Lund University
Faculty of Engineering
Digital and Analogue Projects (EITF40)

Design of a Synthesizer

Submitted By:
Victor Skarler

Instructor:
Johan Wernehag

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Acknowledgements

This project includes allot of accumulated ideas and circuits, where I feel the inspirational sources needs to be credited appropriately. Allot of ideas and solutions were gathered from the designs of ”Music from Outer Space” [7]. Another great source of inspiration were the circuits and labs presented in ”Analog Devices Wiki” and ”Electronic Tutorials” [4] [5]. Also the component CA3080 stood as a foundation for much of this project and the manufacture, Intersil, ”Example Design Document” was of great assistance when designing circuits around the component.[1] More specific acknowledgements and references are presented as they were used.

Contents

1 Introduction

Synthesisers has since their commercial introduction in the 1960s established themselves as an important part of music. The development of synthesizers has since the late 1970s been heavily focused on digital approaches with samplers, DACs and digital signal processing. But in parallel to this development analogue synthesisers have been praised and still maintain a strong presence in music due to their distinct sounds.

This project aims to develop a complete analogue synthesiser with a classic modularity approach.[1] A modular design allows the user to create a wider array of sounds increasing the potential for musical expression and exploration of sound. The modular approach also allows the design of each module to be designed, constructed and verified separately for an easier work flow.

[1]As seen in early synthesisers from Moog and Buchla, as well as modern equivalents such as Doepfers Eurorack standard.

2 Specifications

This project aims to create a standalone synthesizer with the ability to utilize each component modularly. The modular design was set to the Eurorack standard.

The modules chosen for this project were;

- VCO(Voltage Controlled Oscillator) - the main oscillator and sound generator of the synthesiser. Normally operated with either MIDI, 1V/Octave keyboard or a frequency knob.
- LFO(Low Frequency Oscillator) - an oscillator of adjustable frequency that can be used to modulate the sound rhythmically, for example to create tremolo or vibrato or to control a filters operating frequency.
- VCF(Voltage Controlled Filter) - used to shape the sound generated by the oscillators in the frequency domain, often under the control of an envelope or LFO.
- VCA(Voltage Controlled Amplifier) - a controllable amplifier usually at the output stage of the synthesiser. The gain of the VCA is affected by a control voltage (CV), coming from an envelope generator, an LFO, the keyboard or some other source. Can also be used to create amplitude modulation.
- Mixer

2.1 The Eurorack Standard

Excerpt of Eurorack specifications relevant to this project.[10][6]

- +/-12V Power supply.
- Around 10Vpp (+/-5V) audio level.
- Around 5Vpp (+/-2.5V) control voltage level.
- Scale Standard 1V/Octave[2]

[2] 0V = midi note 36. Add 1V advances the octave by 1 thus 12 notes are always represented in 1V.

- Input Impedance 100KΩ.
- Protection from backwards connected power.
- Protection from signals being connected to incorrect ports.

3 Design and Theory

3.1 VCO

The VCO (Voltage Controlled Oscillator) is the foundation of the synthesiser, being the main source of generated waveforms. As an central part of synthesiser design, options and variety are essential for the user to create a variety of different waveforms. In this design the focus has been on waveform stability and consistency. With a stable basic waveform generation that then can be transformed into other shapes utilising different wave shaping circuitry. The complete oscillation component of the VCO module can be seen in figure 1.

With stability and ease of use in focus the design utilizing a Schmitt trigger for the oscillation was chosen. The oscillation is achieved by feed backing the Schmitt trigger to itself. This would generate a square wave but utilizing a integrator component a triangle wave is instead generated in order to both achieve a more consistent waveform(due to slight instability in square shape) and in order to have and option for PWM(Pulse Width Modulation) when generating a square wave later. In order to control the generated frequency a classic synthesiser voltage control approach was utilized with a transconductance amplifier acting as a variable resistor depending on input voltage.

The transconductance amplifier chosen CA3080 is behaving as a variable resistor and thus determines the amount of current flowing through into the integrator component. The negative input resistors to the CA3080 were chosen in order to bias the input in respect to the working range of the CA3080.

Continuing into the integrator the integrator converts the square wave generated by the Schmitt trigger to a triangle wave. The capacitance in the integrator acts as the main component controlling the operating frequency area of the VCO. And where the bias input into the CA3080 is controlling what frequency is generated within that area. After the integrator component the signal is input into the Schmitt trigger as well as the wave shaping circuitry while also acting as a output for the triangle waveform. The output impedance is set according to specifications while the signal strength is adjusted in the Schmitt trigger to be 10Vpp (+/-5V) according to specifications.

The Schmitt trigger were chosen as a discrete version due to tests with a

IC(Integrated circuit) Schmitt trigger proving to be slow and inaccurate as the frequency was increased. As consistency and stability are essential the discrete version were chosen. The design of the Schmitt trigger is based on a general design utilizing two transistors with coupled emitter stages[3]. When biasing the Schmitt trigger the main focus was to achieve the specified signal level of 10Vpp (+/-5V). This meant that the 20K resistor on the collector of the first transistor should be twice the resistance of the emitter resistor of the same transistor. And furthermore the collector resistor of the second transistor should be twice the resistance of the emitter resistor of the first transistor. The rest of the resistors were chosen to bias the bases to work as a Schmitt trigger. The capacitance was added to improve switching speed. This was done by allowing the capacitance to drain any accumulated charge from the base of the second transistor. The addition of this capacitance allows the Schmitt trigger to operate consistent at higher frequencies as well as lower.

The input method to the bias of the CA3080 was constructed as a place holder for prototyping. With the resistors and pots it allows the potentiometer to operate nearly the complete range of the allowed bias input of the CA3080. This would later be replaced with octave/1V keyboard input with a exponential converter.

To summarize, the Schmitt trigger generates a signal according to its input. The output of the Schmitt trigger is then feed backed to the CA3080. Acting as a controllable resistor the CA3080 determiners how much current to flow through into the integrator. Where the integrator capacitance charges and discharges depending on the input. So for example if the Schmitt trigger is high the capacitance begins to charge at a rate defined by the CA3080. When the trigger is low the capacitance begins to discharge as the current is reversed. The output of the integrator is then the input for the next cycle in the Schmitt trigger.

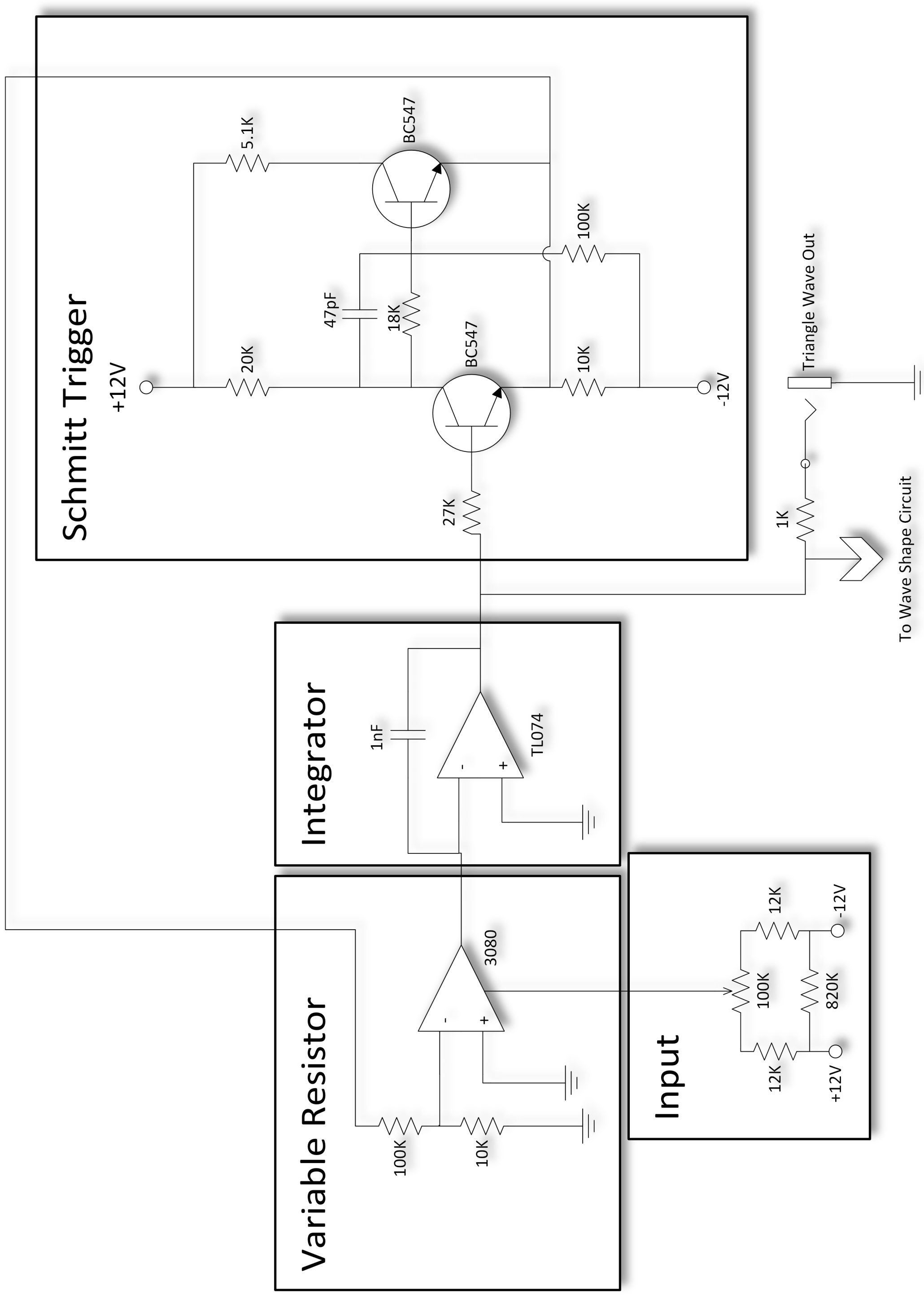

Figure 1: Circuit diagram of the VCO.

3.1.1 Sine Shaping

In order to transform the triangular waveform into a sine wave two methods were considered. The first method included the filtration of the triangular wave so that all harmonics would be filtered out and just leave the the fundamental wave which is a sine wave. This approach was abandoned in favour of a non linear approach because of difficulty in designing a efficient enough filter that works over a wider frequency range. The non linear approach is based on two transistors that cause a non linear change in gain over the amplitude range. Thus as the transistors changes in state the input ramping triangle is more or less attenuated, thereby mimicking the shape of a sine wave.[2] The complete sine shaping circuitry can be seen in figure 2.

From the main VCO circuit the output is connected towards the base of the first transistor which along with the other transistor acts as a differential pair. The base is over driven to a non linear state and thus the adaptation of the triangle to a sine wave starts as the non linear behaviour mimics the shape of a sine wave. The input potentiometer here controls the roundness of the resulting sine wave by changing if we move into the non linear state and then by how much. This allows the user to shape the sine wave from a triangle wave all the way to a pulse shape. But in the middle of this transformation is the smooth sine lines created by the transistors in the non linear state mimicking a sine wave.

The other potentiometer controls the symmetry of the wave. This essentially means that the wave shape needs to be perfectly balanced between the transistors in order to achieve a smooth sine approximation. If adjusted incorrectly harmonics will appear as artefacts and leave the output pointy and flat, respectably.

The transistors feed into a op-amp configured as a differential amplifier to complete the sine wave approximation. The resistor values were chosen to give the specified 10Vpp with 1K output impedance.

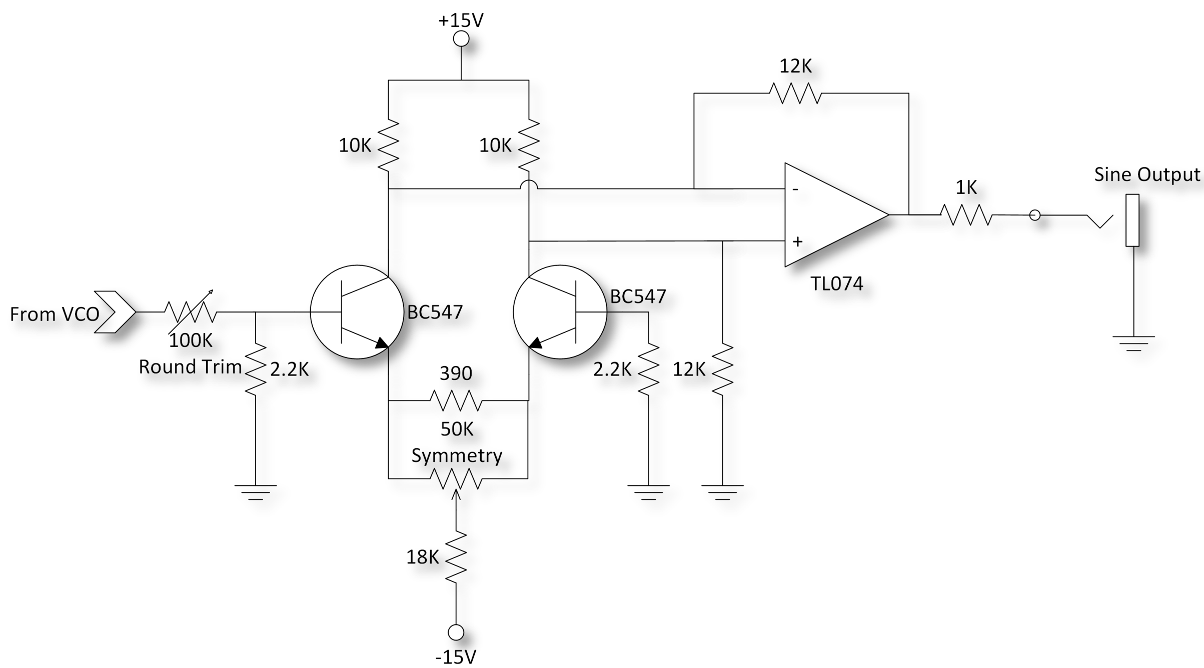

Figure 2: Circuit diagram of the sine shaper.

3.1.2 Square Shaping

The square wave generation from the triangle wave is done in a simple fashion, while incorporating PWM and manual controls for PW(Pulse Width). The complete circuit diagram of the square shaping circuit can be seen in figure 3.

Incorporating a PWM input with the characteristic 100K impedance for use with a CV (Control Voltage), for example a LFO(Low Frequency Oscillator), combined with and initial voltage for the pulse width acts as the control voltage for the pulse width. This voltage is adapted for comparison with a op-amp. The resulting voltage is then compared to the triangle wave input. This results in a square wave output, as the triangle wave and CV differs with oscillation. The voltage division at the end adjusts the output to the standard 10Vpp and 1K out impedance.

The initial pulse width potentiometer is adjusted so the full range of 0% to 100% PW is available for adjustment.

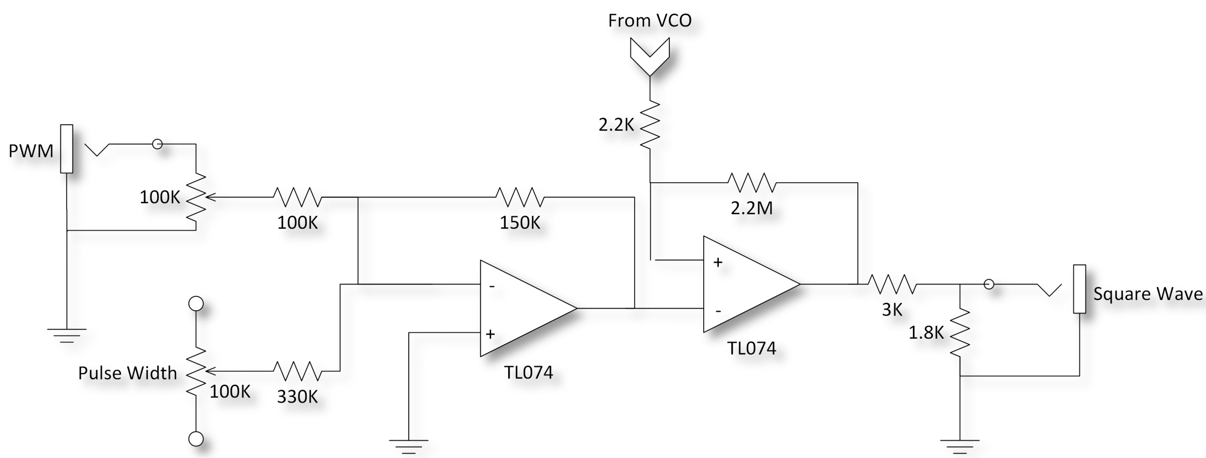

Figure 3: Circuit diagram of the square shaper.

3.1.3 LFO

An LFO was designed with the same basic circuity as the VCO and wave shaping circuity. But with the difference being a higher value capacitance in the VCO integrator stage for a slower charge/discharge which gives a lower frequency range.

3.2 VCA

The VCA(Voltage Controlled Amplifier) might seem like a trivial module in synthesiser design basically acting as a variable resistor. But the VCA opens up the possibility to automate the variable resistor turning and thus creating results such as amplitude modulation and tremolo effects. The VCA design chosen has an audio input as well as both a envelope and control voltage modulation input. The modulating input also has a voltage offset potentiometer that controls the initial offset to both give the ability to control the VCA without modulation input as well as adapting the input signals. The complete VCA schematic can be seen in figure 4.

The circuit was based on a similar idea that the VCO was constructed by. Where the control signals control a CA3080 component that limits the current depending on bias and thus acting as a variable resistor that controls the amplification. The modulation inputs are applied through a PNP transistor to gate the CA3080 amplifier bias current terminals. The grounded base configuration is used to minimize capacitive feed through coupling via the base collector junction of the PNP transistor. Which gives the CA3080 a linear behaviour in accordance to the modulation inputs.[1] The amplification is then based on the current flowing through the CA3080, controlled with the bias.

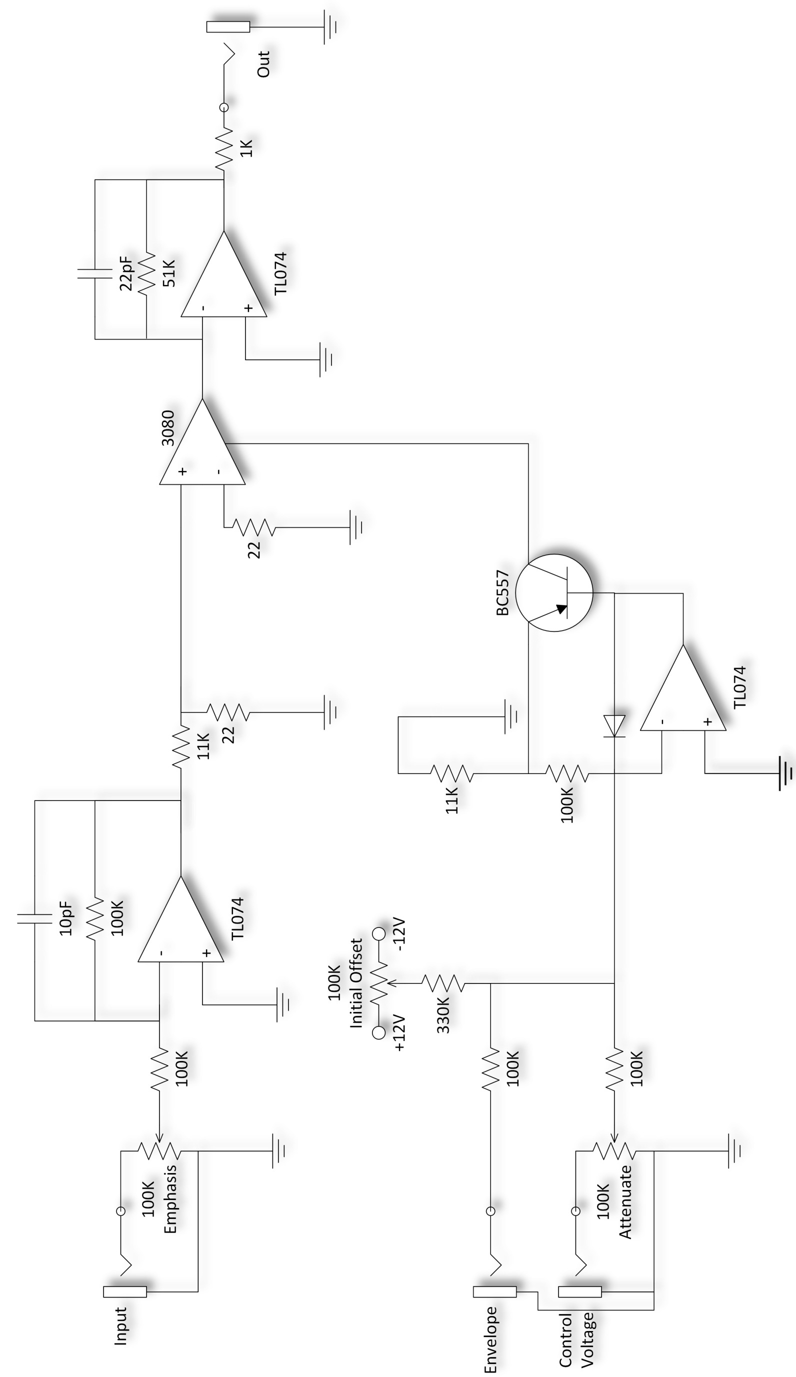

Figure 4: Circuit diagram of the VCA.

3.3 VCF

The VCF(Voltage Controlled Filter) might be considered the most iconic of synthesiser effects with its drastic and iconic switch in tone from the initial VCO sound. Before settling on the final design a transistor ladder design reminiscent of the traditional Moog design was explored but eventually scrapped in favour of a simpler design. The final VCF design makes use of a state variable voltage controlled filter that has low pass, band pass and high pass outputs.[9] The complete design was split to two circuit diagrams, the CA3080 bias circuit and the VCF circuit, they can be seen in figures 5 and 6 respectively.

The filters cut-off frequencies are controlled by an envelope input, and coarse and fine potentiometers. The cut-off frequency control converts the control voltage signal (via two NPN transistors) to an exponential current which is then routed to the two operational transconductance amplifiers in the state variable filter.[1][3] Essentially, this creates a variable resistance at the stages in the VCF which will adjust the cut-off frequency of the filter (or the passband in the bandpass filer).

The resonance potentiometer allows the user to feedback different amounts of the band pass output which results resonance oscillations in the audio signal. This provides an essential sound shaping tool for the VCF but it can also cause self oscillation.

[3] A similar transistor exponential current circuit as bias input was planned but ultimately never completed for the VCO.

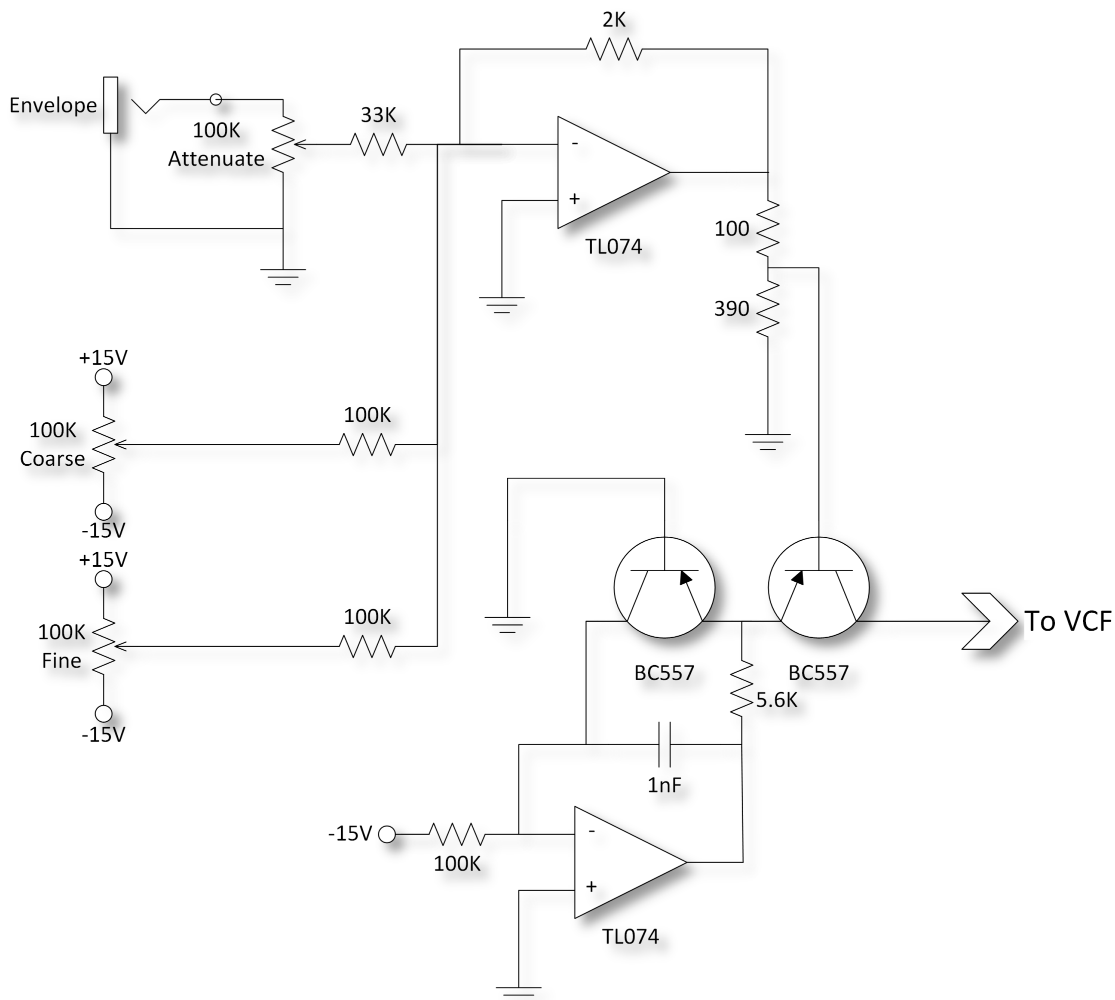

Figure 5: Circuit diagram of the bias input to the CA3080 in the VCF.

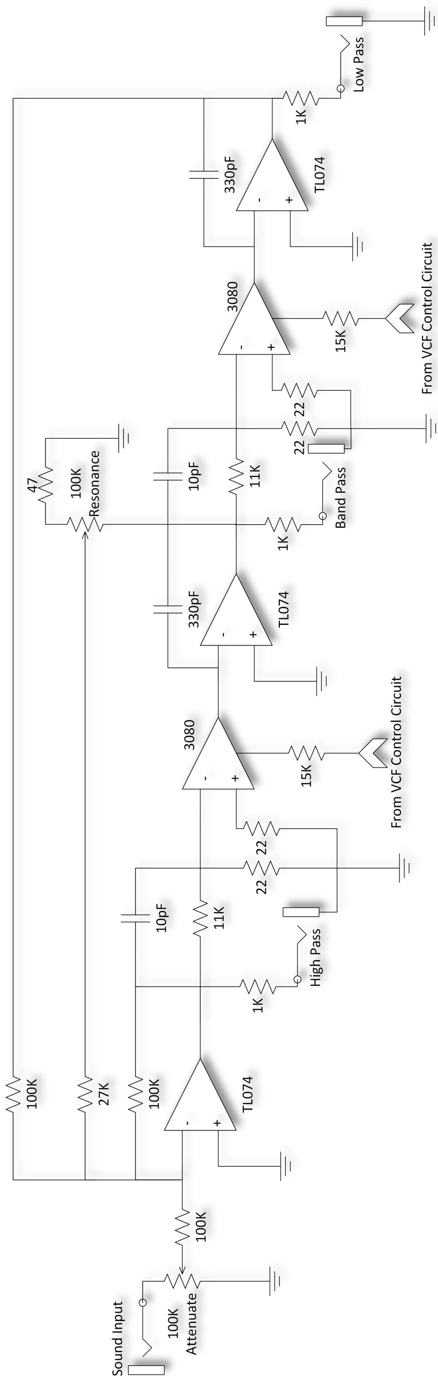

Figure 6: Circuit diagram of the VCF.

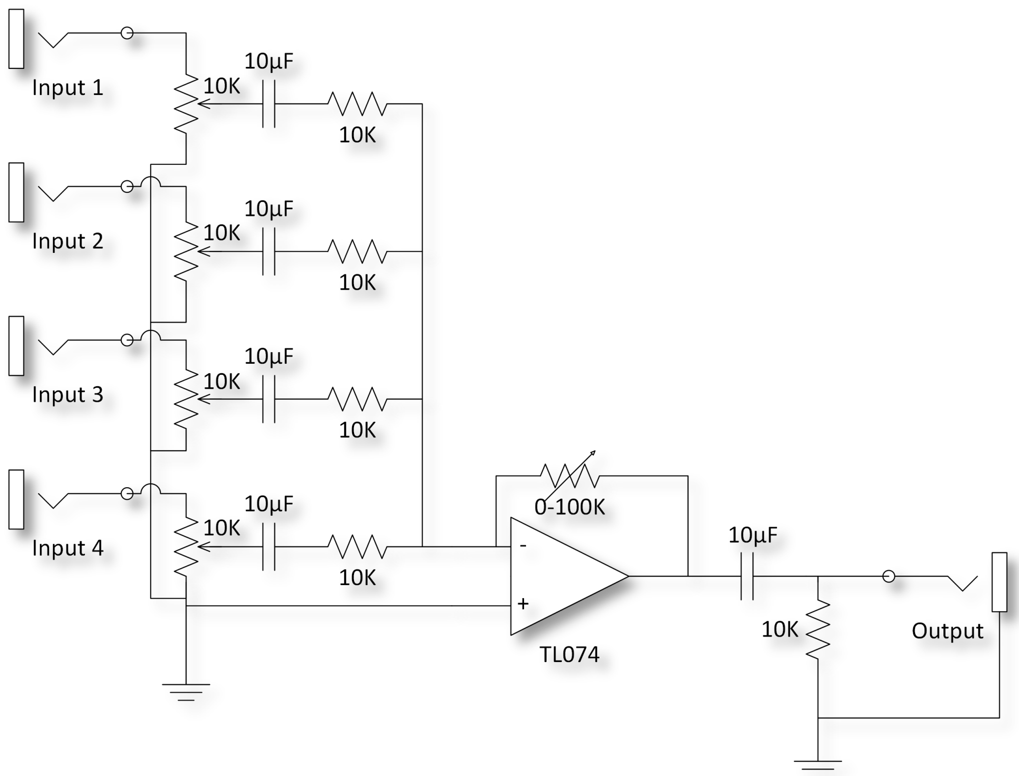

Figure 7: Circuit diagram of the mixer.

3.4 Mixer

A simple mixer was designed to mix different audio signals, with a separate emphasis control on each input and a common gain stage. The schematic of the mixer can be seen in figure 7.

4 Result

As the construction of the circuits took place a scarcity of the key component CA3080 became and increasing issue. And with experimentation and accidents the issue increased with the advancement of the project. This issue made it impossible to properly test the modules together and thus they were only evaluated separately. This approach shouldn't be the source of any issue as the standards were followed in both input and output but still it should be noted.

The scarcity of the component also caused the VCF and VCA to not being able to function when screen captures of the oscilloscope were taken. Instead the results are presented in text, with similar external results being showed for the ease of understanding.

4.1 VCO

Using the VCO with the temporary input method it achieves a range of approximately 20Hz to 4kHz. With the completed biasing circuit and exponential converter the VCO should be able to achieve a even wider range. The triangle waveform is very stable and frequency fluctuations are in sub 1Hz even at frequencies approaching 4kHz. The triangle shape is clear and does not break up at higher operating frequencies. An example of the generated triangle wave can be seen in figure 8.

To further test the stability of the oscillator the range capacitance of the VCO was replaced with a lower value, thus increasing both the minimum and maximum achieved frequencies. This test showed that the oscillations were consistent and stable up to approximately 100kHz. At this frequency artefacts in form of harmonics started to appear and the frequency stability started to decrease.

The VCO was concluded as a very successful component with great stability in the relevant frequency span, i.e. the hearable range[4].

[4] The hearable range is approximately 20Hz-20KHz

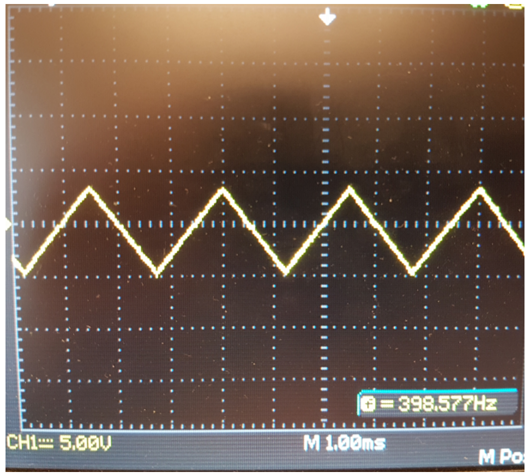

Figure 8: VCO with triangle output.

4.1.1 Sine Shaping

The sine shaper after some adjustments managed to recreate a sine wave very closely. FFT(Fast Fourier Transform) was not available in the used oscilloscope and could not be analysed. The sine wave shaper operated consistently when changing frequency and adjustments were not required to keep the current waveform when adjusting frequency. An example of the generated sine wave can be seen in figure 9.

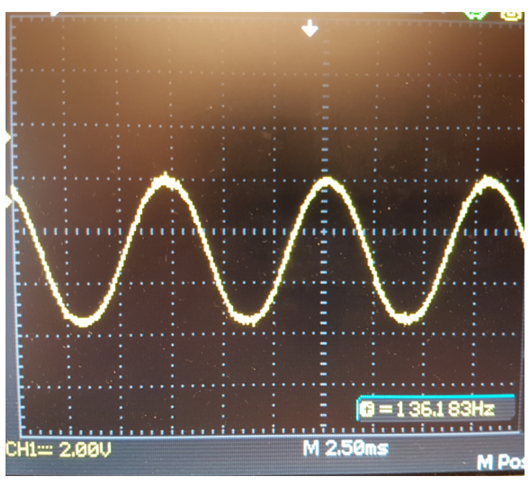

Figure 9: Sine wave output with balanced round and symmetry pots.

When testing the sine shaper for higher frequencies (100kHz+) the shape started to become somewhat distorted. It was concluded that this was most likely caused by limitations in the used transistors. But since the maximum potential operating frequency was defined be the hearable range this wasn't seen as an issue.

When unbalancing the sine wave somewhat interesting and unique sounds could be generated so the initially calibration potentiometers were changed to potentiometers available to the user. Sine waves distorted by unbalancing these potentiometers can be seen in figures 10 and 11.

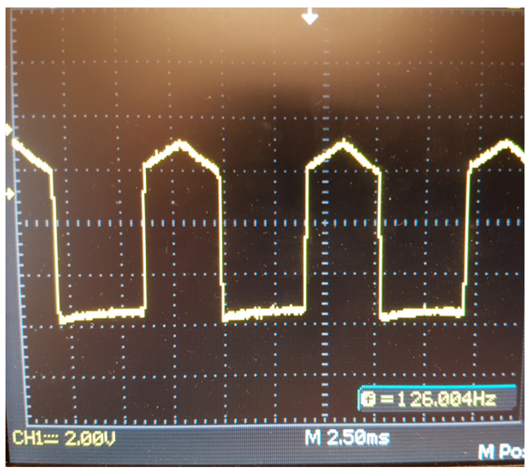

Figure 10: Sine wave output with balanced round pot and unbalanced symmetry pot.

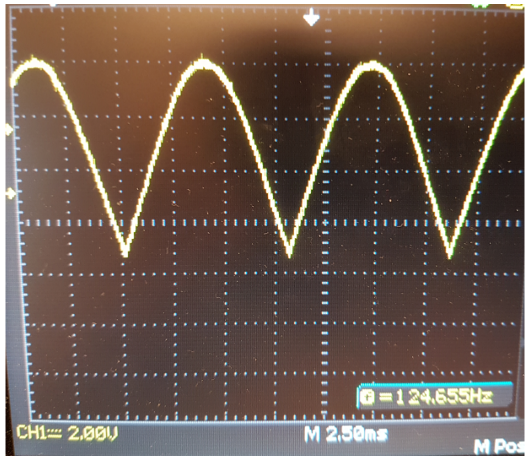

Figure 11: Sine wave output with unbalanced round pot and balanced symmetry pot.

4.1.2 Square Shaping

The square shaping component generated pulses with a slight resonance. See figure 12. The rise and fall time of the squares is fairly fast and doesn't impact the wave shape until the pulses approach 100kHz.

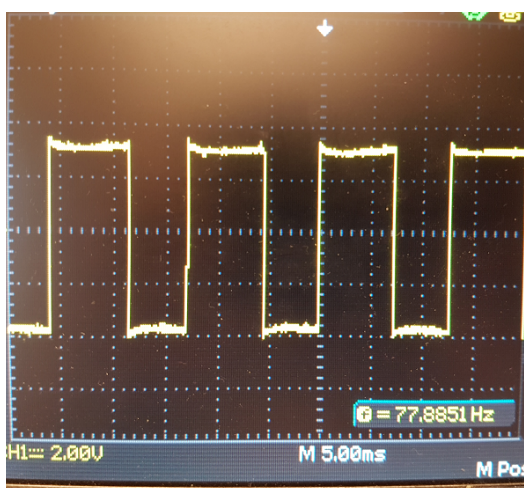

Figure 12: Pulse wave output.

The initial pulse width worked as intended and provided a range of 0%

to 100% pulse width. As seen in figure 13. When using an LFO to modulate the pulse width the waveform correctly followed the low frequency signal. A combination of both a LFO and offset offers the user the opportunity to create interesting PWM and frequency modulations. This is achieved by capping the modulation input to the comparator while the LFO is high. This can be seen in figure 14.

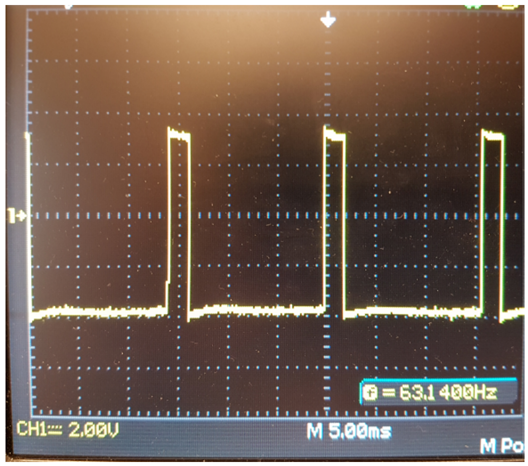

Figure 13: Pulse wave output with low pulse width.

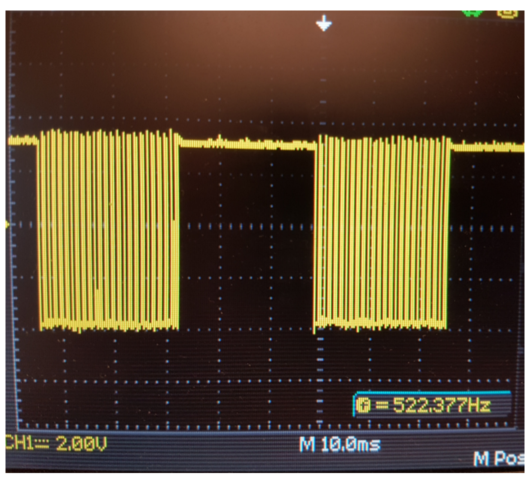

Figure 14: Pulse wave output with offset and LFO PWM.

4.1.3 LFO

As the LFO was constructed in an identical way to the VCO its behaviour was identical. Operating in lower frequencies the waveform was stable and consistent. A functioning range of approximately 0.1Hz to 100Hz that can be extended with the appropriate bias input circuitry constructed was achieved.

4.2 VCF

The VCF circuit included a linear to exponential converter as the bias input to the CA3080. This design was approached with a experimental mindset, with several iterations and value changes until the final design was settled. This design was going to be adapted for the vCO at a later stage.

The VCF itself functioned just as a state variable filter should. with outputs for low pass, band pass and high pass the filter functioned well for each filter type. But as the cut-off frequency was changed the filters behaved aggressively and immediately cut-off the appropriate frequency. This behaviour could be deemed desirable by certain synthesisers, but for this project a more smooth and/or adjustable cut-off was wanted. Several changes were made but none satisfied the adjustable requirement so a slightly smoother filter was eventually settled on.

The filters resonance potentiometer turned out to be one of the more successful design elements in the VCF. Operating the resonance high enough and the VCF turns into self oscillation. But turn it just enough and a very smooth and adjustable resonance was created on top of the input audio.

As there couldn't be any screen grabs taken from the actual design, as core components were damaged, substitute pictures with the same behaviour are provided in figure 15 and 16.

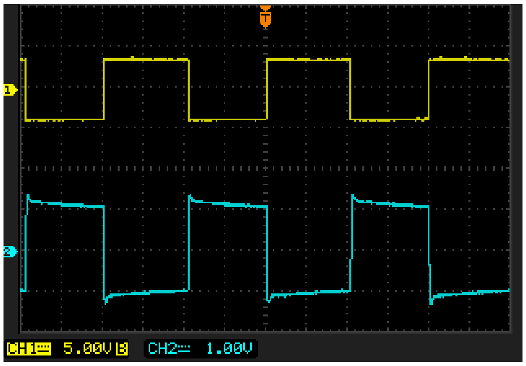

Figure 15: A square wave put through a VCF with no resonance.[8]

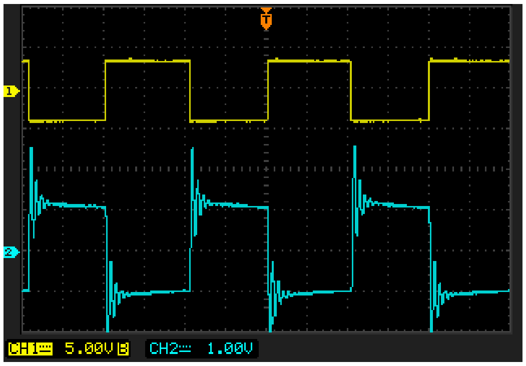

Figure 16: A square wave put through a VCF with resonance.[8]

4.3 VCA

After construction the VCA immediately functioned as intended. A LFO modulation signal adapted the original audio signal to create amplitude modulation and tremolo like sounds.

As the key components CA3080 were damaged before a screen grab could be taken a substitute picture is presented with the same behaviour. See figure 17.

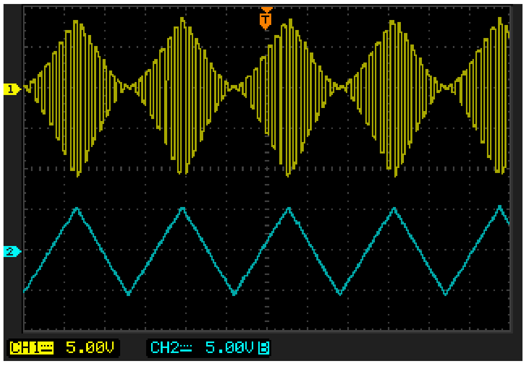

Figure 17: VCA modulated with a triangle LFO.[8]

4.4 Mixer

The basic mixer worked as expected. See figure 18.

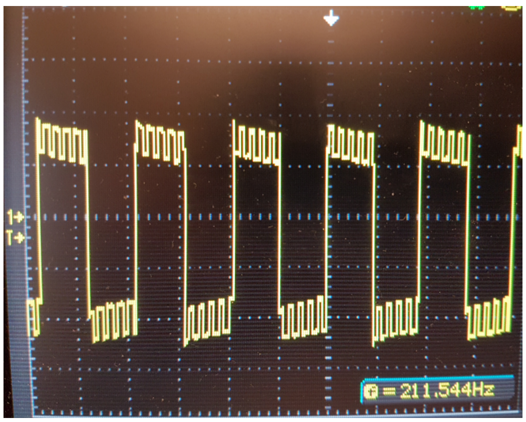

Figure 18: Output from a mixer with two inputs.

5 Discussion

With the project closing there is still much work to be done. Several key functions are still missing and several temporarily solutions are still present. But the modules that are completed are functioning well.

The external control method, the octave/1V input, together with the linear exponential converter is still not implemented for the VCO. But a similar and adaptable circuit was designed for the VCF so it should be able to be implemented fairly easily.

With an heavily dependence on the component CA3080 the project was severely halted by the increasing scarcity of the component. As the CA3080 component is out of manufacturing a switch to another similar component is an essential next step.

In several designs utilized in this project matched pair transistors and thermal common components should be used to stabilize the functionality of the circuits in different operating circumstances.

References

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