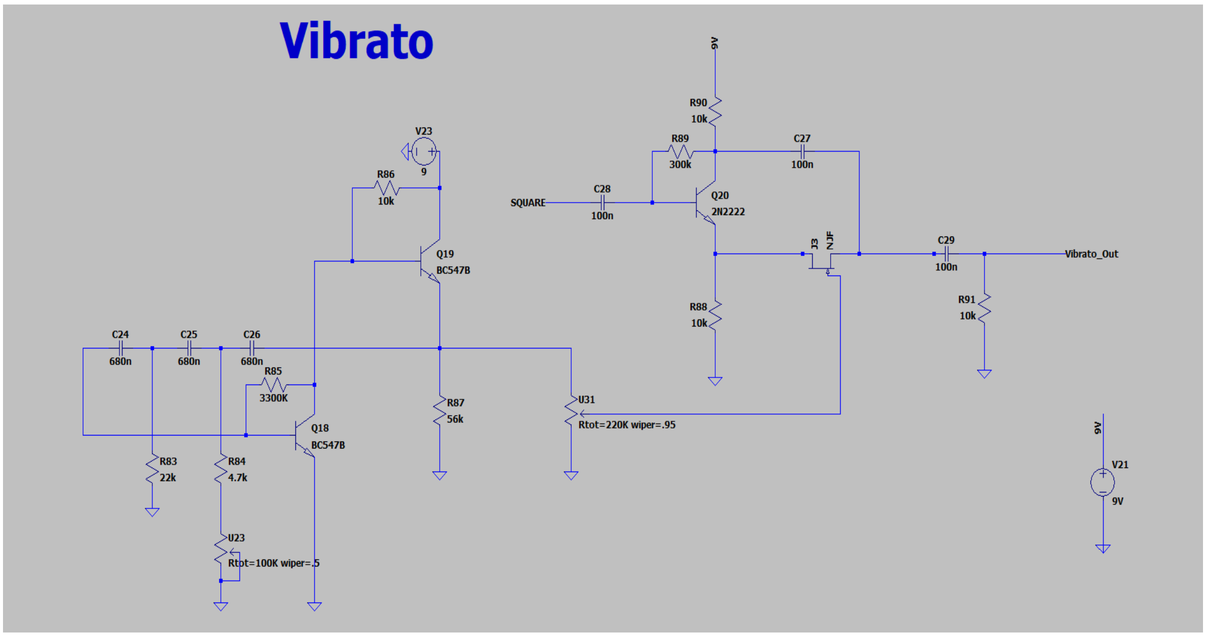


Figure 76:Vibrato

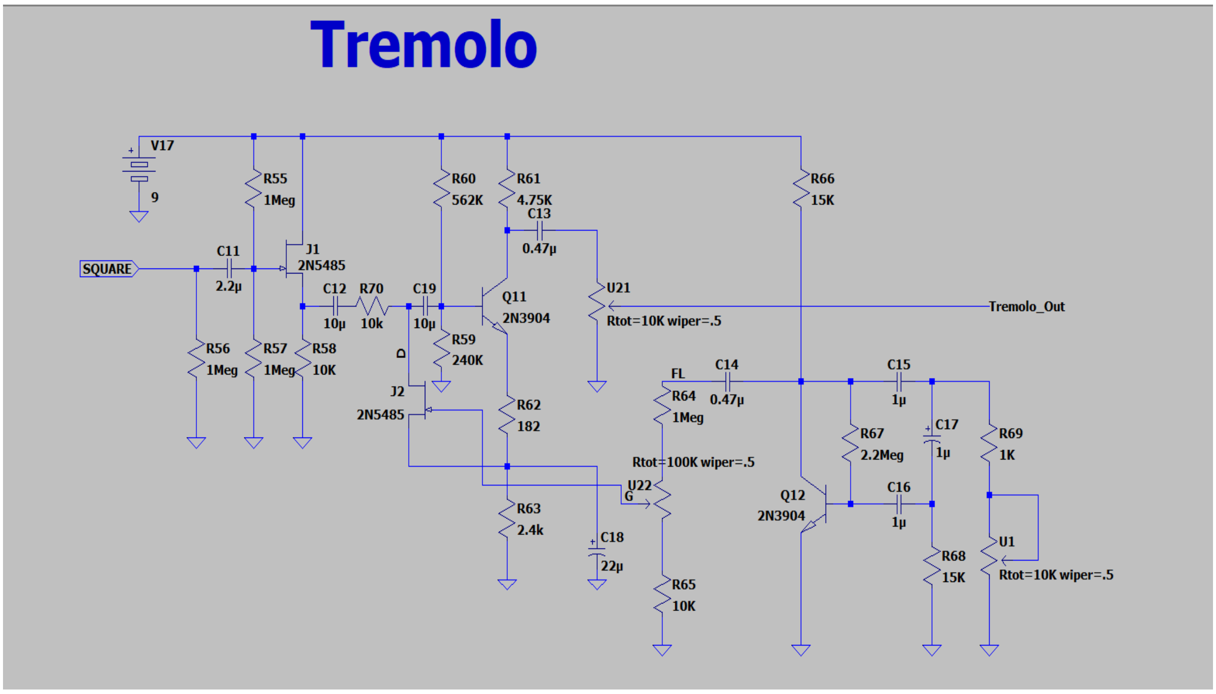


Figure 77:Tremolo

The final waveform is shown as below.

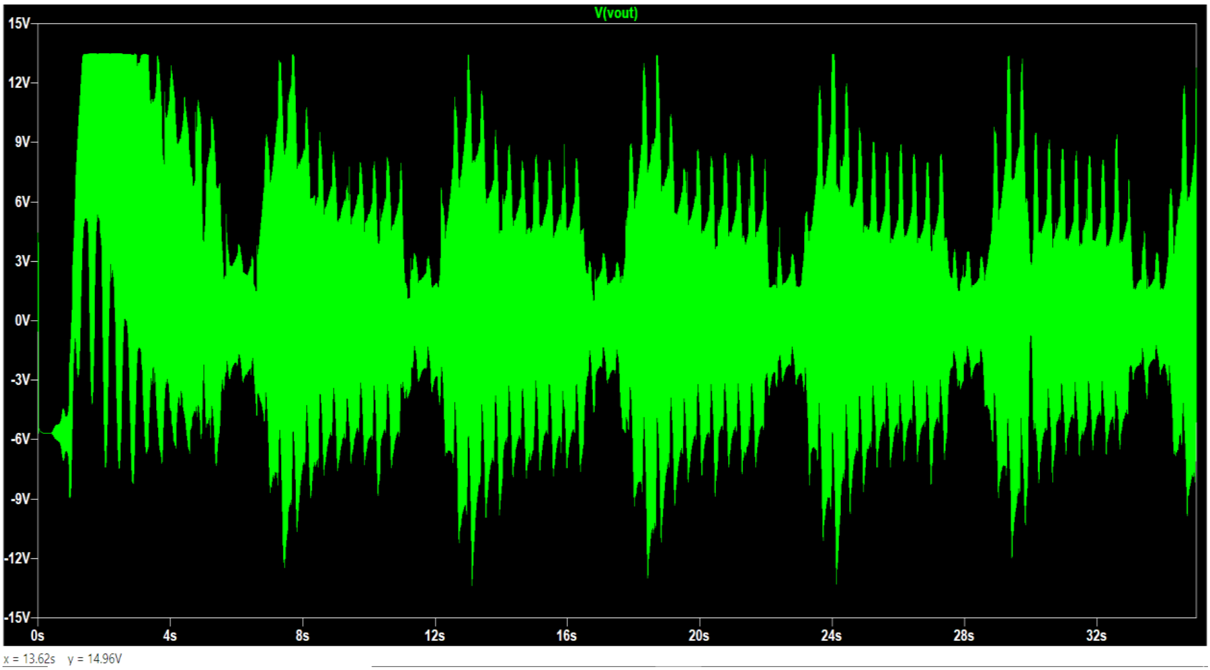


Figure 78:Voltage Out

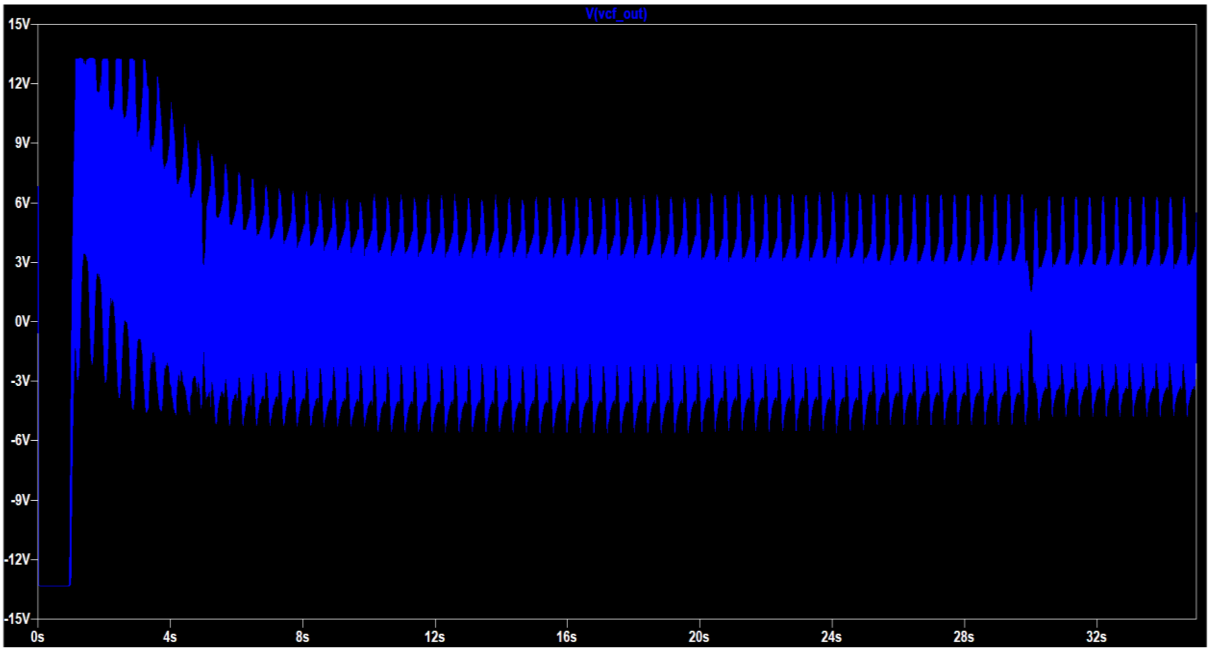


Figure 79: Output of VCF

At the end, the circuit managed to generate note C4, D4, E4, F4, G4, A4 and B4 as expected from the Table 1

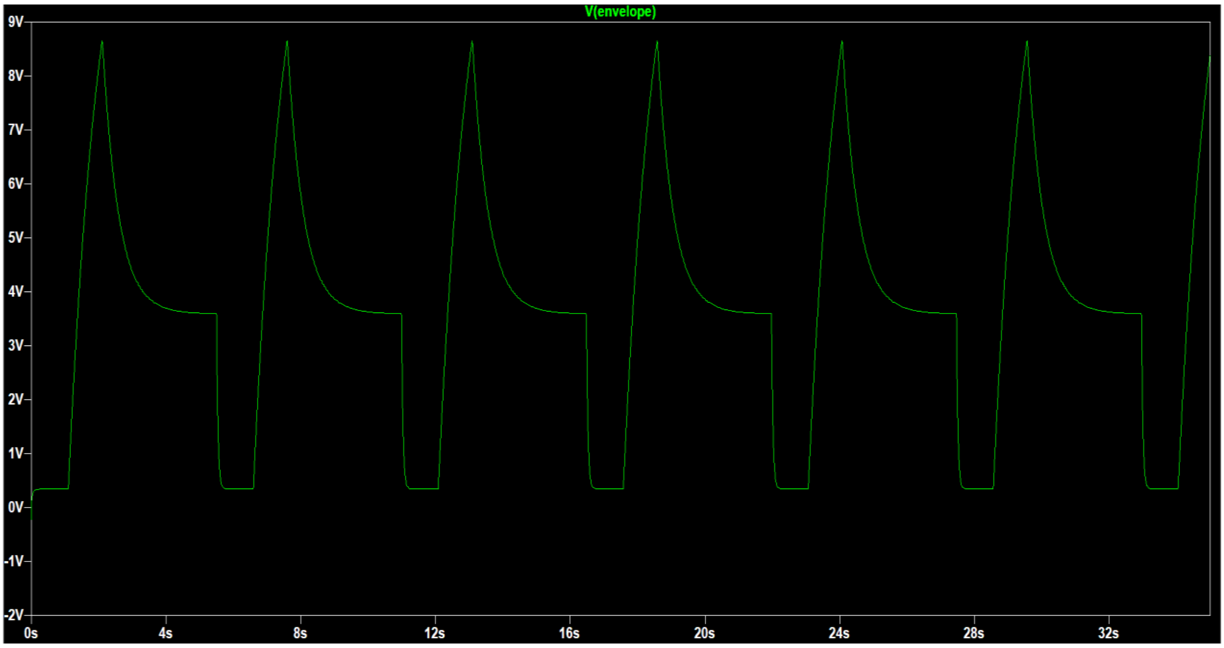


Figure 80: Output of envelope

6.0 SPECTROGRAM ANALYSIS

The MATLAB script was simulated using the original script in blackboard and added a line

ylim([0,1.0]);

as accordance to piazza because the original script causes the frequency range to go from 0 Hz to 20 kHz. We managed to simulate it note by note from C4 to B4. C4 was the first note to be simulated as in Figure 81 without any vibrato and tremolo effect to see the note clearly. D4. To see the spectrogram clearer, we eliminated the effect of tremolo and vibrato initially.

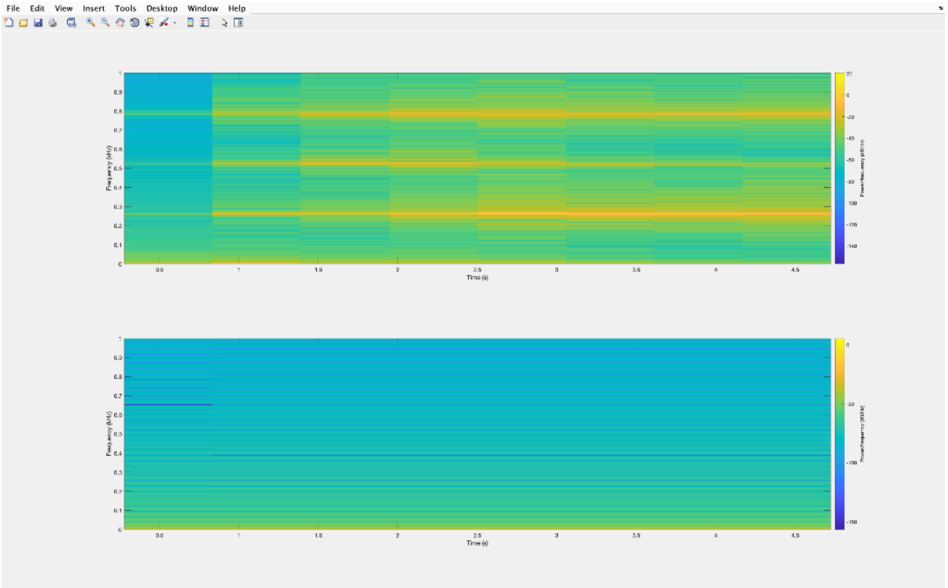


Figure 81:C4 without tremolo and vibrato

As the filter is not perfect, some of the harmonic signals will pass the filter and causing them to be visible at the output. It can be seen from the two yellow lines on top of the fundamental C4 frequency of approximately 260 Hz.

However, the second harmonics can be seen much weaker than the other two, this is expected as the signal started by generating a square wave and they are known to have odd harmonics.

Overall, the notes represent the correct idea of C4 that has a fundamental frequency of 262 Hz, and second harmonics at 524 Hz and third at 786 Hz.

To illuminate the effect of vibrato and tremolo, the circuit was simulated with the note C4 with vibrato and tremolo effect. The result is in Figure 82.

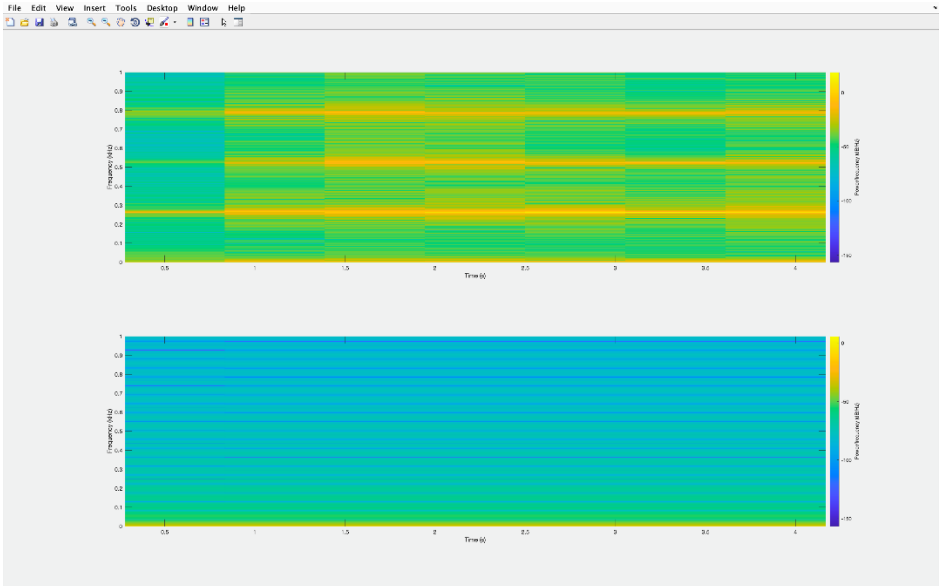


Figure 82: C4 with tremolo and vibrato

From Figure 81 and Figure 82, it can be seen that with AM and FM, the yellow colour seems to be more intense as a result of the modulation. This is true based on the effect of tremolo on spectrogram as referred in [43, Fig. 83]. However, the effect of vibrato seems to be not as apparent as tremolo.

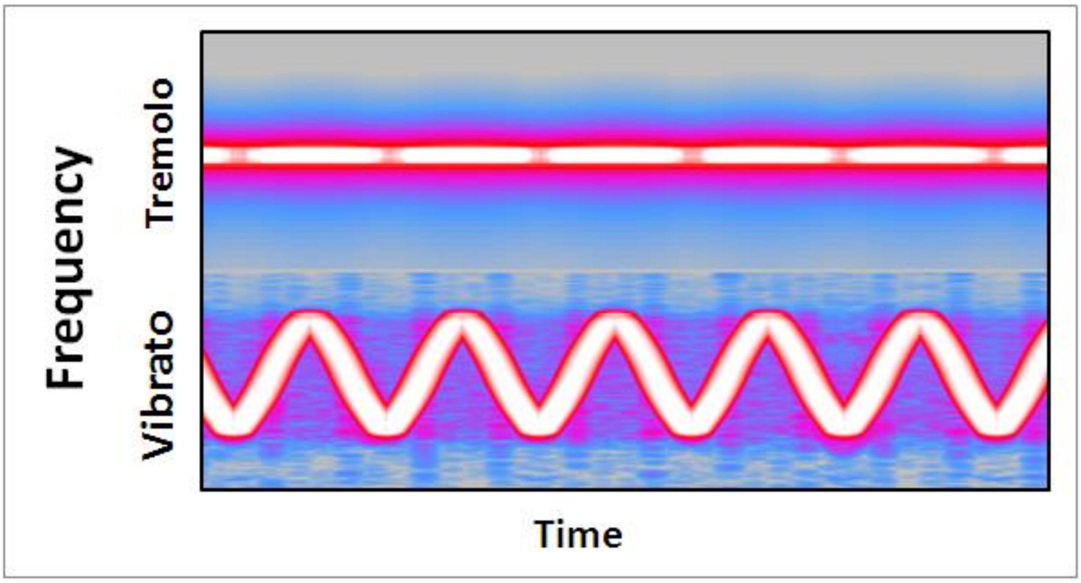


Figure 83: Vibrato and tremolo effect

To further see the discrepancies between both effects, the circuit was simulated with vibrato and tremolo separately as in Figure 84 and Figure 85.

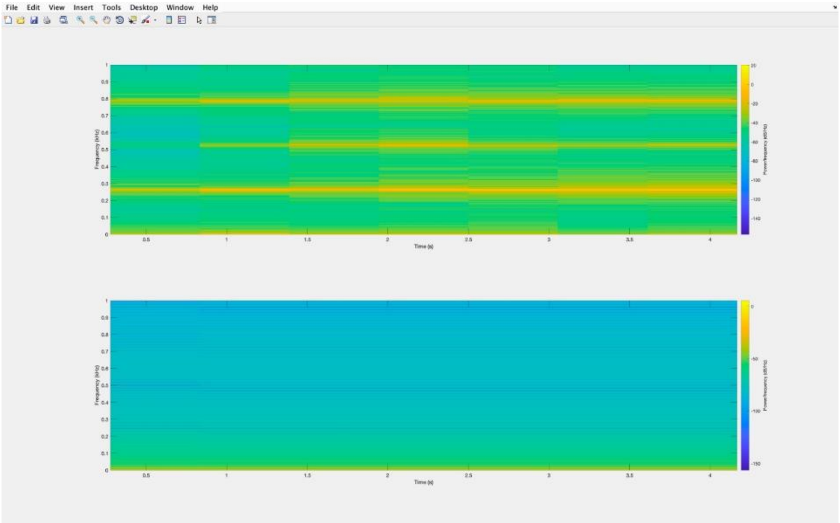


Figure 84: C4 with tremolo

From Figure 84, it can be seen that tremolo causes the yellow lines spectrogram of C4 to be much intense. Also, the onset of the tremolo can be seen from the start of time. This proves that the tremolo effect is apparent in the spectrogram and affects the final sound.

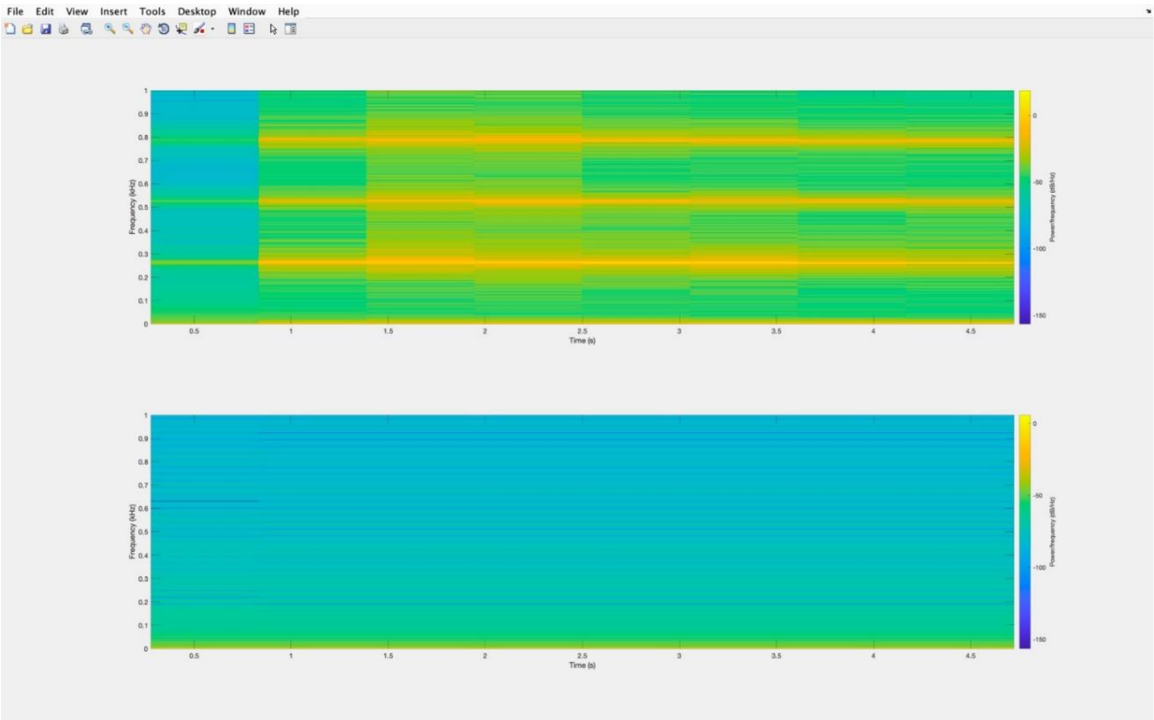


Figure 85: C4 with vibrato from 0 to 1 kHz frequency

However, when the circuit is simulated to highlight the vibrato effect, the effect does not seem as apparent as the tremolo. The MATLAB code was changed to see the effects clearer by scaling the y-axis from 0 to 25 Hz, however the vibrato effect was still unclear.

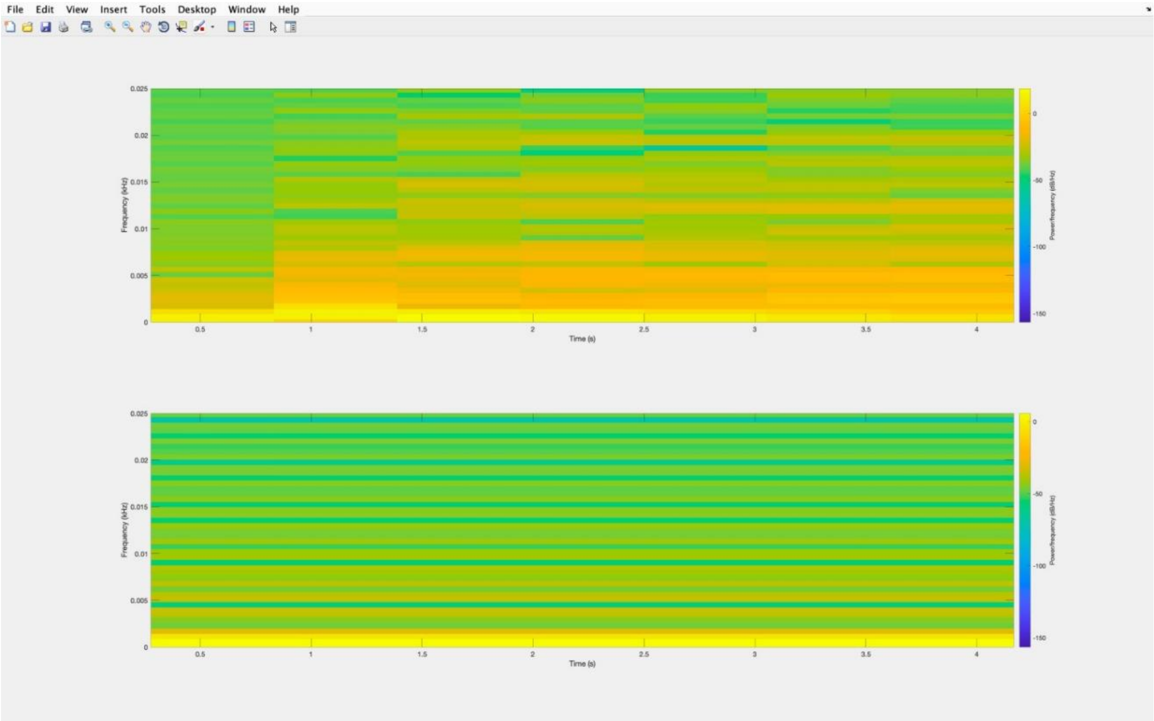


Figure 85:C4 with vibrato from 0 Hz to 25 Hz

After consultation, it was explained to us that the vibrato pattern can only be seen if the vibrato frequency is low, so that the peaks and troughs are not close together. This is as seen as in Figure 86[44, Figure 86].

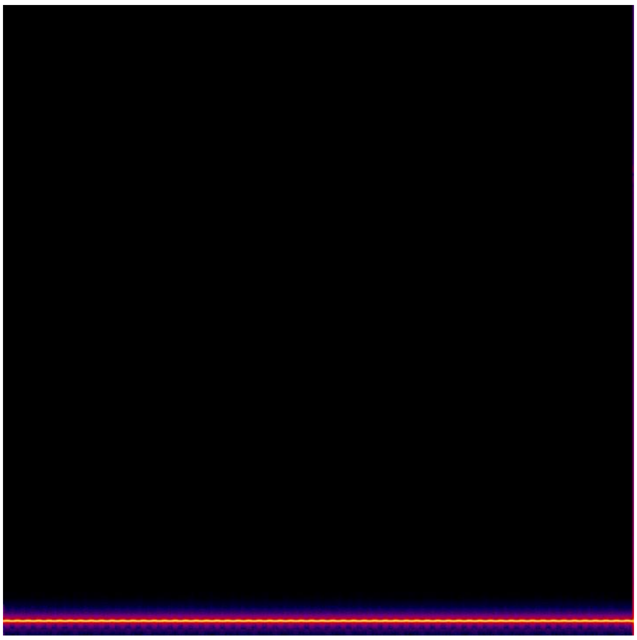


Figure 86:Vibrato at frequency 6 Hz

With a high vibrato frequency, the lines will just appear wider. As the frequency of the analog synth's vibrato is around 200 Hz, this explains why the lines appear as in Figure 85.

From figure 6.0 and figure 6.1, it can be seen that with vibrato and tremolo, the yellow colour seems to be more intense as a result of the modulation. This is true based on the effect of tremolo on spectrogram as referred in [42]. However, the effect of vibrato seems to be not as apparent as tremolo.

Plotted the spectrogram for the different notes produced by our analog synth and got the figures below (Figure 87 to 92). Table 2 displays the fundamental frequency, second harmonics and third that complies with the figures (Figure 6.31 to 6.36).

Note	Fundamental Frequecy	Second Harmonics/H	Third Harmonics/Hz
C4	262	524	786
D4	294	588	882
E4	330	660	990
F4	350	700	1050
G4	392	784	1176
A4	440	880	1320
B4	494	988	1482

Table 2

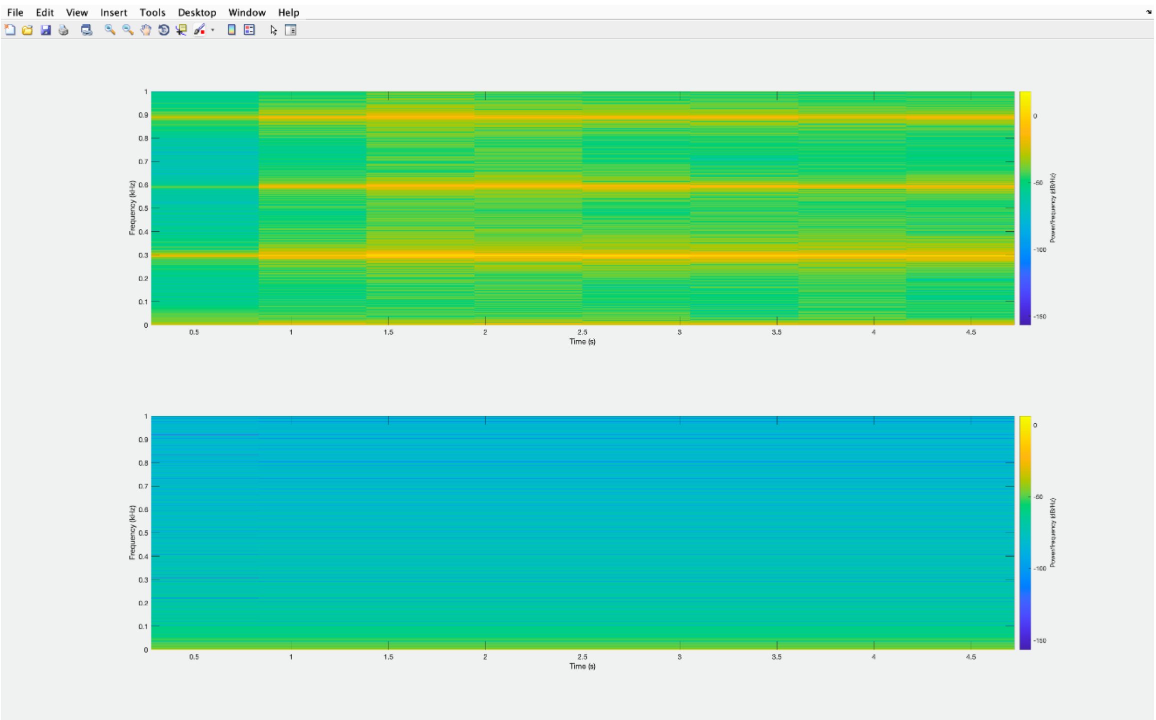


Figure 87: D4

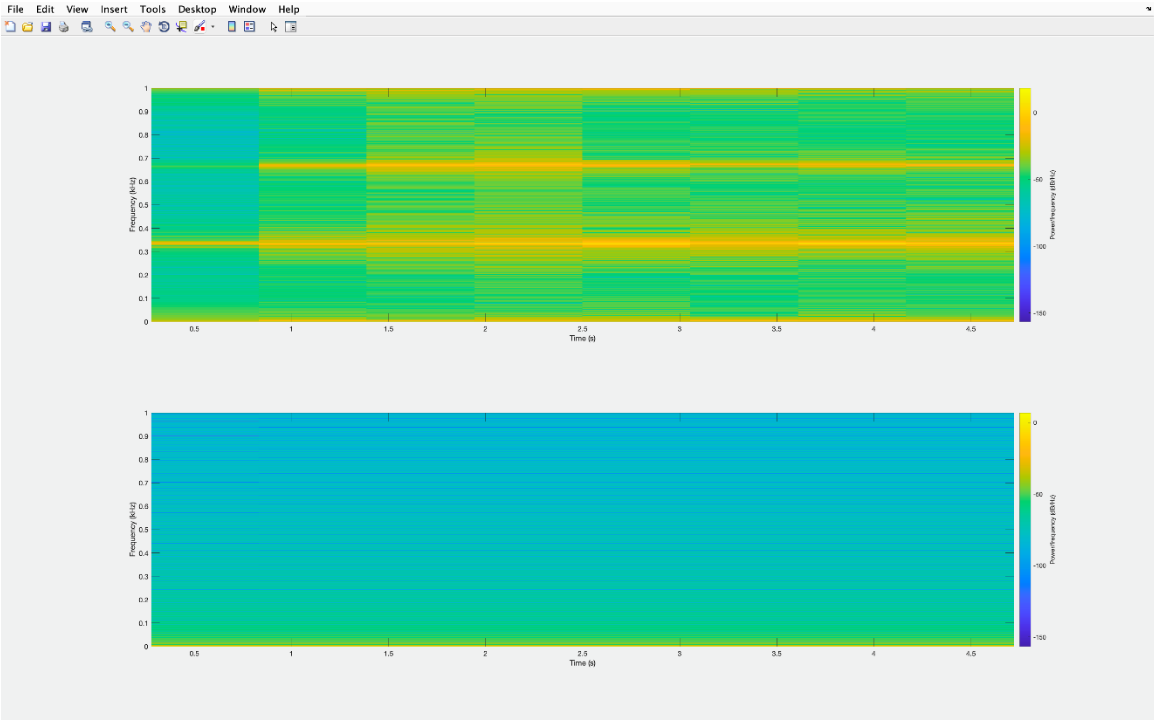


Figure 88: E4

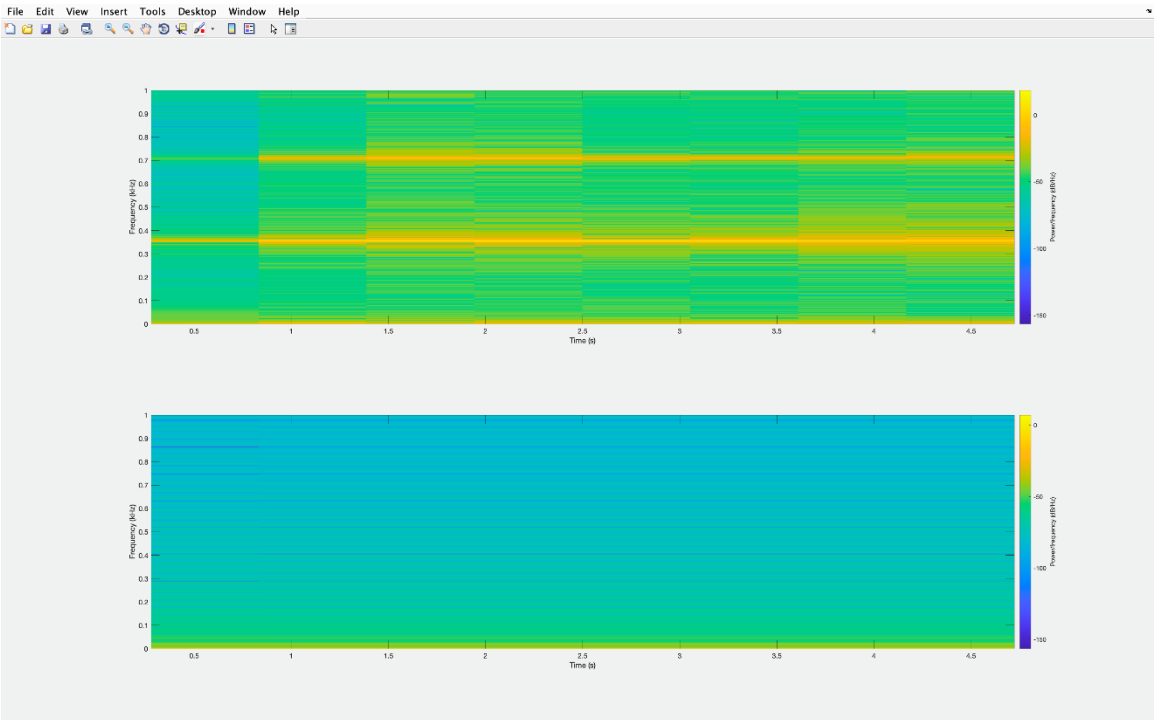


Figure 89: F4

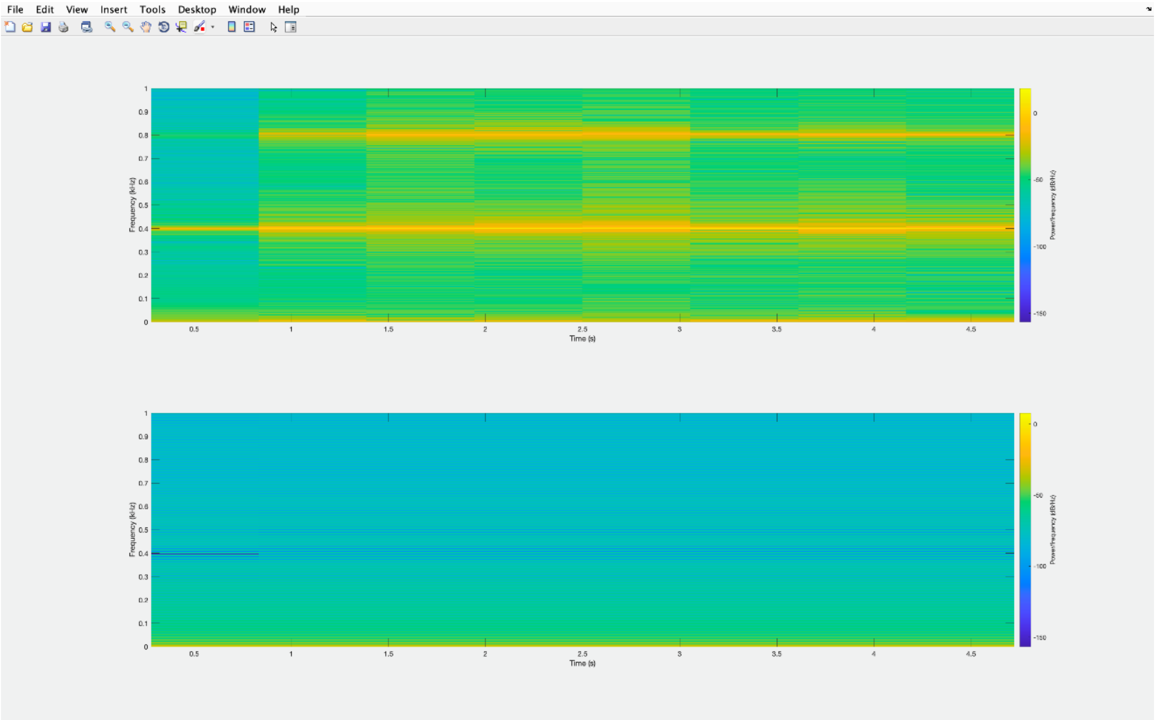


Figure 90: G4

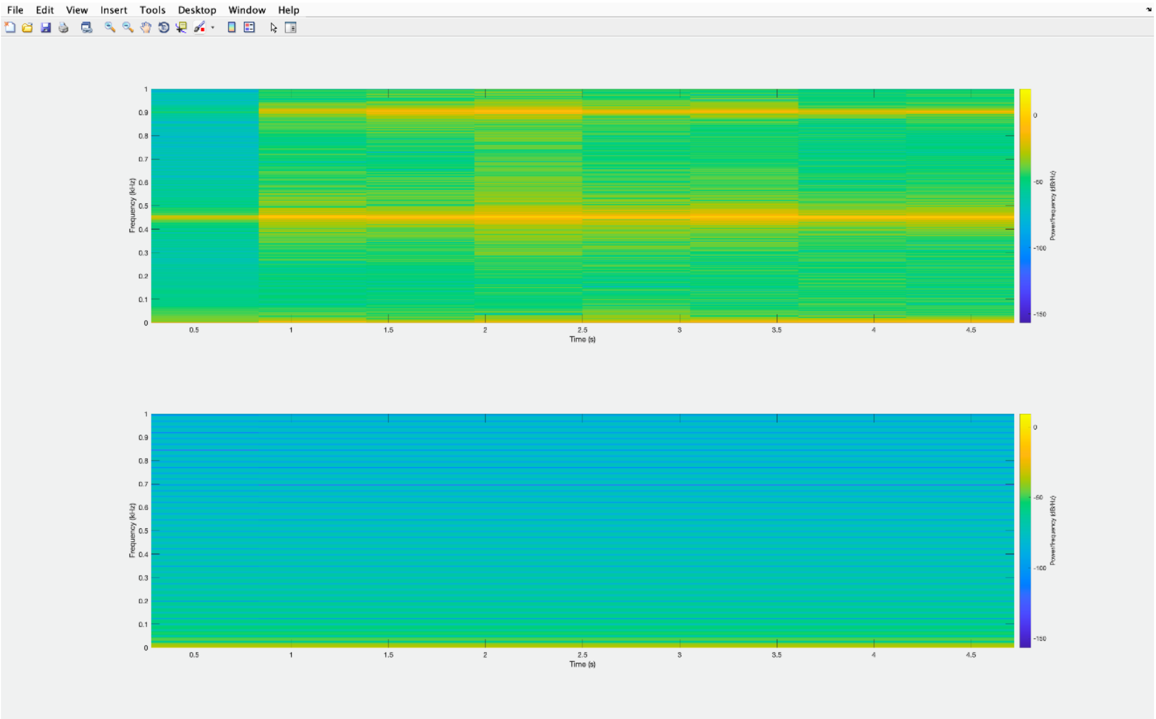


Figure 91: A4

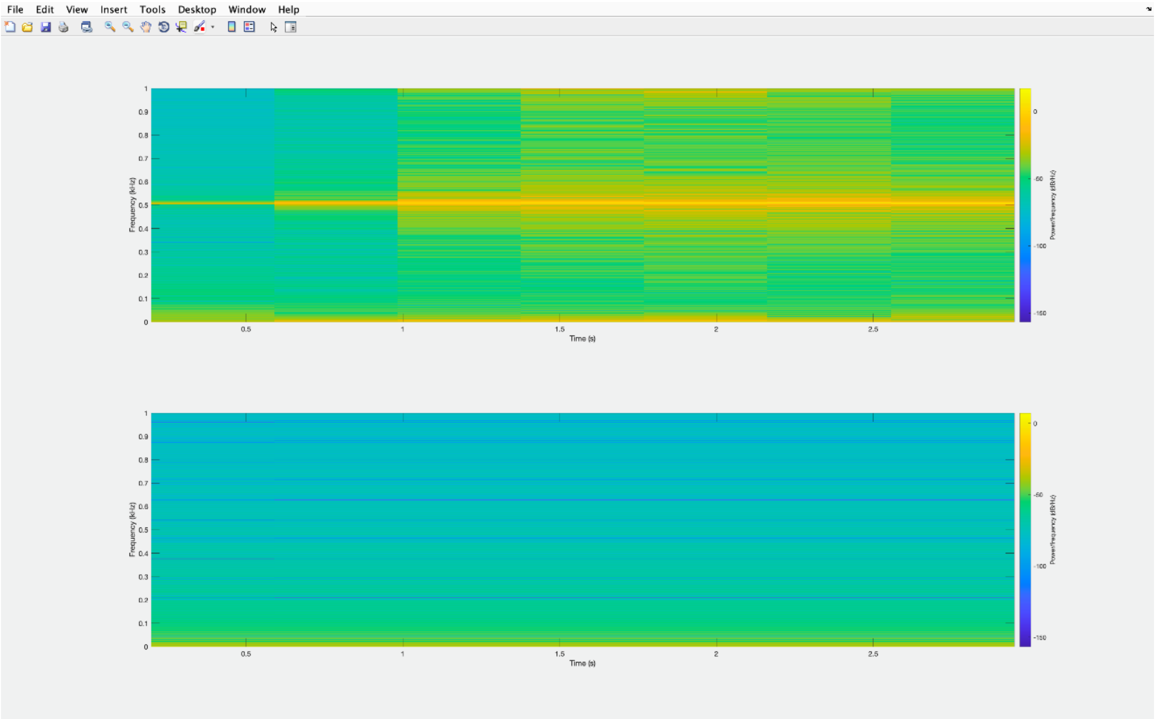


Figure 92: B4

From the spectrograms, one can see the 1st, 2nd and 3rd harmonics of the fundamental frequency. Although the VCF is designed to filter the frequencies such that only the 1st harmonic passes through, the VCF is not perfect, hence there are still traces of the 2nd and 3rd harmonic. On top of that, the scale of the spectrogram is written in dB, which is a logarithmic scale, hence it is sufficient to say that the difference in signal looks similar.

Taking note C4 as an example, it is showing approximately the fundamental frequency, 261Hz and its 2nd and 3rd harmonics, 522hz and 783Hz respectively. It can also be seen that the 2nd harmonic appears to be weaker than the 1st and 3rd harmonics, which is expected for a signal which starts off as a square wave.

We used MATLAB initially to plot the result of our output. However, to compare the outputs to a normal sound we use a web-based audio to spectrogram converter stated in [45].

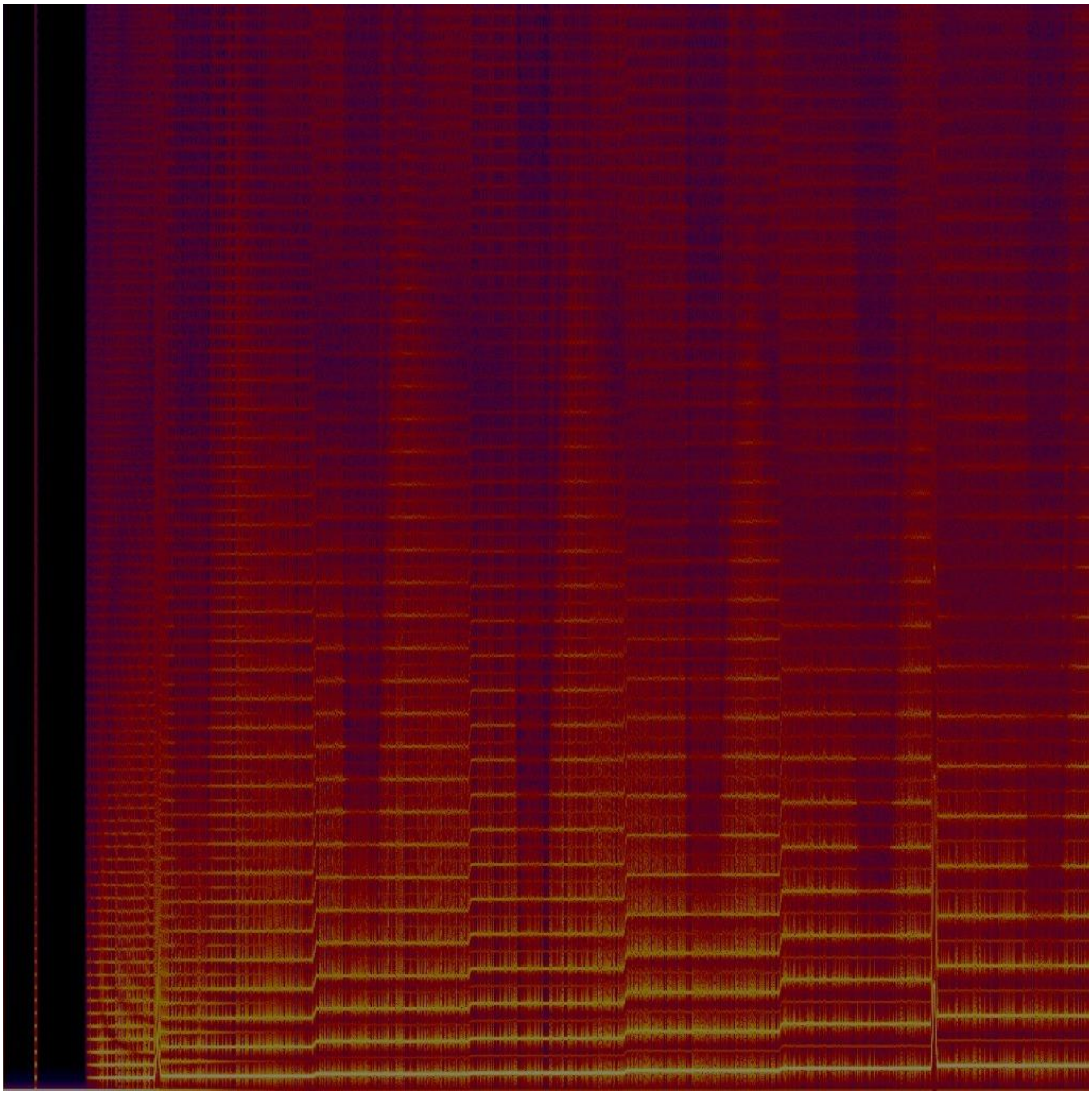


Figure 93: Spectrogram for 7 notes of analog synthesiser without vibrato and tremolo

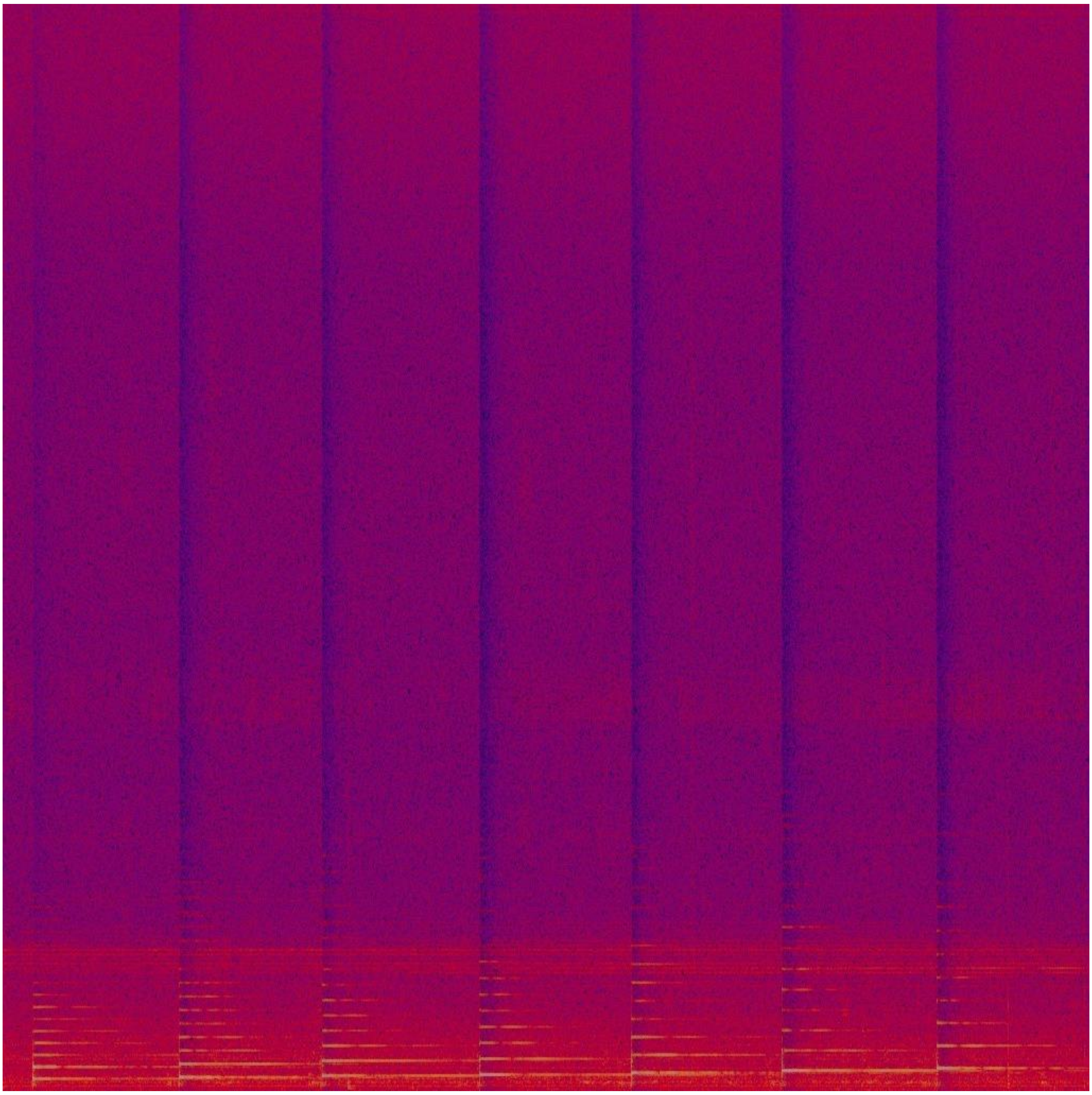


Figure 94: Spectrogram for 7 notes on piano without vibrato and tremolo

It can be seen that both diagrams seem to be not similar. This is because instead of an analog synthesiser, we used a piano to confirm that the synthesizer is producing the right notes. The difference in colour also can be attributed to different amplitudes of both audios. Also, it was hard to make sure the audio from the piano has the same continuous sounds as in the analog synth audio, as they start to decrease in amplitude after about 3 seconds, hence giving the non-similar spectrograms. Besides that, there is also a certain minimal degree of noise and vibrations in the analog synth audio which may also contribute to the difference between the two spectrograms.

However, comparing both spectrograms, it can be seen that the analog synth spectrogram follows the same pattern of the piano in terms of the gapping between the lines as the notes increases. This explains that the frequency increases as the note increases.

7.0 QUALITATIVE ANALYSIS

Keyboard + VCO:

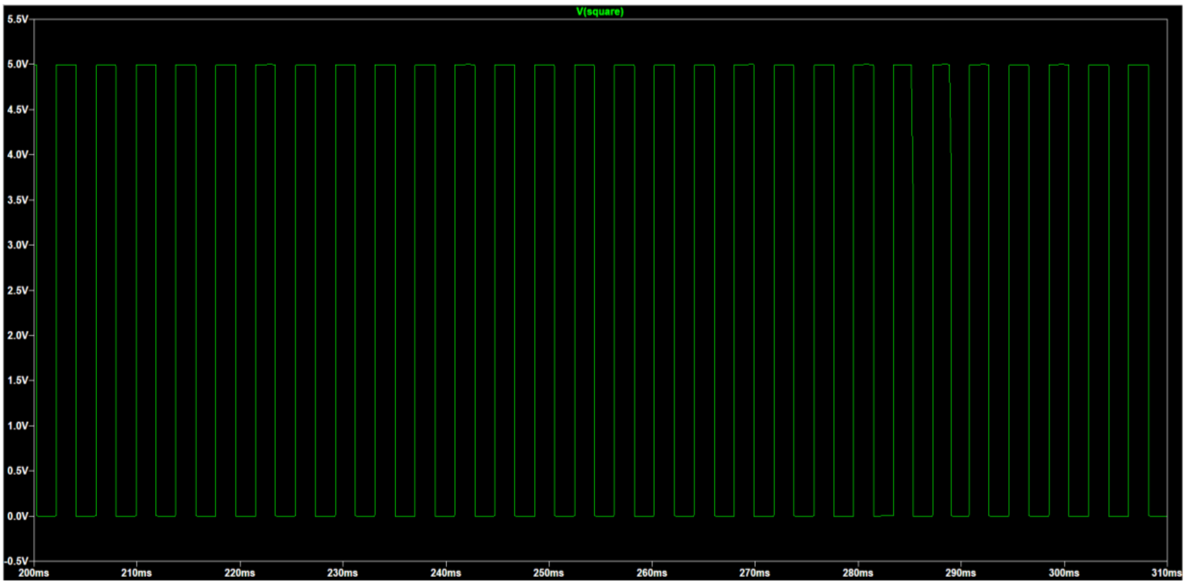


Figure 95

From the simulation, it can be seen that it is a perfect 5V square wave.
Audio file:https://drive.google.com/file/d/1ugzoC0ZsxsloOu-7QtHRo7HLDGkabqDa/view?usp=sharing

From the audio file, we can hear that there is a certain degree of noise in the background. This may be due to oscillator phase noise [46]. This kind of noise cannot be filtered by the VCF as this will also result in the removal of the oscillator signal.

VCF:

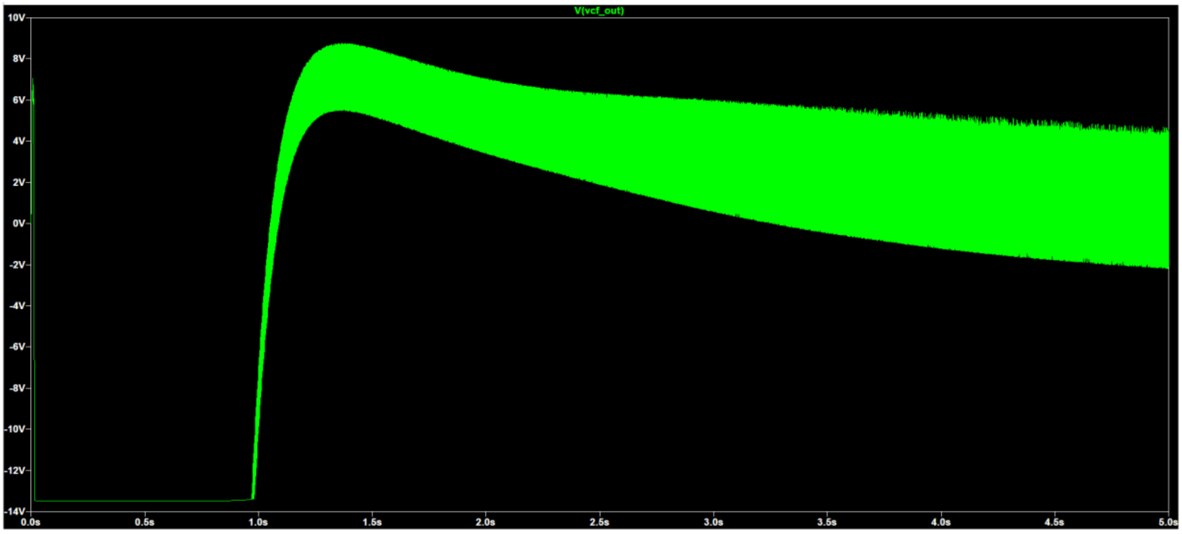


Figure 96

Figure 97

A square wave is made up of a fundamental frequency and its 2nd and 3rd harmonics. The output of the VCF shows an almost sine wave, showing that the band pass filter did filter out the 2nd and 3rd harmonic.

Audio file:

https://drive.google.com/file/d/1vCRpW_CA7x0Q7LUBGkhrflq_4loszvs3/view?usp=sharing

From the audio file, we can hear that the amplitude of the audio is not always constant, getting louder towards the end. There is also a beep at the beginning of the audio which is undefined. This may be due to transient voltage when the output of VCO is first applied to the VCF. It may be also due to the fact that there is no buffer between the output of VCO and the input of VCF, causing a loading effect. However, the noise from VCO did reduce slightly after passing through the VCF.

VCF+Vibrato:

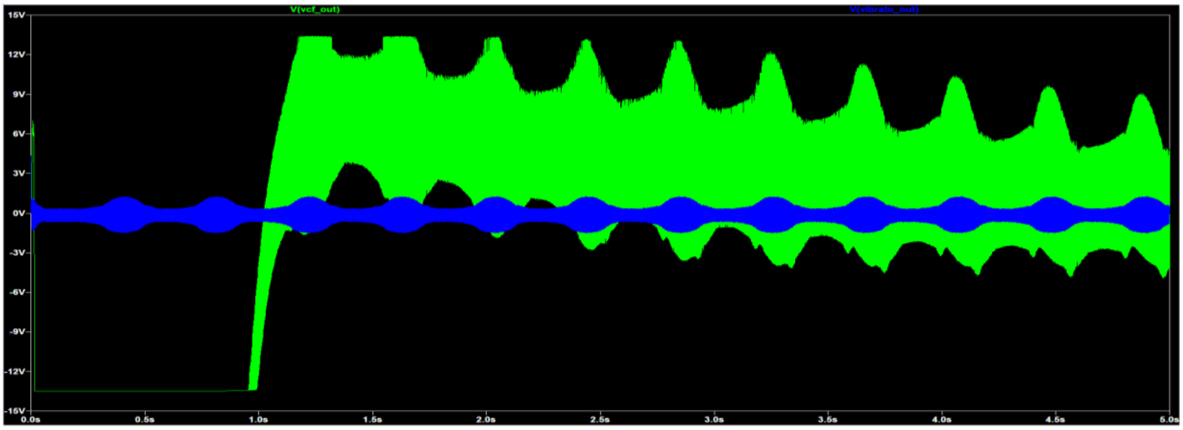


Figure 98

Audio:
https://drive.google.com/file/d/1kjw5tTMLPYKjXqJvqRdYtstBYbYACNO/view?usp=sharing

From the simulation, it can be seen that the waveform of VCF conforms to the shape of the waveform of vibrato. It can also be heard from the audio that there are changing tones, showing that the vibrato is performing as expected.

VCA:

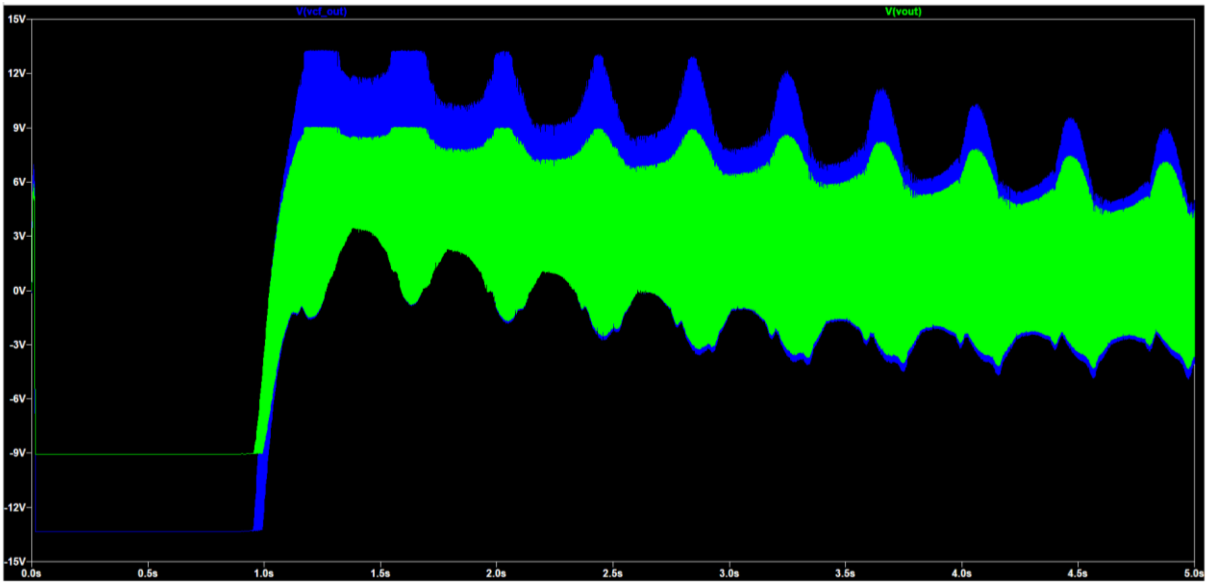


Figure 99

Audio: https://drive.google.com/file/d/1BxocQFxNR-lwgn2T8LMdF8xeoGPDflta/view?usp=sharing

The simulation shows that the waveform of VCA is following the shape of the waveform of VCF. The level of amplification can be controlled by trimming the potentiometer at VControl. Furthermore, the audio sounds like the output from VCF.

VCA+ADSR:

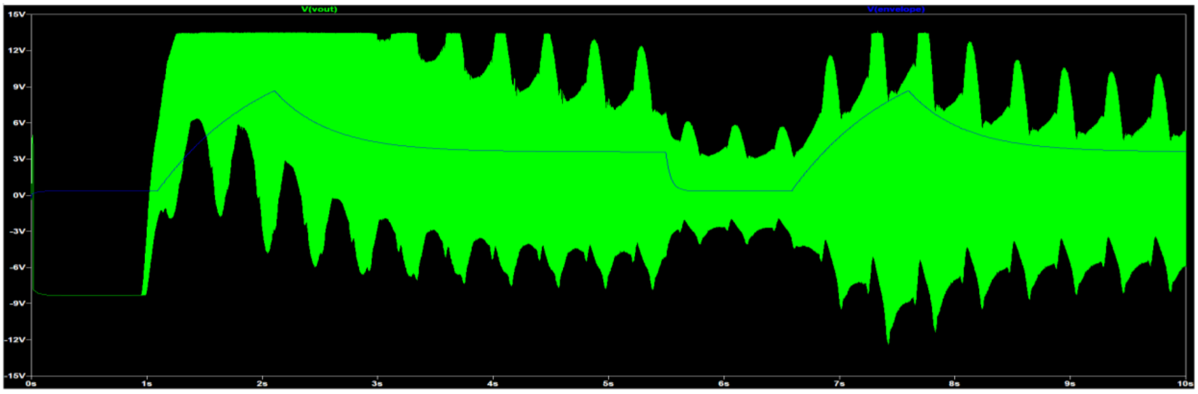


Figure 100

Audio: https://drive.google.com/file/d/1ePYenUfmSCKyuxD-BqVNlEMT-BaCq4uX/view?usp=sharing

From the audio file, we can hear that there is variation in loudness corresponding to the shape of the envelope generator. Hence, we can say that ADSR is working as expected.

VCA+ADSR+Tremolo:

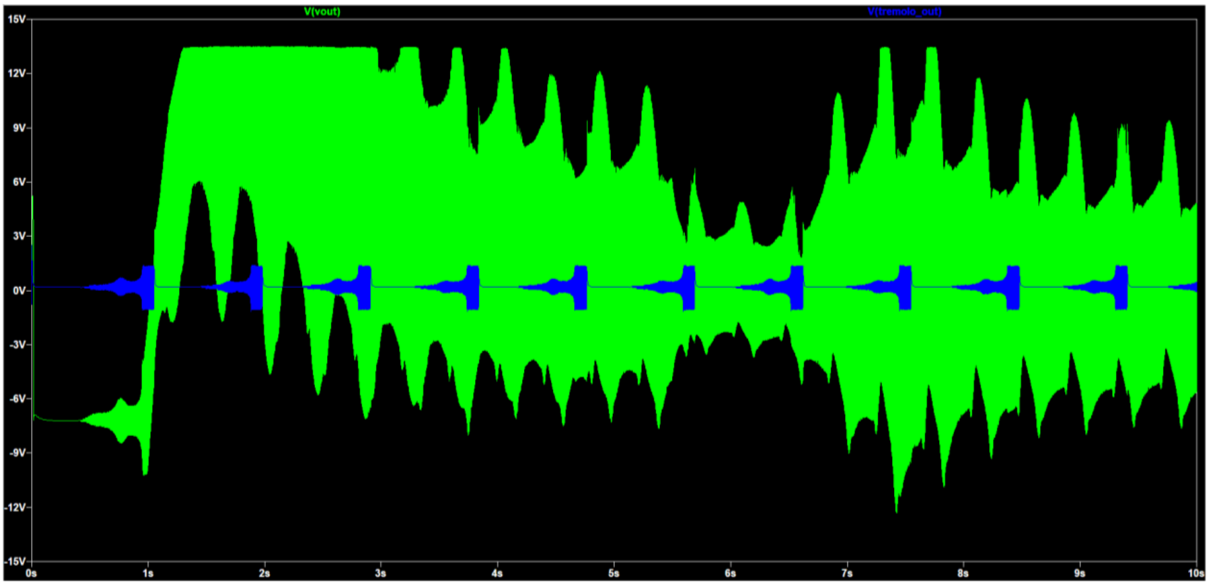


Figure 101

Audio: https://drive.google.com/file/d/1yERLVS_NqVbCito8s-0_OZ3qmym6BPnp/view?usp=sharing

From the audio file, the effects of tremolo and vibrato are a bit difficult to differentiate. However, judging from the shape of the waveform, it can be seen that tremolo does have an effect on the final waveform. There are also traces of exponential wave drop at the beginning of the tremolo waveform.

8.0 POWER CONSUMPTION

The first data from appendix [v] is by measuring the power supplied to the circuit and the power out of the circuit. This is made by using LTSpiceIV measurement of power. From the data it can be seen that the highest amount of power lost coming from the VCF and the least amount of power lost coming from pulse generator. The power consumption follows the pattern Table 3.

Circuits	Power consumption
Pulse generator	8.53E-03
Vibrato	8.781E-03
Tremolo	1.1469E-02
VCO	1.469E-02
VCA	0.5
VCF	1.8393

Table 3: Power consumption in ascending order

From the table, the power consumption of the sub circuits (vibrato and tremolo can be considered acceptable as it is lower than the main circuits (VCO,VCF,VCA).The total power loss of the whole analog synthesiser is around 3.89 watts which is acceptable. The power is used in all the circuits to generate and process the analogue signals that is needed.

The second data from Appendix [vi] is taken by calculating the power consumption of individual components in individual circuits from LTSpiceIV. It follows almost the same pattern as the first data. It gives a breakdown of the power consumption of each components in the circuit to investigate if the power consumption can be lessen. The data is in Appendix [vi]. From the data- it can be seen that the VCF seems to be consuming the most energy-which amounts to 1.43 watts compared to other circuits. It seems that the TL072 consumes the most power which amounts to around 450 milliwatts per component on average. Even though the TL072 has a modest power consumption [47] compared to other models, it still is much compared to other to other components in the circuit. In addition, the VCF circuit has numerous other components affecting its power consumption.

The pulse generator of course has the lowest power consumption. This is attributed to the fact that the pulse generator has the least number of components. The NE555 which is the timer also consumes little power. This is because the NE555 consumes power like an LED when operating as an oscillator [48].

It can also be observed that the VCA seems to be consuming high power even though the components are not as much as the VCF. Again, this has contributed to the existence of the LT072 (U17) that consumes 426miliwatts of power from the circuit. U20 which is a variable resistor consumes a high power due to the high voltage flowing through it which is 35 volt which functions as a control voltage.

The ADSR also seems to consume 0.645 watt of power. This is due to the existence of the TL071[48]. After skimming through the datasheet, it is still considered a low power consumption product compared to other op amps. As example, the AD8510, is a replacement for TL071 [16], has a high gain with the tradeoff of a high-power consumption in signal transmission application [49]. Other than that, the components inside seem to be consuming a very small amount of energy.

The VCO, tremolo and vibrato consume a small amount of power. None of the components in a tremolo circuit consumes more than 7 milliwatts of power. The vibrato's circuit maximum power dissipation for a component also never reached 10 milliwatts. The VCO LM358 output current can be improved by replacing it with other components such as the TL052[for a higher current output [50].

9.0 FUTURE DESIGNS

As mentioned in the introduction, this project serves as a starting point for future adventures in creating new versions of analogue music synthesisers. Although the current synthesiser is a success, there is still plenty of room for improvement or modifications.

Starting off with the keyboard, future designs may include making me a new keyboard which is more complicated but more useful. The new keyboard will auto generate gate and trigger signals which will be fed to the ADSR, thus removing the need for a pulse generator. Also, the keyboard should include voltage input for tune and low frequency oscillator as in [1]. This is to give extra effects to the music produced. Besides that, the keyboard would also be able to generate signals that can be fed into the input of tremolo and vibrato, instead of using the output of the VCO as in our original design. This will give the choice to give the music of tremolo or vibrato or none at all.

For the VCO, future designs may see new improvements on the exponential converter to improve its accuracy. A buffer circuit can also be added at the output before being fed into the input of the VCF. Moving on to the VCF, there is still room for improvement in perfecting the filter so that only the fundamental frequency can pass through, as opposed to what was observed in the spectrograms where traces of second and third harmonics can be seen. As the VCF has the highest power consumption out of all the blocks, future designs may also look to cut down the number of components or replace components that have high power consumptions.

For the VCA, a sink transistor may be added to improve the tail current. Ways to increase the range of gain can also be explored. For the ADSR, it can be useful to replace the op amp before the output as it has the highest power consumption.

Finally, it is also entirely possible to modify the original monophonic synthesiser into a polyphonic synthesiser. To do that, multiple VCOs will be built and then mixed with a mixer to combine the waveforms. As the process is considered repetitive, we decided to create a monophonic synthesiser, however, the polyphonic synthesiser is certainly more suited for the real one.

10.0 CONCLUSION

At the end of this project, we have successfully produced an analogue music synthesiser that is able to generate audio frequencies of 7 notes in the C major scale in the 4th octave. The end product is also able to drive a loudspeaker of 8Ω impedance with a lower amplitude detected. Furthermore, effective and adjustable ADSR, tremolo and vibrato are also produced, which can be mixed with the three core blocks in the synthesiser to create different effects. On top of that, this device is modeled with real world devices, making it accurate to simulate in the real world.

While the device is a success, there is still room for improvements. Firstly, a more effective 1V/octave keyboard can be created which will generate gate and trigger inputs for the ADSR so it will be more user-friendly. This is because in our experiment we are only able to manipulate the key only, resulting the notes to change. However, there is an opportunity to add an element such as tune for trimming the sound. Next, a VCF that handles transient voltages better can also be built, thus removing the spikes at the beginning of the audio. The spikes cause a very minor distortion at the sound output hence this would be a suitable improvement. Other circuits, such as vibrato, could also be improved with further iterations. The vibrato effects could be enhanced in the final sound. Furthermore, as this is a monophonic analog synthesizer, it would be useful to build a polyphonic one by using multiple VCOs, VCFs and other components.

All in all, every aim that was listed at the beginning of the report was achieved. The project was a success and all team members gained a lot of knowledge and interpersonal skills from it.

11.0 PROJECT PLANNING AND MANAGEMENT

The group was constructed according to the Belbin roles:

Jing Lin Loh: Resource Investigator, Completer Finisher

Husna Fathiah: Co-Ordinator, Shaper

Yuhan Diao: Team Worker, Specialist

The team was constructed with a distinct and diverse set of Belbin roles. As each member has their own specialties and personalities, we delegated tasks according to our strengths and weaknesses.

A Gantt Chart (refer to Appendix[ii]) was created to keep track of our work and to show the development of our works over the days. Consultations and discussions are added to preview the designing process changing aspects from the initial plan and to improve our design. We also researched different ways to improve the sound online. Some tasks ran over time, and the Chart is updated to show these changes.

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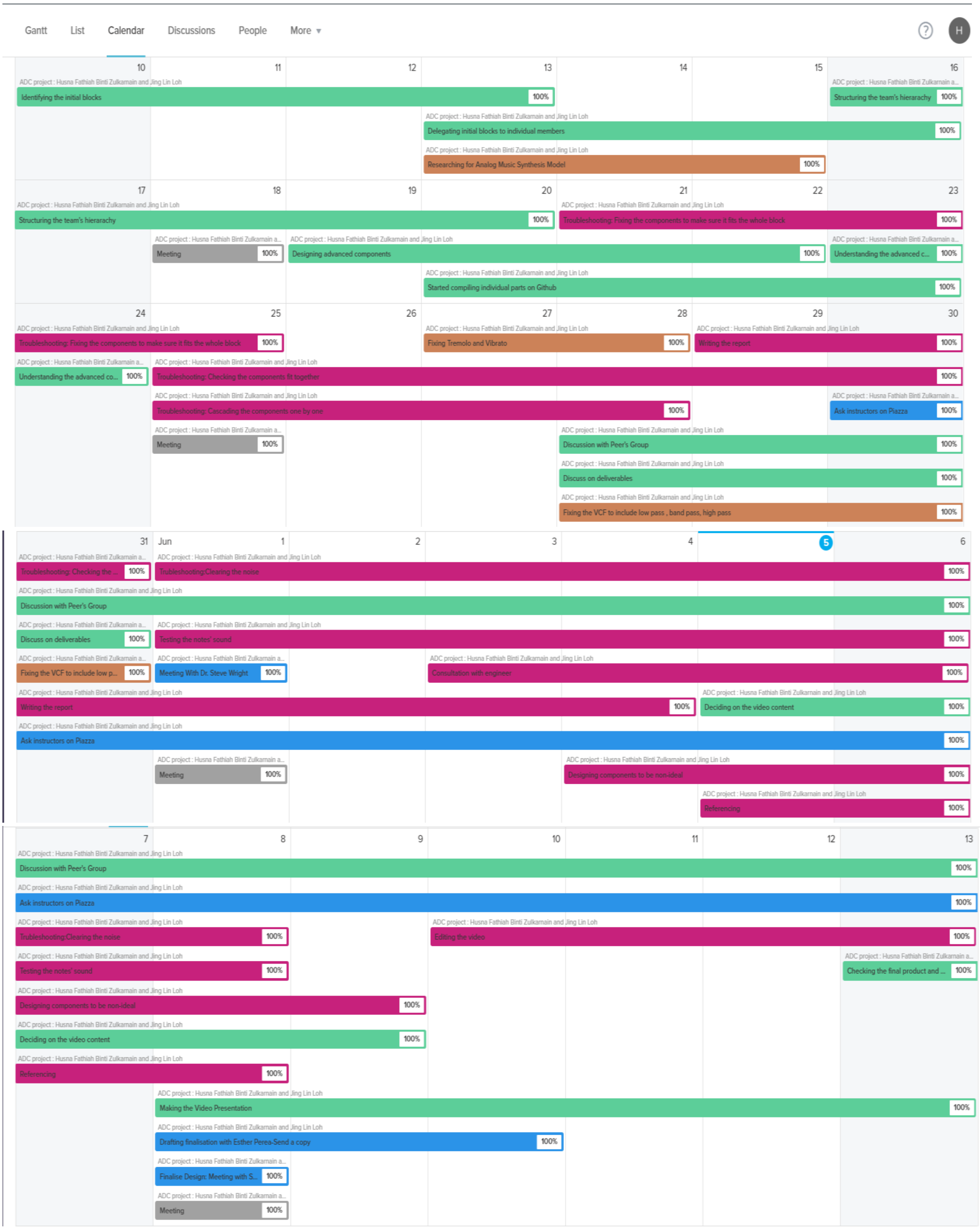
14.0 APPENDIX

14.1 Appendix [i] Bill of Materials (BOM)

Figure 102: Bill of materials

Sum = 16.84577 GBP

14.2 Appendix [ii] Gantt Chart



Group Meeting: Grey
Testing, editing and troubleshooting: Magenta
Discussion: Green
Consultation: Blue
Individual work: Brown

14.3 Appendix [iii] Keys, Voltage and Frequency

Key	Key #	1v Octave V	Expo Output	Frequency
C2	1	0.083	0.166	65.41
C#2/Db2	2	0.167	0.175	69.3
D2	3	0.25	0.186	73.42
D#2/Eb2	4	0.333	0.197	77.78
E2	5	0.417	0.209	82.41
F2	6	0.5	0.221	87.31
F#2/Gb2	7	0.583	0.234	92.5
G2	8	0.667	0.248	98
G#2/Ab2	9	0.75	0.263	103.8
A2	10	0.833	0.278	110
A#2/Bb2	11	0.917	0.295	116.5
B2	12	1	0.313	123.5
C3	13	1.083	0.331	130.8
C#3/Db3	14	1.167	0.351	138.6
D3	15	1.25	0.372	146.8

D#3/Eb3	16	1.333	0.394	155.6
E3	17	1.417	0.417	164.8
F3	18	1.5	0.442	174.6
F#3/Gb3	19	1.583	0.468	185
G3	20	1.667	0.496	196
G#3/Ab3	21	1.75	0.526	207.7
A3	22	1.833	0.557	220
A#3/Bb3	23	1.917	0.59	233.1
B3	24	2	0.625	246.9
C4	25	2.083	0.662	261.6
C#4/Db4	26	2.167	0.702	277.2
D4	27	2.25	0.743	293.7
D#4/Eb4	28	2.333	0.788	311.1
E4	29	2.417	0.834	329.6
F4	30	2.5	0.884	349.2
F#4/Gb4	31	2.583	0.936	370
G4	32	2.667	0.992	392
G#4/Ab4	33	2.75	1.051	415.3

A4	34	2.833	1.114	440
A#4/Bb4	35	2.917	1.18	466.2
B4	36	3	1.25	493.9
C5	37	3.083	1.324	523.3
C#5/Db5	38	3.167	1.403	554.4
D5	39	3.25	1.487	587.3
D#5/Eb5	40	3.333	1.575	622.3
E5	41	3.417	1.669	659.3
F5	42	3.5	1.768	698.5
F#5/Gb5	43	3.583	1.873	740
G5	44	3.667	1.984	784
G#5/Ab5	45	3.75	2.102	830.6
A5	46	3.833	2.227	880
A#5/Bb5	47	3.917	2.36	932.3
B5	48	4	2.5	987.8
C6	49	4.083	2.649	1047
C#6/Db6	50	4.167	2.806	1109
D6	51	4.25	2.973	1175

D#6/Eb6	52	4.333	3.15	1245
E6	53	4.417	3.337	1319
F6	54	4.5	3.536	1397
F#6/Gb6	55	4.583	3.746	1480
G6	56	4.667	3.969	1568
G#6/Ab6	57	4.75	4.205	1661
A6	58	4.833	4.455	1760
A#6/Bb6	59	4.917	4.719	1865
B6	60	5	5	1976

14.4 Appendix [iv] Voltages and resistances

Voltage Out/V	Voltage source/V	Notes	Fixed R/Ω	(R)Resistance/Ω
0.0833	5	C0	100	5902.40096
0.1666	5	C#0	100	2901.20048
0.2499	5	D0	100	1900.80032
0.3332	5	D#0	100	1400.60024
0.4165	5	E0	100	1100.480192
0.4998	5	F0	100	900.4001601
0.5831	5	F#0	100	757.4858515
0.6664	5	G0	100	650.30012
0.7497	5	G#0	100	566.93344
0.833	5	A0	100	500.240096
0.9163	5	A#0	100	445.6728146
0.9996	5	B0	100	400.20008
1.0829	5	C1	100	361.7231508
1.1662	5	C#1	100	328.7429257
1.2495	5	D1	100	300.160064
1.3328	5	D#1	100	275.15006
1.4161	5	E1	100	253.0824094
1.4994	5	F1	100	233.46672
1.5827	5	F#1	100	215.91584
1.666	5	G1	100	200.120048
1.7493	5	G#1	100	185.8286172
1.8326	5	A1	100	172.8364073
1.9159	5	A#1	100	160.9739548
1.9992	5	B1	100	150.10004
2.0825	5	C2	100	140.0960384
2.1658	5	C#2	100	130.8615754
2.2491	5	D2	100	122.3111467
2.3324	5	D#2	100	114.3714629
2.4157	5	E2	100	106.9793435
2.499	5	F2	100	100.080032
2.5823	5	F#2	100	93.62583743
2.6656	5	G2	100	87.57503001
2.7489	5	G#2	100	81.89093819
2.8322	5	A2	100	76.54120472
2.9155	5	A#2	100	71.4971703
2.9988	5	B2	100	66.73336001
3.0833	5	C3	100	62.16391529
3.1667	5	C#3	100	57.89307481
3.25	5	D3	100	53.84615385
3.3333	5	D#3	100	50.00150002

3.4167	5	E3	100	46.34003571
3.5	5	F3	100	42.85714286
3.5833	5	F#3	100	39.53618173
3.6667	5	G3	100	36.36239671
3.75	5	G#3	100	33.33333333
3.8333	5	A3	100	30.43591683
3.9167	5	A#3	100	27.65848801
4	5	B3	100	25
4.0833	5	C4	100	22.44997918
4.1667	5	C#4	100	19.99904001
4.25	5	D4	100	17.64705882
4.3333	5	D#4	100	15.38550297
4.4167	5	E4	100	13.20669278
4.5	5	F4	100	11.11111111
4.5833	5	F#4	100	9.091702485
4.6667	5	G4	100	7.142091842
4.75	5	G#4	100	5.263157895
4.8333	5	A4	100	3.448989303
4.9167	5	A#4	100	1.694225802
5	5	B4	100	0

*Equation 10: (500-100*Voltage)/Voltage*

14.5 Appendix [v] Power consumption per circuit

VCO

Category	Type	Voltage	Current	Power
Voltage in	VCC	5	2.06E-03	1.03E-02
Voltage in	VEE	-5	-1.50E-03	7.50E-03
Voltage in	C4	2.0833	4.62E-13	1.37E-13
Voltage in	D4	2.25	-2.25E-05	-7.23E-06
Voltage in	E4	2.4167	-2.42E-05	-8.34E-06
Voltage in	F4	2.5	-2.50E-05	-8.93E-06
Voltage in	G4	2.6667	-2.70E-05	-1.03E-05
Voltage in	A4	2.8333	-2.83E-05	-1.15E-05
Voltage in	B4	3	-3.00E-05	-1.29E-05
Voltage in	VREF	2.5	1.70E-05	4.24E-05
Voltage out	SQUARE	5	5.68E-04	2.84E-03

Power out= 2.84E-03

Power supplied=1.78E-02

Total power lost=0.01496

Tremolo

Category	Type	Voltage	Current	Power
Voltage in	SQUARE	5	5.68E-04	2.84E-03
Voltage in	V17	9	1.01E-03	9.11E-03
Voltage out	TREM_OUT	2.43E+00	2.18E-04	5.31E-04

Power out= 5.31E-04

Power supplied=1.20E-02

Total power lost=0.011469

ADSR

Category	Type	Voltage	Current	Power	
Voltage in	V10	15	6.19E-02	9.28E-01	
Voltage in	V11	-15	-6.04E-02	9.06E-01	
Voltage in	VPULSE	5	4.14E-05	2.07E-04	
Voltage out	Envelope	2.964536	2.12E-04	6.29E-04	
Voltage out	V2	-15	-1.98E-15	2.97E-14	
Voltage out	V3	15	2.10E-02	3.15E-01	

Power out= 3.16E-01

Power supplied= 1.83E-0

Total power lost=1.51437

Pulse generator

Category	Type	Voltage	Current	Power	
Voltage in	VC	5	1.65E-03	8.26E-03	
Voltage Out	VPULSE	5	4.14E-05	2.07E-04	

Power out=2.07E-04

Power supplied= 8.26E-03

Total power lost= 8.053E-03

VCA

Category	Type	Voltage	Current	Power	
Voltage in	VCF_OUT	8.16575	8.13E-05	6.64E-04	
Voltage in	VCONTROL	35	1.06E-03	3.71E-02	
Voltage in	TREM_OUT	2.43E+00	2.18E-04	5.31E-04	
Voltage in	V12	15V	1.54E-02	2.31E-01	
Voltage in	V13	-15	-1.53E-02	2.29E-01	
Voltage in	ENVELOPE	8.322302	7.53E-04	6.27E-03	
Voltage Out	VOUT	3.23E-02	4.12E-03	1.33E-04	

Power out= 1.33E-04

Power supplied= 5.04E-01

Total power lost= 0.504432

VCF

Category	Type	Voltage	Current	Power
Voltage in	SQUARE	5	5.68E-04	2.84E-03
Voltage in	CV1	5	1.12E-04	5.59E-04
Voltage in	VIB-OUT	3.139191	6.99E-05	2.19E-04
Voltage in	V10	15	6.19E-02	9.28E-01
Voltage in	V11	-15	-6.04E-02	9.06E-01
Voltage out	VCF_OUT	8.16575	8.13E-05	6.64E-04

Power out= 6.64E-04

Power supplied= 1.84E+00

Total power lost= 1.8393

Vibrato

Category	Type	Voltage	Current	Power
Voltage in	SQUARE	5	5.68E-04	2.84E-03
Voltage in	V23	9	4.49E-04	4.04E-03
Voltage in	V21	9	2.36E-04	2.12E-03
Voltage out	VIB-OUT	3.139191	6.99E-05	2.19E-04

Power out= 2.19E-04

Total power lost= 8.781E-03

Power supplied= 9.00E-03

14.6 Appendix [vi] Power consumption per component

Voltage source power consumption for each component in a circuit

VCO

Components	Power lost per component
R92	4.13E-05
LM358	1.61E-02
BC549B	1.32E-05
R3	1.23E-05
R8	9.24E-07
R9,R10,R11	1.72E-06
R16	1.83E-04
R12	2.88E-05
R13	1.35E-05

Total power consumption=1.64E-02

Tremolo

Components	Power loss per component
R56	2.90E-05
R55	5.00E-05
R60	9.50E-05
R61	2.80E-03
R66	8.00E-04
U21	110 E-06
C13	600 E-06
Q11	5.87E-09
C19	7.00E-06
R70	7.70E-04
C12	1.20E-03
J1	6.08E-04
C11	4.50E-05
R56	2.70E-05
R57	5.00E-05
R58	4.32E-03
J2	1.80E-05
R62	1.30E-04
R63	600 E-06
U22	1.40E-06
R65	1.40E-07
R64	1.50E-05
R67	6.60E-06
Q12	1.35E-03
R68	1.38E-06
R69	1.01E-05
U1	8.70E-05

Total power consumption=1.24E-02

ADSR

Components	Power loss per component
R54	1.63E-13
D13	2.23E-09
Q13	8.00E-04
R71	7.91E-02
R73	2.13E-01
Q14	1.56E-08
R72	1.30E-02
R77	5.73E-03
C23	small
R74	small
R75	small
D14	small
Q15	2.25E-08
R76	2.72E-12
C33	9.80E-11
U26	7.73E-02
C39	small
U33	1.35E-05
M1	3.23E-09
U30	1.35E-04
Q17	3.54E-04
R81	2.64E-03
U29	1.08E-02
Q16	9.49E-09
R79	2.58E-03
R78	4.24E-03
R80	small
U28	8.00E-12

M2	5.02E-08
U34	4.26E-01
U27	7.40E-03
Q14	2.15E-08
C38	-1.51E-12
C39	-7.90E-16
V3	3.14E-01

Total power consumption =1.16E+00

Pulse Generator

Components	Power loss per component
C20	small
R4	small
R7	small
1N4148	6n
U25	21.87n
U13	small
C22	90n
U13	8.05506m

Total power consumption =8.055E-03 watt

VCA

Components	Power consumption per component
U19	1.98E-03
U18	9.50E-05
R47	2.82E-03
U20	1.55E-02
Q10	9.80E-03
Q9	4.16E-04
Q8	3.50E-03
R53	2.40E-03
R52	1.90E-06
Q6	6.60E-03
Q7	5.10E-03
R45	3.30E-04
R51	1.20E-09
R41	2.80E-03
R42	2.80E-03
R43	2.90E-04
R44	2.90E-04
R48	7.00E-03
U17	4.27E-01
R49	4.41E-03
R50	4.80E-03

Total power consumption= 4.97E-01

VCF

Components	Power consumption per component
R23	600 E-06
U7	2.83E-04
C8	6.00E-04
U14	4.53E-01
R22	6.00E-04
R27	1.20E-04
R29	small
R30	2.40E-09
R28	2.60E-06
C5	1.80E-05
C6	9.00E-06
C7	9.00E-06
1N4914	4.80E-06
C3	2.40E-04
R21	1.18E-02
R18	1.28E-02
C10	1.20E-02
R17	5.00E-03
R25	3.00E-07
R24	3.00E-07
U16	4.25E-01
R20	5.80E-03
D10	small
D9	small
R26	6.60E-08
U8	2.70E-08
R34	7.00E-05
U15	4.26E-01
R35	3.3 E-06
R33	1.40E-06
C9	small
Q4	1.30E-02

Q5	1.10E-02
R31	5.00E-02
R32	1.06E-03
C4	1.40E-05
R36	1.00E-06
U9	5.50E-08
R39	1.10E-06
R38	3.30E-06
R37	2.50E-05
U10	5.33E-04
U11	7.00E-05
U12	8.06E-04

Total power consumption= 1.42951246

Vibrato

Components	Power Consumption per component
R85	1.64E-05
BC547B.Q18	7.82E-04
R83	1.34E-06
R84	2.02E-06
U23	2.00E-05
R87	1.25E-04
U31	6.00E-04
BC547B.Q19	5.19E-04
R86	1.03E-04
C28	3.37E-06
R89	1.80E-04
Q20,2N2222	4.40E-05
R88	1.60E-03
R90	1.20E-03
C27	7.91E-04
J3, NJF	1.00E-03
C29	2.55E-04
R91	1.10E-03
C28	3.37E-06

Total power consumption=8.35E-03

14.7 Appendix [vii] Product Design Specification

Date: May 15,2020
[Revised June 12,2020]

This product design specification is a statement of what this analog music synthesiser is intended to do. The aim of this document is to ensure that the subsequent design and development of the product meets the requirements of the client.

Background Introduction

The analog music synthesiser is an electronic design project that is conducted under Imperial College London to first year students in Electrical and Electronic Engineering. It is designed to produce 7 notes in the 4th octave in the C major scale.

Basic Operation

The project will have voltage sources that will determine the note produced by the loudspeaker. In the simulation, the voltage sources include a pwl text file to simulate the condition of users playing the analog synthesiser

Scope

This specification covers the general operation characteristics of the product and provides an overview of the requirements for the electronics of the finished article. This is a response to the criteria laid out by the client.

Product Design and Performance

1. Performance

   The monophonic analog synthesiser should perform the function of delivering notes C4 to B4 as efficiently and accurately as possible, coupled with the effects of tremolo and vibrato.

2. Maintenance

As the materials are very affordable and long-lasting, it is expected that the project should be easy to maintain and requires little cost for any maintenance. The project should be easily maintained by clients with affordable resources

3. Target Product Cost

The product should have a much lower cost than the cost of analog synth in the market (approximately £200) as it has lesser functionalities.

4. Quantity

Produce one monophonic analog synthesiser model for testing. The schematic should be uploaded to GITHUB so that it can be shared and built if required.

5. Customer

The schematic is made for clients that are getting familiar with a simple analog synthesiser. It is targeted to audience that wants to understand the building blocks of a simple analog music synthesiser.

6. Size

Should be able to accommodate only for 7 keys and a small compartment at the bottom for the circuits build. The dimension is possibly 12 x 5.0 x 10cm as it only accommodates 7 mini keys.

7. Weight

Less than 2 kg.

8. Materials

Should be made from affordable materials for students to be able to construct. The materials should also be widely used.

9. Aesthetics, Appearance and Finish

There should be 8 circuits within the product. The circuits should be interconnected between each other. The product should produce the 7 notes in the fourth octave.

10. Ergonomics

Should take into account the strengths and weaknesses of all team members. A suitable workplace and time should be dedicated for the project.

11. Standards and Specifications

Should reach the requirement stated in the project introduction specification. It should also be able to produce the tremolo and vibrato effects. Ensure that there are no potential instrument health and safety issues e.g. sharp edges, poisonous substances. Check that instruments conform to appropriate EU legislation, e.g. rules concerning nickel and nickel plating.

12. Quality and Reliability

The product should have low maintenance and is reliable to use for notes C4 to B4. It should be able to be insured by the users by conforming to rules and regulations of musical instruments. The product should also have a warranty of minimum 1 year.

13. Testing

Use the testing method stated such as MATLAB for plotting spectrograms and LTSPICEIV for hearing the output sound. Other applications are also used to detect the notes compare the results.

14. Processes

The initial process should be researching the individual circuits. After compiling the findings, a group discussion should ensue to make sure all the circuits are compatible with one another. Consultations and questions are attended by all team members to make sure every question is answered. All team members should cooperate to produce the deliverables and the full schematic.

15. Time Scale

The project should take a month approximately to research, assemble, produce and document. A Gantt Chart is created to make sure all progresses are tracked.

16. Safety

The connections should be safe for use and handling. The project should use a reliable connection between components. The documentation and files of the project should also be kept in a safe folder and shared privately between team members.

17. Company Constraints

The project's report and video are due on the 14^{th} of June 2020 and must be submitted via Blackboard. The project should be finished by that date.

18. Patents, Literature and Product Data

The project should avoid any accusation of plagiarism by referencing the right sources in the documentation. The project's documentation should be shared privately. There should not be any plagiarism between peers as well.

19. Installation

The full schematic should be referred to LTSpiceIV.

20. Documentation

The full documentation must be submitted to the company, Imperial College London.