LULEÅ UNIVERSITY OF TECHNOLOGY

How to Design and Build an Analog Synthesizer from Scratch

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This document presents the concepts of designing and evaluating an analog synthesizer. The synthesizer consists of a few standard functions found on a commercial synthesizer. The circuits are constructed with price as a driving consideration. The documentation include a discussion about what problems occur when designing an analog synthesizer and what can be done to eliminate them. The purpose is to give a deeper understanding of analog electronics and creating a user interface suited for adjusting settings in a live environment. The author assumes the reader has good knowledge of both signal processing and electronics.

Contents

Preface

Thanks to;

Roger Jonsson: For comments and guiding on the project and letting me do this.

Joakim Bergs: For introducing me to LaTeX.

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My parents: Who sponsored me with food and material to the body construction when my money went to electronics.

Everyone else: Who has contributed with discussion and feedback during the project.

Summary

An analog synthesizer can be split into different building blocks, such as the oscillator, filter, and amplifier. The oscillator, filter and amplifier are often controlled by a control voltage signal.

These circuits was designed and constructed on experimental boards. Measurements were done and everything was placed inside a body, mounted on a sheet of wood.

The synthesizer can reach about one octave with 12 keys, though it depends on the ground frequency the oscillator is tuned to. A lower base frequency tends to reach a little more than one octave and higher frequency a little less then one octave. This was solved by a redesign of the control circuit so that it set an amount of current to the oscillators instead of a voltage, As desribed in chapter 15.2 at page 51. This required the oscillators and filters to be redesigned as well by changing the tuning potentiometer to a lower value.

There are unsolved shielding problems that give some output hum and noise. To reduce this, a shielding plane was installed and connected to common ground.

Chapter 1

Introduction

The *Noiztortion* is an analog synthesizer built in course *L0006A, Senior Sound Design Project II* at *Lulea University of Technology.* The goal with the project is to design and build a fully functional analog synthesizer and determine the sound quality of the instrument. Another goal is the measure the noise and distortion and figure out what causes this. The synthesizer should be able to reach for at least one octave with variable control voltage. The filter should have at least three different outputs. Another goal with this project was also to get a good understanding of oscillator and filter design and principles considering construction of electronic applications.

Chapter 2

Theory

2.1 *Barkhausen Condition*s

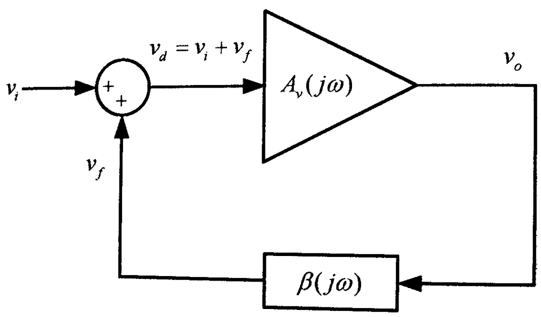

Figure 2.1: A simple feedback oscillator circuit [4]

The classic *Barkhausen Condition*s can be used to calculate minimum gain of a circuit and also used to calculate the frequency of oscillation. [4]. The conditions are given by equation 2.1 and 2.2.

$$\beta_r(\omega)A_v(j\omega) = 1 = A_v(j\omega) = \frac{1}{\beta_r(\omega)} \tag{2.1}$$

$$\beta_i(\omega)A_v(j\omega) = 0 = \beta_i(\omega) = 0 \tag{2.2}$$

These conditions are derived from the gain expression from a feedback oscillator as in figure 2.1. The condition given by equation 2.1 is known as the gain condition and the condition given by equation 2.2 is known as the condition for oscillation. From figure 2.1, the expression of the gain can be written as equation 2.3.

$$A_{vf}(j\omega) = \frac{v_{out}}{v_{in}} = \frac{A_v(j\omega)}{1 - \beta(j\omega)A_v(j\omega)} \tag{2.3}$$

Because the oscillator should work without the input signal v_{in}, the expression in equation 2.4 derives from equation 2.3.

$$\beta(j\omega)A_v(j\omega) = 1 \tag{2.4}$$

The complex form of equation 2.4 can also be written with separate real and imaginary parts, as shown in equation 2.5. The *Barkhausen Conditions* are then derived from equation 2.5.

$$\beta_r(\omega)A_v(j\omega) + j\beta_i(\omega)A_v(j\omega) = 1 \tag{2.5}$$

Chapter 3

Analog Synthesizer Building Blocks

An analog synthesizer consists of several blocks with different functions as seen in figure 3.1. These are interconnected to create a complete application that can be used as a musical instrument. A short description of the blocks is presented below.

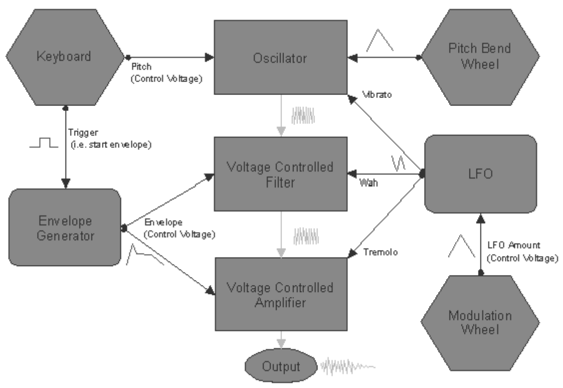

Figure 3.1: Practical correlation between different parts of an analog synthesizer, [1]. An enlargement can be found at page 59.

3.1 The Keyboard

The keyboard is the part mainly used for interaction and playing. It usually sets a control voltage to control the pitch of the oscillators and filters. It also sends a trigger signal, or gate signal, which is used to trigger an envelope generator.

3.2 Voltage Controlled Amplifier

An important building block is the voltage controlled amplifier. It takes a control voltage from the envelope generator and adjusts the amplification based on its potential. Usually when the envelope signal is ground ($0\ V$) the amplifier blocks the signal completely. It can also be controlled by the LFO to create tremolo effects.

3.3 Envelope Generator

To control the VCA[1] the main use is an envelope generator. This block generates a continuous control voltage signal. The user can often decide some options for the envelope, such as attack time, decay time, sustain level and time and release time. This is important because it allows the user to create more realistic sounds. For example, a snare drum sound could be described with a fast attack, low sustain and short release time. This would sound *snappy*. Flute and other instruments could be designed in the opposite direction of a snare drum, with quite slow attack, high sustain and a decent amount of release. If you study figure 10.1 at page 37, the amplitude of the curve could be described as the amount of signal that is audiable depending on the time. The envelope generator can also be used to modulate filters and oscillators.

3.4 Voltage Controlled Oscillator

The block that creates the tones are the oscillator. Usually a synthesizer has more than one oscillator. The pitch, or frequency the oscillator produces is as described in section 3.1, determined by the control voltage from the keyboard. Modern analog synthesizers can also be controlled by midi. Because of midi being a digital interface, a D/A conversion is needed to convert the digital pitch signal to usable control voltage [2]. The oscillators can also take signals from the LFO[2] and bend wheel. Similar conversion applies with midi control.

3.5 Voltage Controlled Filter

All analog synthesizers use some kind of active filter to adjust harmonics, or timbre, to the sound. This is necessary to be able to create different sounds. For example a low pass filter that is used on a square wave oscillator signal will sound hollow or woody, like a clarinet. If a classic sawtooth wave signal is filtered by the low pass filter, it will sound more like a cello. Usually an analog synthesizer has low pass, high pass and band pass filter outputs, often of both 2^{nd} and 4^{th} order. The cutoff frequency and resonance can often be controlled by a control voltage signal. This can come from the keyboard, the envelope generator or LFO.

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[1] Voltage Controlled Amplifier
[2] Low Frequency Oscillator

3.6 Low Frequency Oscillator

This block is similar to the voltage controlled oscillator but produces a lot lower frequencies, usually below 30 Hz. Its main usage is for modulation of other blocks and has often sine wave or triangular wave output. The output signal can be used as a vibrato with the oscillator or a wahwah effect if used with the filter. The speed of the oscillator is usually controlled by a panel potentiometer.

Chapter 4

Electronic Filter and Oscillator Guidelines

There are several guidelines when designing an active filter or oscillator. The selection of components can have a great impact of the results and there is often a lot of non ideal problems that has to be considered. This can be critical in filter or oscillator design. The designer has to be aware of these problems. [3]

4.1 Non-linearities and Non-ideality

When designing an electronic circuit it's often preferred to work with ideal components to make calculations easier. A problem though is that components never are ideal. Non linear components are also treated in a more linear way, with simplified formulas. [4]

Frequency stability: Components like capacitors among others are affected by aging and temperature in a way that causes it's value to change. This can result in unwanted frequency instability. Other things that affect this frequency are noise and mechanical vibrations.

Amplitude noise (AM): To reduce amplitude noise, a limiter can be designed to reduce distortion.

Phase noise (FM): There are a few different things that should be considered;

- Chose a transistor with a low flicker noise
- Use a resonator with a high Q-value
- Chose a transistor with a low noise at input impedance for the amplifier
- Design the oscillator for a wide noise threshold, i.e. the lowest noise the transistor deliver, and avoid saturation for the transistor.

There are a lot of *Computer Aided Design* programs that are good with analysing/simulating the non ideality and non linearities. This is why a *Computer Aided Design* program, like *Cadence Orcad Pspice A/D*, is highly advised to use when designing the circuits.

Some non idealities with operational amplifiers are bias offsets and current offsets. [5] These can be quite big if the operational amplifier has high gain.

4.2 Components

Ceramic capacitors should be avoided as those are quite dependent on temperature and has quite high tolerance values. Electrolytic capacitors should also be avoided based the same statement as ceramic capacitors, with addition that they require a bias voltage and are often polarity dependent. This can cause problems with signals that alter sign of polarity.

Most resistors work well but it's often preferred to use metal-film resistors instead of the ordinary carbon-film. Metal-film resistors have less then 1 % tolerance while carbon-film usually has 5 %. A trick is to use trim potentiometers in important positions that determine frequency. It can give a 5 % to 10 % adjustment range if placed in series with the resistor. There are also precision resistors available but those are far greater in price than metal-film resistors.

One should also regard the power dissipation by the components in the circuits. In micro electronic active filters and oscillators, a power rating at $\frac{1}{4}$ W is usually enough.

Chapter 5

Design Basics

5.1 Basic Definitions

Some different words are used throughout the report. See table 5.1. In these schematics, `VCC` is $+12\ V$ and `VDD` is $-12\ V$.

Table 5.1: Voltage Definitions

`VCC`: Used as a potential reference.

`VDD`: Used as a potential reference.

`GND`: Always ground with $0\ V$ potential

`CV`: Control Voltage. Used to describe a variable voltage potential.

5.2 Circuit Design

Every design is first drawn by hand with a quick overall assumption of the function. Then each circuit is drawn in *Cadence Orcad Capture CIS* and simulated using *Cadence Orcad Pspice A/D*. The operational amplifiers used throughout the designs are the *TL082* [6]. The operational amplifiers *TL082* are cheap dual package operational amplifiers that are relatively noisy and have relatively high bias offsets compared to more expensive amplifiers. They were chosen because of the low price. For the transconductance amplifiers, *LM13700* [7] was chosen because of high quality and matched pairs in one `DIL`[1]-package.

[1] Dual In-Line

Chapter 6

Low Frequency Oscillator

6.1 Background

The LFO is based on the classical *Wien Bridge* oscillator, figure 6.1. The *Wien Bridge* oscillator is capable of producing sine wave output of distortion below 0.2 % when using a good amplitude limiting circuit. The frequency of the oscillator is determined by the values of R and C. The feedback gain is determined by R_1 and R_2.

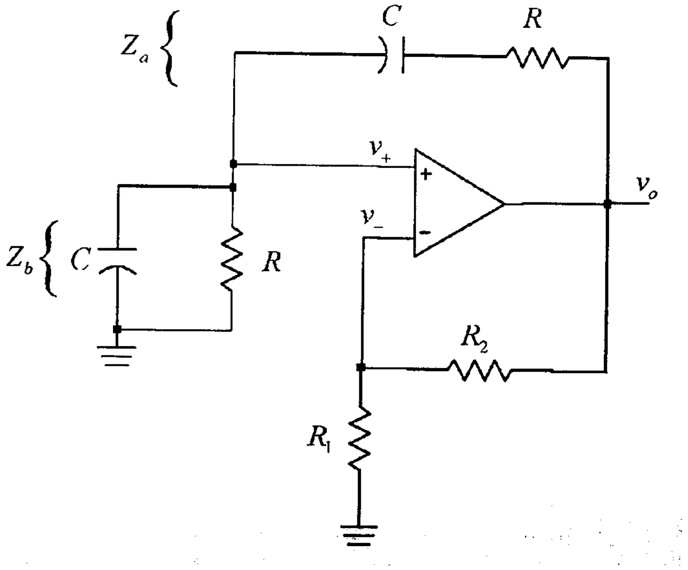

Figure 6.1: The classical *Wien Bridge* Oscillator [4]

The gain for the *Wien Bridge* oscillator can be easily obtained by a circuit analysis. The operational amplifier works in a non inverting connection so the gain is basically as shown in equation 6.1.

$$A_v(j\omega) = \frac{v_o}{v_+} = 1 + \frac{R_2}{R_1} \tag{6.1}$$

The non inverting input voltage of the operational amplifier is given by equation 6.2.

$$v_+ = v_o \frac{1}{3 + j(\omega RC - \frac{1}{\omega RC})} \tag{6.2}$$

According to *Barkhausen Condition* from equation 2.1 at page 13, the imaginary part of the feedback has to be zero for oscillation to start. If *Barkhausen Condition* is applied to equation 6.2 the frequency of oscillation can be derived to equation 6.3.

$$f = \frac{1}{2\pi RC} \tag{6.3}$$

The *Barkhausen Condition* given by equation 2.1 at page 13 applied to equation 6.1 gives a minimum gain of the circuit for oscillation to continue. The gain can therefore be written as equation 6.4. The relationship between R_1 and R_2 can then be extracted.

$$A_{vo} = \frac{1}{\beta_r(\omega_0)} = 3 \tag{6.4}$$

$$A_v(jw) = 1 - \frac{R_2}{R_1} = 3 \tag{6.5}$$

$$R_2 = 2R_1 \tag{6.6}$$

The value of R_2 should be slightly greater than $2R_1$ to make sure the oscillation is sustained. The oscillator starts faster with a higher gain, but it increases distortion of the output.

6.2 Circuit Design

The final circuit for the `LFO` can be seen in figure D.2 at page 66, where $R_{28} = 1\ k\Omega$ which is R_1 in figure 6.1 at page 23 and $R_{27} = 2.2\ k\Omega$ which is R_2 in figure 6.1. This gives a gain between $[3.156, 3.244]$ depending of the resistors tolerance of in this case 1 %

The bipolar electrolytic capacitors C_{15} and C_{16} have a value of 47 uF. The frequency is controlled by a logarithmic stereo potentiometer connected in series with two resistors of 100 Ω.

6.3 Simulation

The calculated frequency reach is about 0.335 – 33.86 Hz. A higher frequency is produced by a lower value of the resistance.

6.4 Analysis

The simulated frequency range is really close the constructed results of $0.2 - 30\ Hz$. The frequencies seem to be a bit lower than the theoretical values, which probably is because of resistor and capacitance tolerance.

The four *1N4448* diodes work as a simple limiter. When the voltage is below or above a certain level the current through the diodes are limited. It works somewhat, and seems to work better for a high frequency than a low frequency. The U_2A is the main operational amplifier for the oscillator while U_2B, $U_{20}B$, $U_{21}B$, $U_{27}B$, $U_{28}B$ are used as buffers. The use of buffers allows the oscillator to work independently of the load of the outputs. The output from buffer U_2B is used to drive two LEDs. The $R_{38} = 4.7\ k\Omega$ limits the current through the LEDs, to protect them for burning to quickly. These LEDs work as an indication of the oscillation speed and also help shaping the square wave output. The sine wave is obtained from the two *1N4448* diodes before the inverting input of the U_2A. Between the $U_{20}B/U_{21}B$ and $U_{27}B/U_{28}B$ are two potentiometers. The potentiometers adjust the amplitude of the signal.

Chapter 7

Voltage Controlled Filter

7.1 Background

The filter is based on a design by Don Lancaster [3]. It is a state variable bandpass filter with additional high pass and low pass outputs. The gain is always 1, except for the bandpass which has gain of `Q`. See figure 7.1.

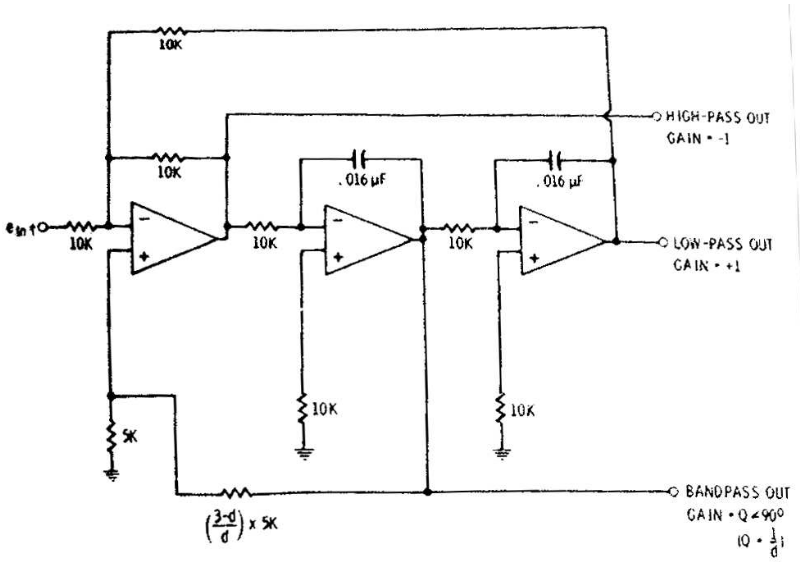

Figure 7.1: A unity gain, state-variable filter [3]

The resistors at the intersection between operational amplifiers 1 – 2 and 2 – 3 determine the cutoff frequency together with the capacitors. Either the capacitors or both resistors need to change at the same time and with the same amount to change frequency. The resistors connected from the positive inputs of the operational amplifiers to ground are used to compensate for offset variations. These are not critical and can be replaced by a short circuit. The resonance/Q-value, or damping, can be adjusted by adjusting the resistor marked with $\frac{3-d}{d}5k$. For example a value $d = 0.2$, the low pass and high pass outputs will have a damping value of 0.2 and the bandpass Q will be 5. All outputs will have ideally identical amplitude and frequency.

To be able to adjust the cutoff frequency with a control voltage, the two frequency-determining resistors of figure 7.1 are replaced with two *LM13700* with a configuration to work as a voltage controlled resistance. See figure 7.2.

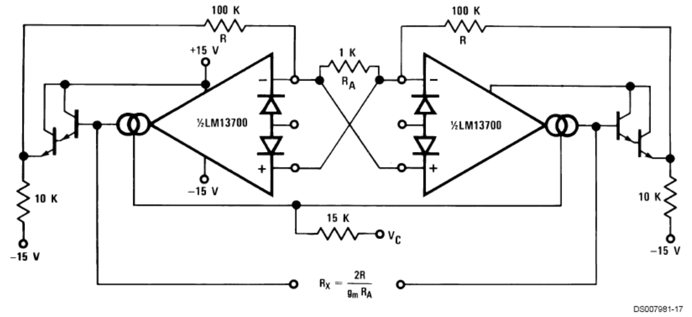

Figure 7.2: Floating point voltage controlled resistance, [7]

The resistance between the outputs of the amplifiers can be expressed as equation 7.1, where g_m is the transconductance of the amplifiers. R and R_A are the resistors shown in figure 7.2.

$$R_x = \frac{2R}{g_m R_A} \tag{7.1}$$

The transconductance is depending on the amplifier bias current, see figure C.1 at page 63. A simplified expression, equation 7.2, for the transconductance can be found in the data sheet of *LM13700*, where I_{ABC} is the amplifier bias current at 25 *degrees C*.

$$g_m \approx 19.2 I_{ABC} \tag{7.2}$$

7.2 Circuit Design

The final design is seen in figure D.3 at page 67. To avoid unwanted distortion when the resonance is adjusted, the input signals should be lower then 1 V peak to peak. To adjust this, a summing amplifier $U_{29}A$ is used with a gain of -10. The input is obtained from high level sources, such as the oscillators, and they have amplitude of about 11 V_{rms}. R_{118} could be replaced with a potentiometer to be able to adjust the input gain if used in other applications.

The resonance is adjusted with the feedback gain by potentiometer R_{RES}. The $U_{14}A$ and $U_{14}B$ are one *LM13700* package and $U_{15}A$ and $U_{15}B$ are another. This configuration for a voltage controlled resistance is found in the data sheet for the *LM13700* [7]. The potentiometer R_{TUNE_F} adjusts the frequency by adjusting how much current to feed the *LM13700* with. It is actually the current to the amplifier bias input that controls the resistance. The CV input is used to fine tune the filter over one octave. The CV range is from $0 - 12$ V. The diode bias inputs of the *LM13700* are not used. They can be used to linearize the amplifier bias input, but because of the logarithmic nature of audio, it is preferred to not use the diode bias inputs.

Each output is buffered with operational amplifiers so the load won't affect the behavior of the filter.

7.3 Simulation

The resulting Baude-plot for each output for a test CV signal can be seen in figure 7.3, figure 7.4 and figure 7.5 at page 30.

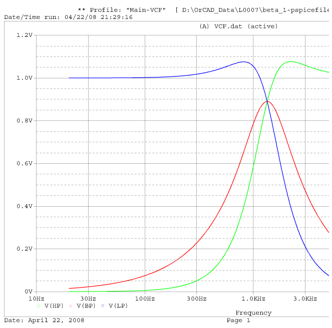

Figure 7.3: Simulated frequency response plot of the voltage controlled filter with 50 % resonance and control voltage of 1 V. The cutoff potentiometer is held at 50 $k\Omega$

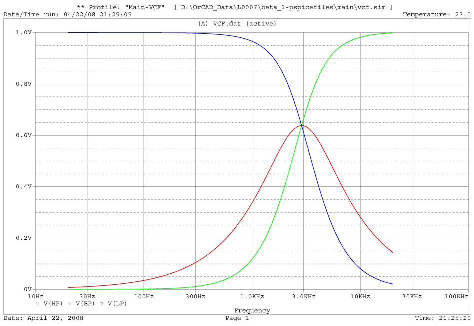

Figure 7.4: Simulated Baude-plot of the Voltage Controlled Filter with resonance at 0 % and a cutoff at 100 % and 1 V control voltage

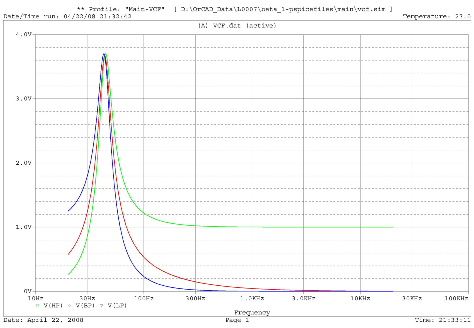

Figure 7.5: Simulated Baude-plot of the Voltage Controlled Filter with 100 % resonance and 0 % cutoff and 1 V control voltage

Chapter 8

Voltage Controlled Oscillator

8.1 Background

The voltage controlled oscillator is based on the voltage controlled bandpass filter. The difference is that the bandpass output is feed back to the filter input, see figure 8.1 at page 31. The gain of the limiter should be adjusted so that it fulfills the *Barkhausen Conditions*.

The frequency of oscillation is set by adjusting the center frequency for the bandpass filter. The distortion of the sine wave output is adjusted with the Q value of the filter. In theory a sine wave output can be obtained with under 0.2 % distortion. [3]

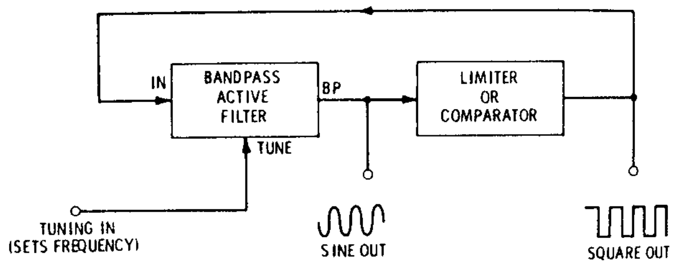

Figure 8.1: A way of creating a voltage controlled oscillator based on an active bandpass filter. [3]

8.2 Circuit Design

The oscillator used in this analog synthesizer has two other output wave forms. It has one square wave/triangular wave output and one sine pulse waveform. The finished design can be seen in figure D.4 at page 68.

It works the same way of adjusting the frequency as the voltage controlled filter described in the previous section. The difference is that the output of the filter is fed back to the input, with a gain of at least 8. The output of the first operational amplifier U_5A will be square wave of constant amplitude. The other two operational amplifiers U_5B, U_6A performs the filter operations. The frequency is determined by the two capacitors C_{17} and C_{18} together with the resistance generated by the two *LM13700* components. The ground frequency can be adjusted with the potentiometer R_{TUNE_O} together with the bend wheel potentiometer R_{BEND_O1}. The operational amplifiers U_6B and U_7B are additional buffers to allow the oscillator to work independently of the load.

8.3 Simulation

A simulation of the oscillator with observation point at the square wave output and the square wave/triangular wave output are shown in figure 8.2 and 8.4. The square wave can be obtained at the output of U_5B. The frequency of the oscillator can be analyzed with a *Fast Fourier Transform* analysis, shown in figure 8.3 and 8.5 respectively. The simulated frequency is centered about 75 Hz with 1 V CV and 150 Hz with 12 V CV.

The amplitude is about 11 V_{rms}, the maximum output the *TL082* can deliver with a power supply of $+/-$ 12 V. [6]

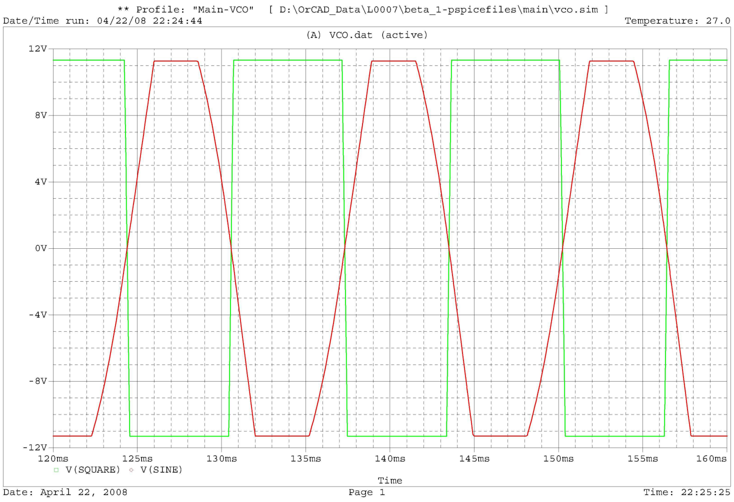

Figure 8.2: A simulated output of the voltage controlled oscillator with 1 V control voltage

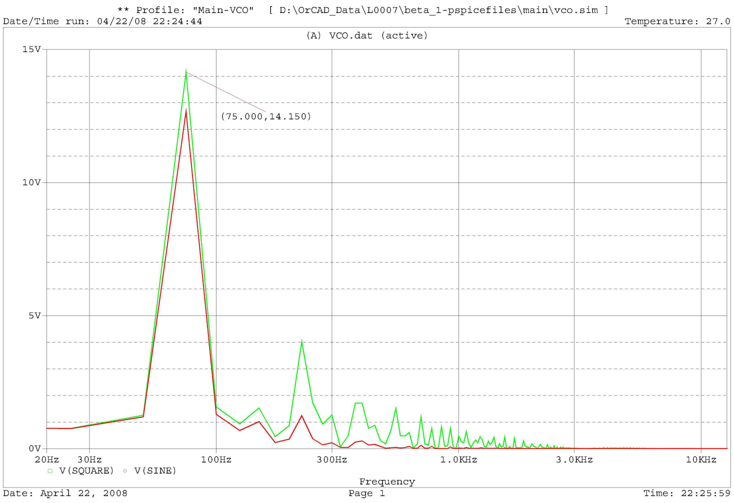

Figure 8.3: A *Fast Fourier Transform* analysis of the simulated output of the voltage controlled oscillator with 1 V control voltage. Ground frequency is 75 Hz

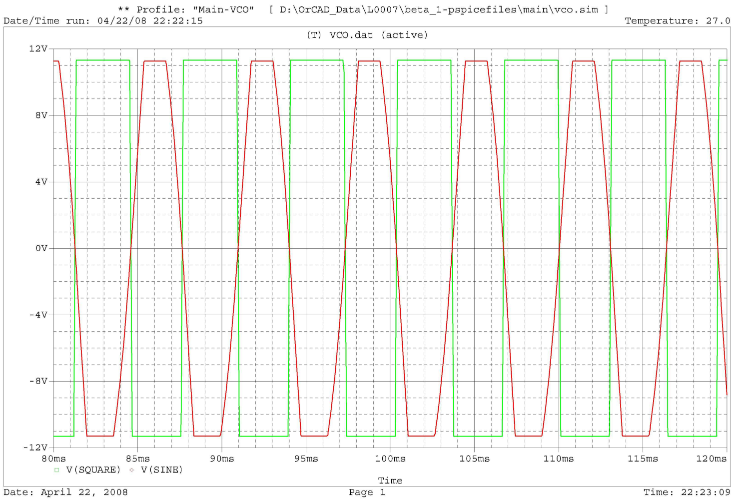

Figure 8.4: A simulated output of the voltage controlled oscillator with 12 V control voltage

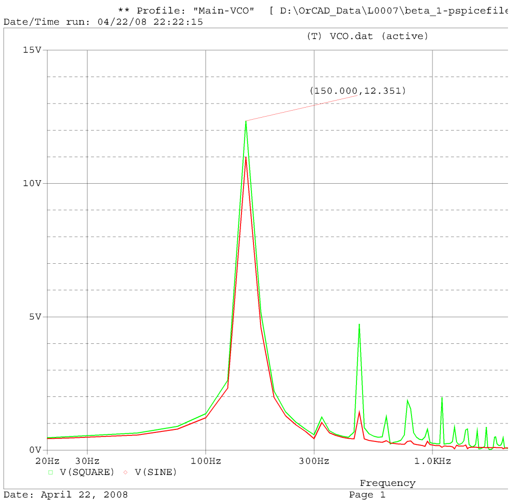

Figure 8.5: A *Fast Fourier Transform* analysis of the simulated output of the voltage controlled oscillator with 12 V control voltage. Ground frequency is 150 Hz

Chapter 9

Keyboard Control Circuit

9.1 Circuit Design

The keyboard control circuit was designed without simulation of the function because the key model was not present in the available libraries for *Cadence Orcad Pspice A/D*. The schematic of the first design is shown in figure D.5 at page 69.

The potentiometers R_{95} to R_{106} are used to adjust the voltage level passed to the buffers, $U_{22}B$, $U_{19}A$ and $U_{23}B$. The switches Sw_1 to Sw_{12} are the keys of the keyboard and therefore select which potentiometer to be used. The keyboard layout only allows one switch to be pressed at once. When all switches are depressed, the voltage level will be $-12\ V$. This is because of the resistor $R_{112} = 1\ M\Omega$ connected to the `VDD` terminal.

Between the first buffers $U_{22}B$, $U_{19}A$ and $U_{23}B$ and the second buffers $U_{22}A$, $U_{23}A$ and $U_{24}A$ there are modulation inputs. These can be connected to any waveform to modulate the output control voltage. The secondary buffers deliver the control voltage to each block, in this case the two voltage controlled oscillators and the voltage controlled filter.

The operational amplifier $U_{19}B$ is used in a comparator connection [8].

9.2 Analysis

When the voltage level of the non-inverting input of the operational amplifier is above the voltage level set on the inverting input, the output will be at VCC. When the voltage level of the non-inverting input of the operational amplifier is below the voltage level of the inverting input, the output will be at VDD. The inverting input of the operational amplifier is connected to ground, so when any switch is pressed, the output of $U_{19}B$ will be VCC and VDD otherwise. The output of $U_{19}B$ serves as a gate signal, which can be used to trigger envelope generators or other functions.

Because of the output control voltages is VDD when no switch is pressed, this results in a current being drawn from the *LM13700* components used in those circuits given the control voltage. [5] This results in that the oscillators won't oscillate and the filter will be cut off completely and thus serves as an on/off gate.

There is one big problem with the design seen in figure D.5 at page 69. The circuit sets the control voltage as it should, but together with the other circuits which uses the control voltage to control frequency, it's range is too small. There are two easy ways to make the interrelation better.

- Change the keyboard control circuit so it delivers a control current instead of a voltage.
- Design a voltage to current driver that can deliver a wider range of current depending on the voltage.

The selected approach in this project is the first one, change the keyboard control circuit to a current output. This can easily be accomplished by connecting every potentiometer R_{95} to R_{106} as variable resistance instead of a voltage divider.

Chapter 10

The Envelope Generator

10.1 Background

An envelope generator takes a gate signal and outputs a generated envelope. Most analog synths have envelope generators that produce an envelope with variable time constants of attack, decay and release and also a sustain level. One example of a classical `ADSR` envelope generator is shown in figure 10.1.

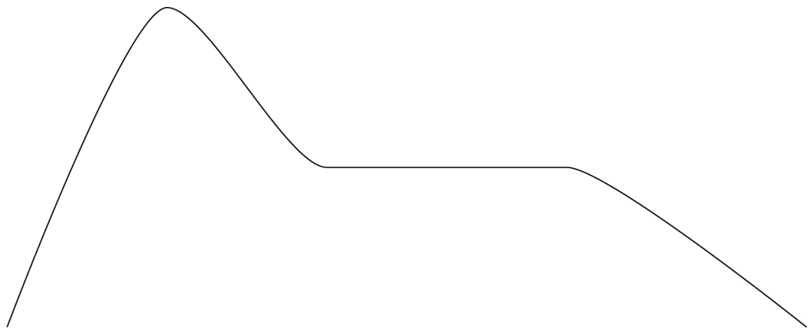

Figure 10.1: A control voltage envelope of a classical ADSR envelope generator

10.2 Circuit Design

The circuit design used in this synthesizer only uses attack and release, and sustain level is always kept at `GND`. The circuit design is shown in figure D.1 at page 65.

10.3 Analysis

The envelope generator works like a digital `TTL` inverter. When the gate signal is below `GND`, the `PNP` transistor Q_1 [9] will allow current to pass from `VCC` through the transistor and charge the capacitor to `VCC`. The time of charge is set by the potentiometer R_{122} and the value of C_{23}. The time constant can be written as equation 10.1.

$$\tau = RC \tag{10.1}$$

When the gate signal turns high, the `PNP` transistor turns off, and the `NPN` transistor Q_2 [5] turns on. This allows the capacitor to uncharge through the `NPN` transistor with the time constant set by the potentiometer R_{123}. It might be noted that the schematic is simulated using the `NPN` transistor *BC550B* instead of *BC537* [10] used in final construction. This is because that *Cadence Orcad Pspice A/D* did not have the *BC537* in the standard library available for simulation. Anyhow the behavior is almost the same. The `ADSR` output is shown in figure 10.2. The output from the buffer $U_{24}B$ is shown in figure 10.3. In this synthesizer, the envelope generator is used mainly for frequency modulation.

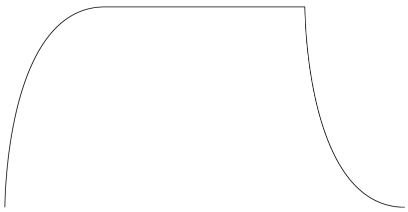

Figure 10.2: The Control Voltage generated with the circuit in figure D.1 at page 65

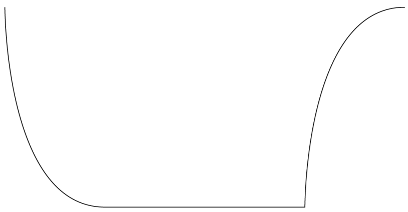

Figure 10.3: The control voltage generated with the inverted circuit output

Chapter 11

Body design

When designing the body and layout of the Interconnection, a *Computer Aided Design*-program *NX 4.0* was used. Each potentiometer, switches and etc was measured and modelled. In figure 11.1, the concept of the keyboard module can be seen. And the first concept of the main body can be seen in figure 11.2 at page 40.

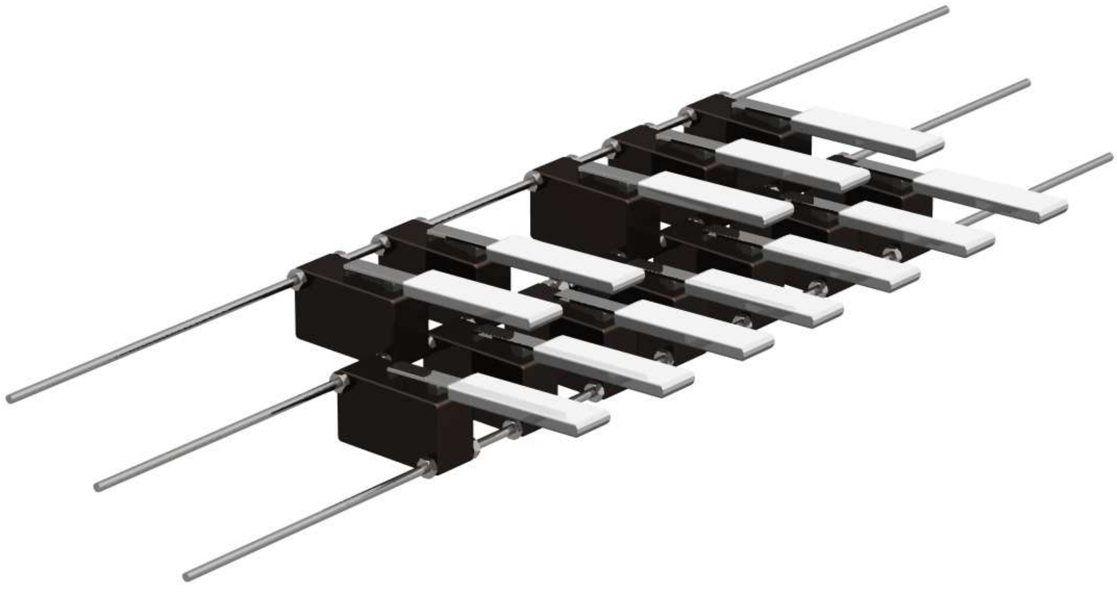

Figure 11.1: A concept draft of the keyboard module design created in *NX 4.0*.

Figure 11.2: A concept draft of the main body design created in *NX 4.0*.

Chapter 12

Construction

12.1 Circuit Construction

All capacitors used in the voltage controlled filter and the voltage controlled oscillators are metal-coated polypropylene of 47 nF. These have great performance over aging and temperature, but are somewhat expensive. They are also low inductive and very suitable for audio applications. All resistors are of metal-film type with 1% tolerance.

The capacitors used in the low frequency oscillator are bipolar electrolytic. Even though they require a small bias voltage, they work well. The capacitor used in the envelope generator is a low leakage electrolytic of 47 μF.

Each schematic was laid out on experimental boards. Every component was placed so a minimum of extra connections were needed. When every component was in place, they were fixed with tape and then soldered.

Every schematic has its own experimental board except the voltage controlled oscillators. Both oscillators are placed on the same board for simplicity reasons.

The power supply uses a *Traco Power* component, the *TEL3-0522* [11]. This allows the input power to range from $4.5 - 9.0\ V$ DC. The component output is a dual supply of $+12\ V$, $-12\ V$ and common ground. From `VCC` to `GND` there are one ceramic capacitor of 22 nF to make the power supply more stable. This capacitor should be chosen in respect to the output ripple. There is also one capacitor from `VDD` to `GND`.

Every `DIL`[1] package is mounted on sockets for easy reparation and debugging. Especially the *LM13700* is very sensitive against static discharges.

[1] Dual In-Line

12.2 Keyboard Construction

The keyboard uses 12 *Camden Electronics CMNS2830D* [12] switches. These have long levers and serve as a clav right away. Some shrink tube was mounted on the levers in three layers to give a better feel of the keys. All switches was connected together using three threaded cylinders of `M3` dimension, see figure 12.1 at page 42.

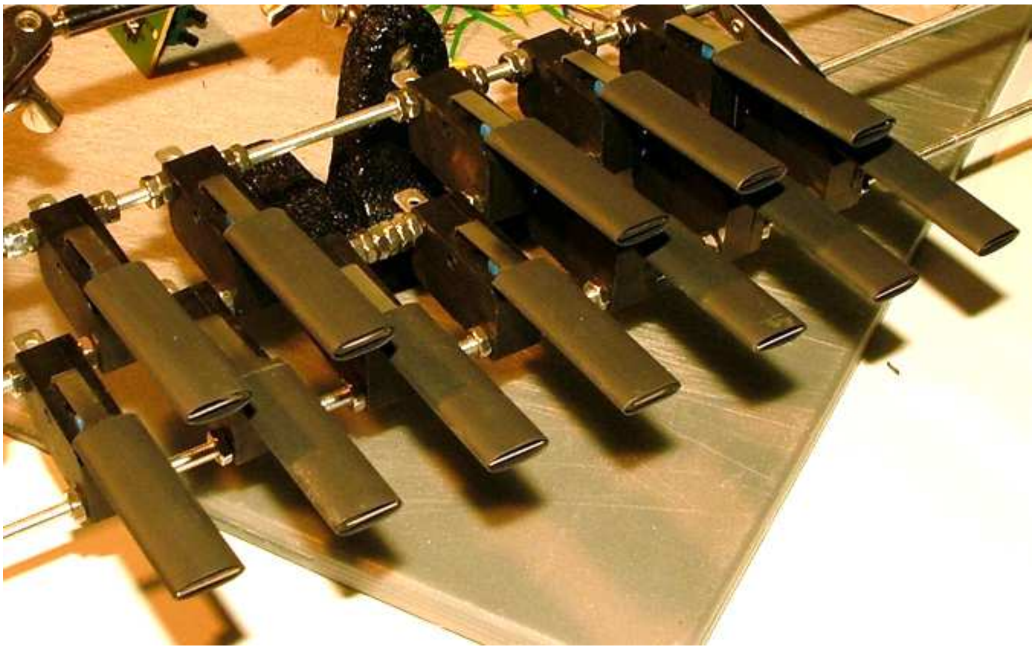

Figure 12.1: Connected keys

12.3 Body Construction

The body was constructed from a hard sheet plastic material. It was heated with 590 $\deg C$ and then bent to create a chassis. Holes were drilled to hold every potentiometer and control voltage output and input connections. The body was spray painted with matte black acrylic color. Controller names were written with a silver permanent water proof marker. Hinges were mounted on the front of the body. The body was mounted on a thick wood sheet. The keyboard module was also mounted on the wood sheet. See figure 12.2. The reason for the keyboard control module to be placed outside of the cover, was space issues. See figure 13.1 at page 45.

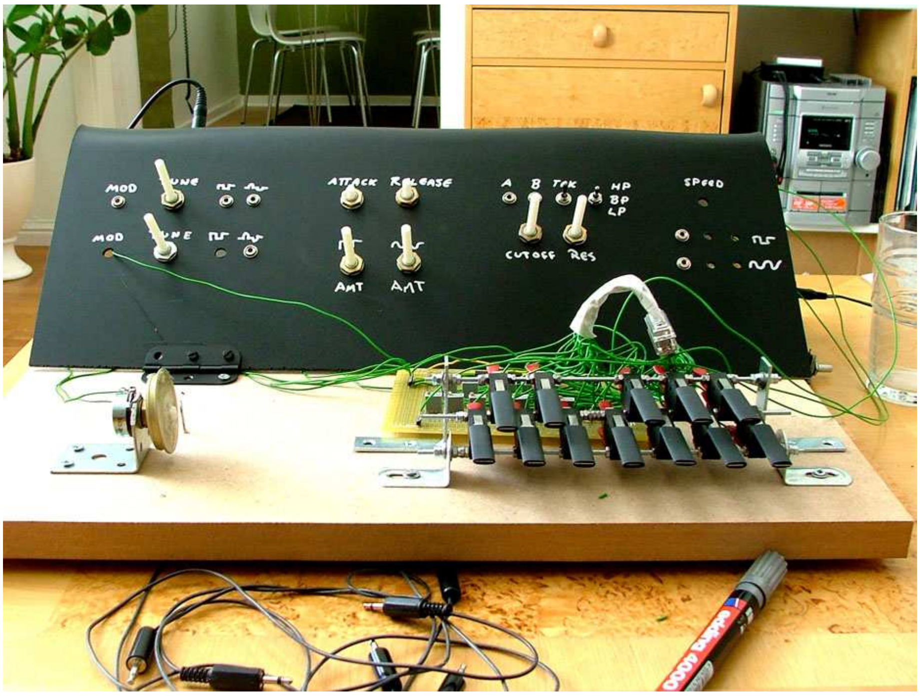

Figure 12.2: The mounted body with control potentiometers, keyboard module and bend wheel

Chapter 13

Circuits and body interconnection

The circuit boards were mounted on the sheet of wood by either wood screw or tape depending on available options on the experimental boards. See figure 13.1 at page 45.

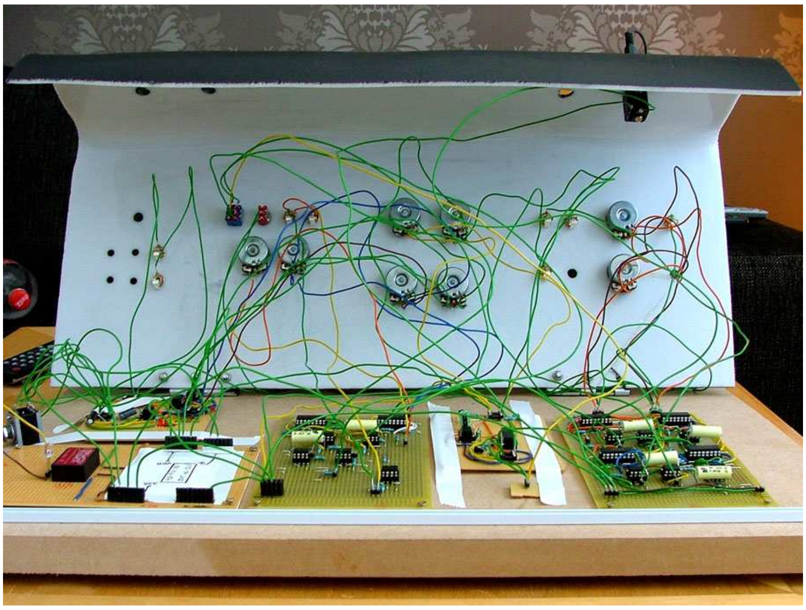

Figure 13.1: Interconnection of the Power Supply Unit, Voltage Controlled Filter, Attack-Release Envelope generator and the Voltage Controlled Oscillator. On the top left there is the Low Frequency Oscillator, control potentiometers and more

Chapter 14

Results

14.1 Oscillator Outputs

After a circuit board was built, it was tested with oscilloscope to make sure it worked as it should. A listening test was also made on the voltage controlled oscillator and voltage controlled filter.

An analysis with oscilloscope was done of the oscillator outputs. The waveforms produced by oscillator 1 are shown in figure 14.1 and 14.2. The waveform produced oscillator 2 is the almost exactly like the output from oscillator 1.

It can be noted that the output level of the sine/pulse output is lower than the square/tri wave output. This might be a problem, and should be fixed by either dampen the square/tri wave or amplify the sine/pulse wave.

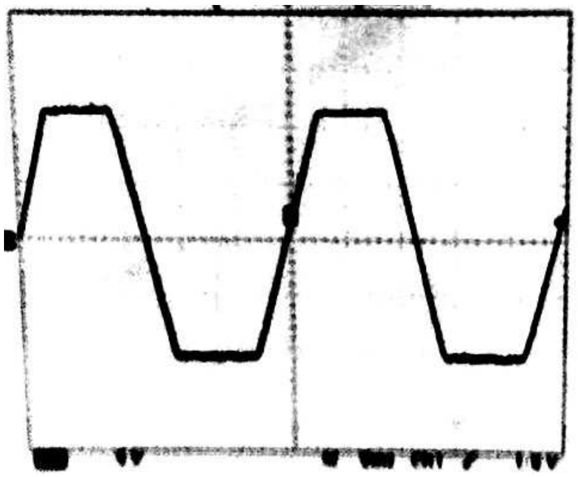

Figure 14.1: Oscillator 1 square wave/triangular wave output

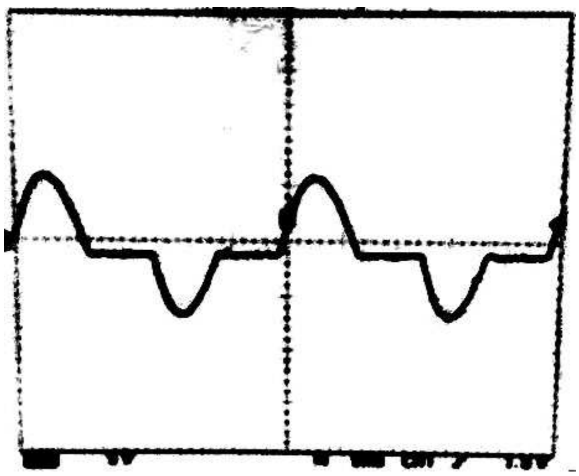

Figure 14.2: Oscillator 1 sine pulse output

14.2 Low Frequency Oscillator Outputs

The square output of the low frequency oscillator is shown in figure 14.3.

There is quite a lot high frequency noise noticeable in the waveform. The low frequency oscillator sine wave output is shown in figure 14.4 and 14.5. The shape of the sine is a lot better in higher frequencies. The high frequency noise that can be seen in the square wave output is less noticeable in the sine wave output.

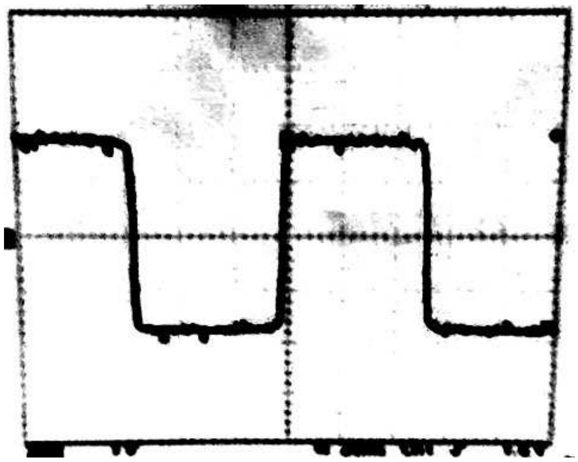

Figure 14.3: Low Frequency Oscillator square wave output

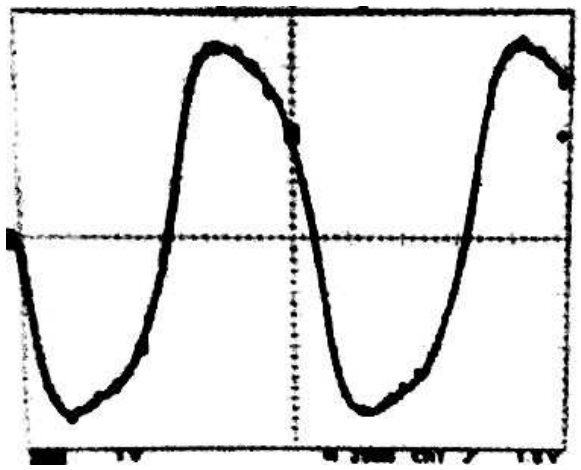

Figure 14.4: Low Frequency Oscillator sine wave output at about 7.4 Hz

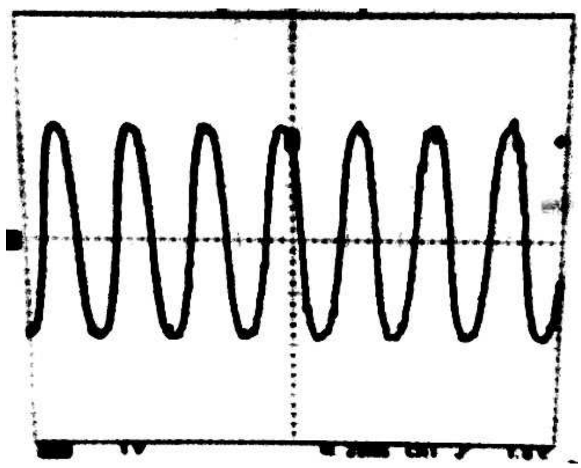

Figure 14.5: Low Frequency Oscillator sine wave output at about 30 Hz

Chapter 15

Enhancements

15.1 Circuits

Some trimming could be done to the circuits to enhance noise and other effects. A critical error was done in the design where the decoupling capacitors for each power supply was forgotten. This will increase noise and make the power supply unstable.

Decoupling ceramic capactitors with a value of 100 nF was used to enchance the circuits.

To reduce humming due to shielding another body was resigned with a metal case connected to ground.

15.2 Control Layout

Due the to linear function of the *LM13700* the control circuit or the circuits using the *LM13700* should be compensated. The easiest way, because of space issues, was to change the control circuit to drive a logarithmic current to the oscillators and filters.

Chapter 16

Discussion

The construction resulted in a playable synthesizer. The range of playable frequencies depends on the ground frequency of the oscillators. This results in a problem when user plays in other frequency ranges then the keyboard control is tuned for. For example, if the user wants to play in a higher frequency range, the keyboard does not hold for one octave. If the user wants to play in a lower frequency range, the keyboard overshoots the tones, resulting on reaching a little bit more than one octave. The tuning should be weight such as minimum offset variations occur when selecting higher or lower frequency ranges of the oscillator. This could be solved by a logarithmic current driver design or re-design the control module to set control current instead of control voltage.

The low frequency oscillator seems to interfere with the other circuits all the time. This might be a shielding problem, caused by relatively high currents and cheap interconnection cables, but it sounds pretty nice actually.

The high pass output of the `VCF`[1] has unsolved problems that still need to be addressed. See figure B.1 at page 61. This is probably a soldering error. It appears that the high pass only applies a negative bias offset of almost $-4\ V$. But the sound it produces indicates the cutoff is always too high for the playing frequency. This is quite strange because of the `VCO` has the exact same control for frequency as the `VCF`. If the error is caused by poor soldering, it will also affect the other outputs of the filter.

The price for the complete construction was below *3500 SEK* which is quite fair. The electronics cost about *2500 SEK*. If better potentiometers are wanted, the price goes up radially.

[1] Voltage Controlled Filter

References

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[4] G. Gonzales, *Foundations of Oscillator Design.* Norwood: Artech House, Inc., 2007.

[5] Sedra/Smith, *Microelectronic Circuits.* Oxford: Oxford University Press, 2004.

[6] "TL082." http://www.elfa.se/pdf/73/731/07311806.pdf, 2008.

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[10] "BC537." http://www.datasheet4u.com/html/B/C/5/BC537_MicroElectronics.pdf.html, 2008.

[11] "TEL3-0522." http://www.elfa.se/pdf/69/06959308.pdf, 2008.

[12] "CMNS2830D." http://www.elfa.se/pdf/35/03570140.pdf, 2008.

List of Figures

Appendix A

Enlargements

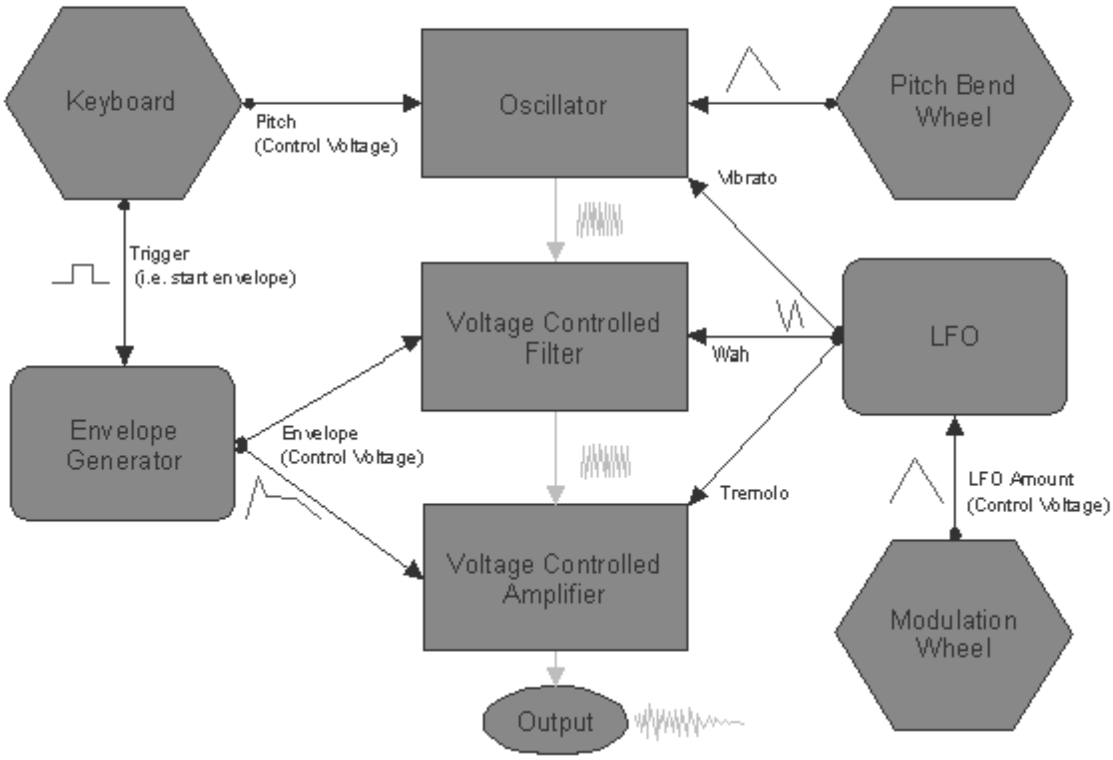

Figure A.1: Practical correlation between different parts of an analog synthesizer, [1]

Appendix B

VCF Outputs

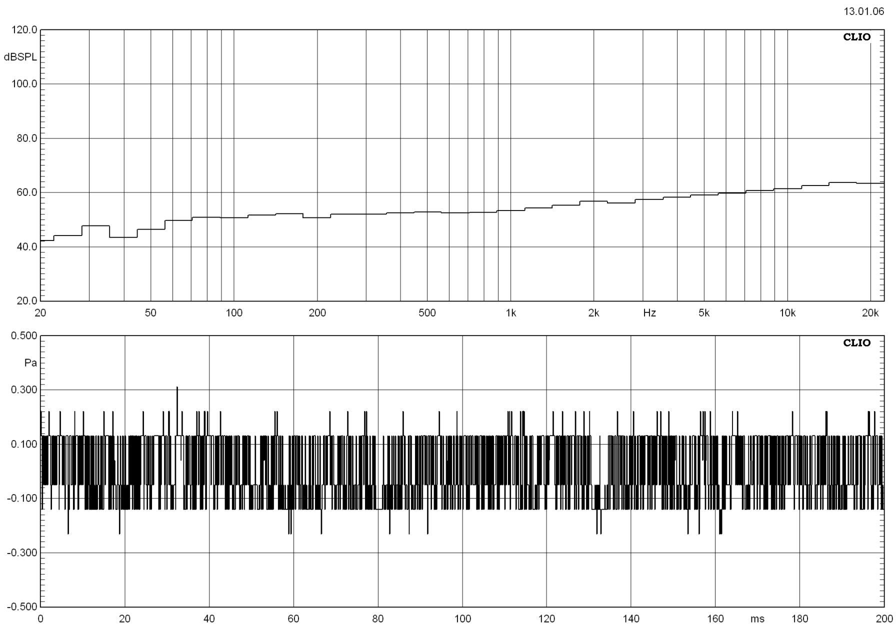

Figure B.1: The strange output of the High Pass Filter

Appendix C

Component Data

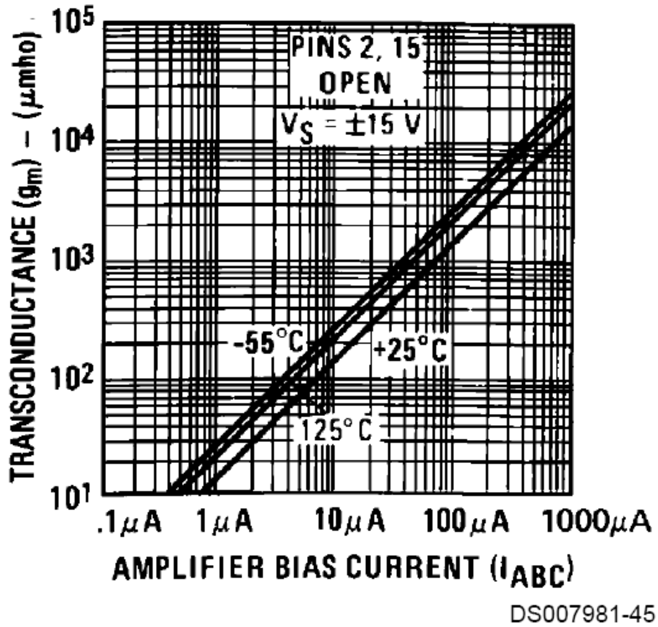

Figure C.1: Transconductance of the *LM13700*

Appendix D

Schematics

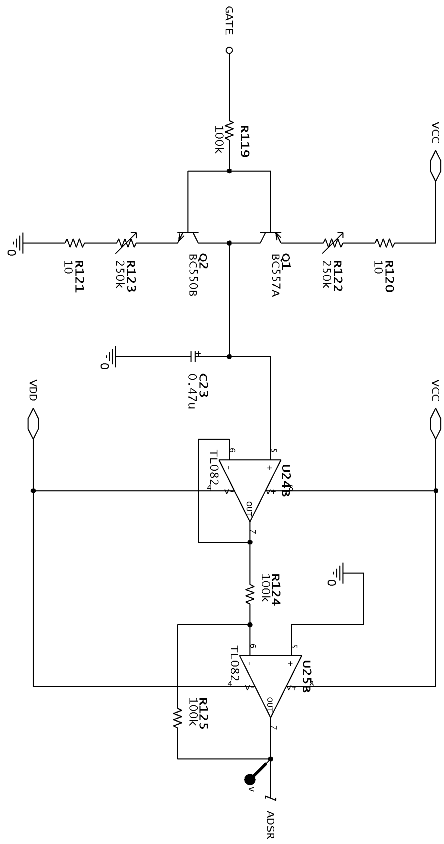

Figure D.1: The finished Attack/Release envelope generator schematic

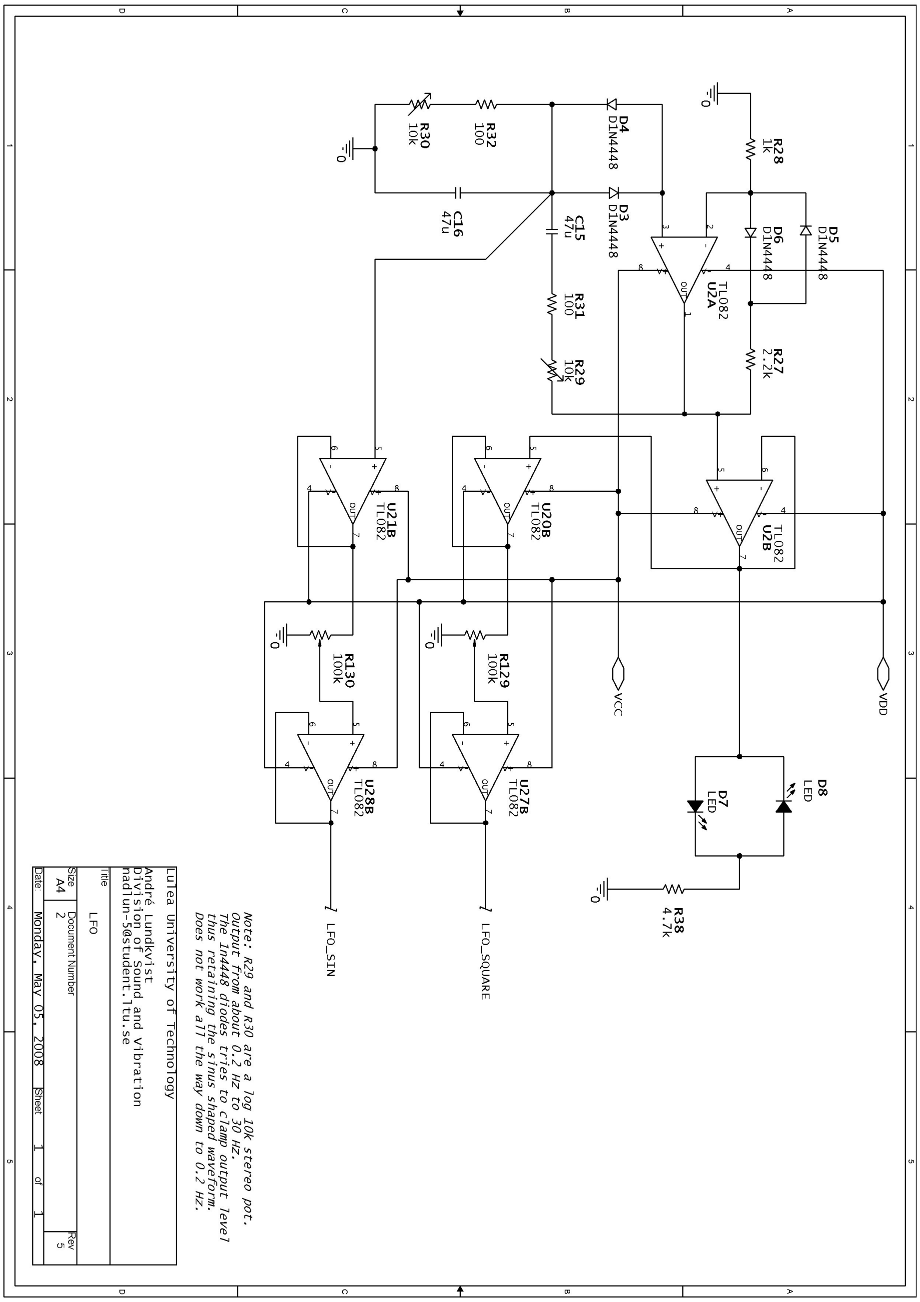

Figure D.2: Final circuit design of the Low Frequency Oscillator

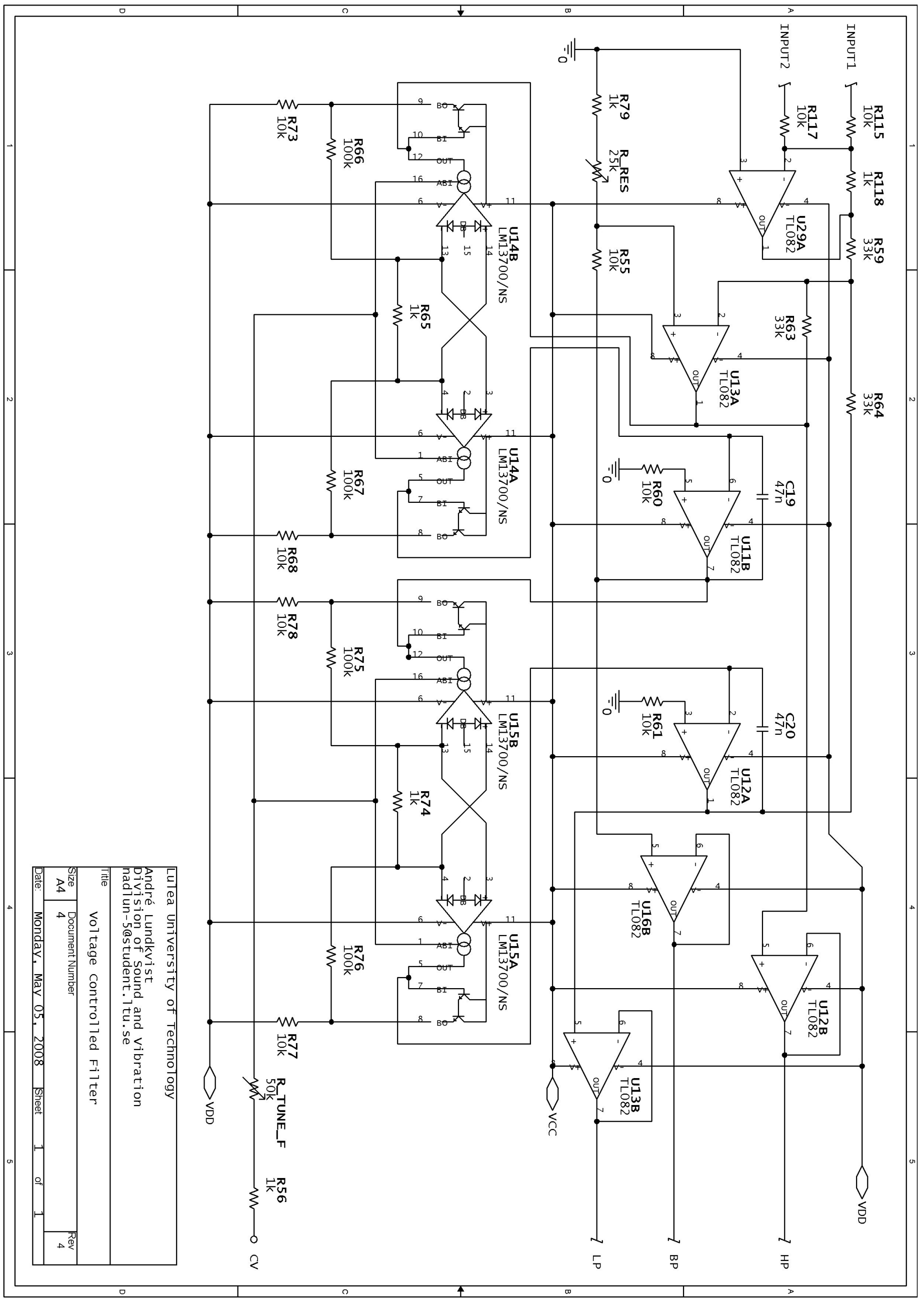

Figure D.3: Final circuit design of the voltage controlled filter

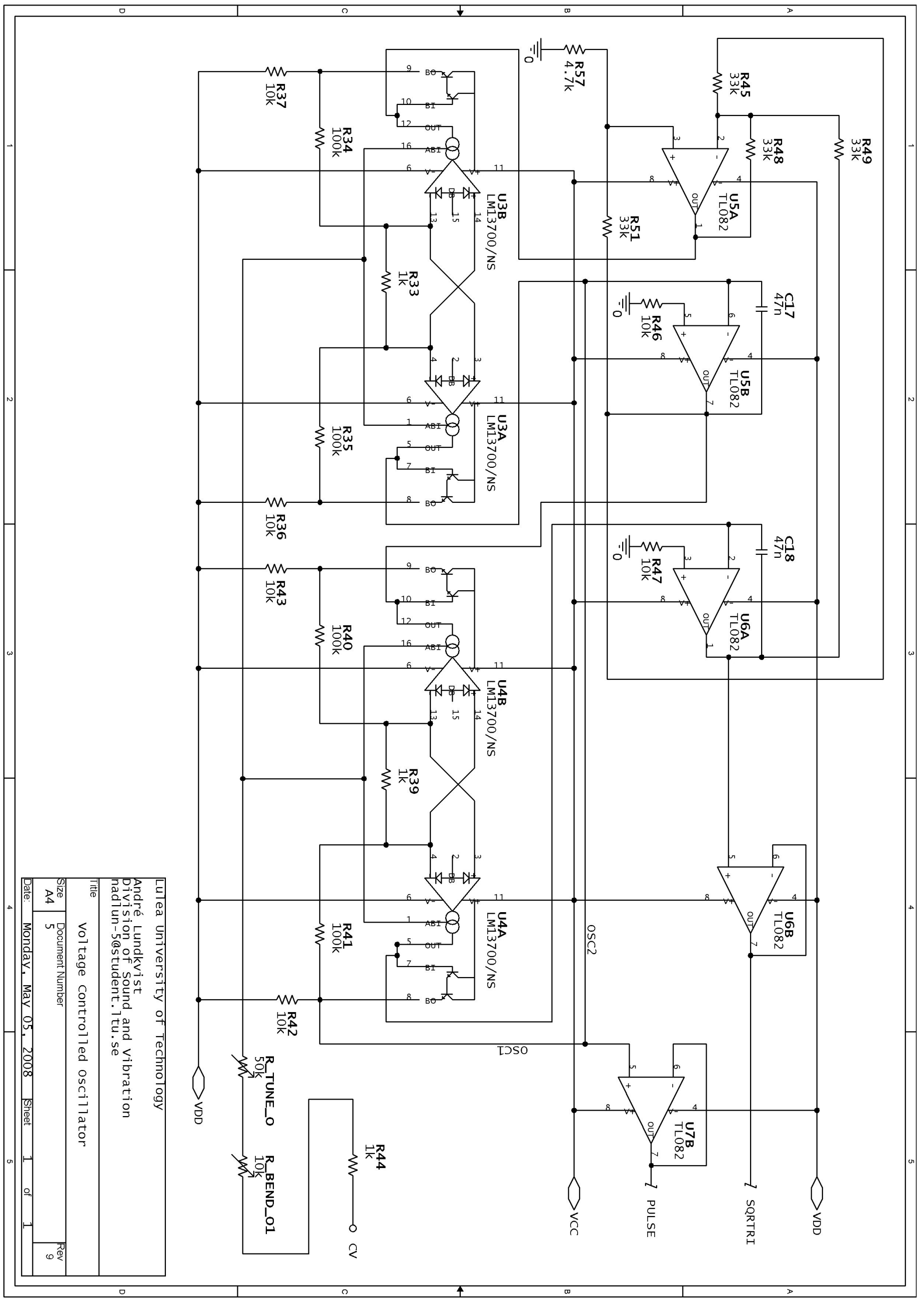

Figure D.4: The finished design of the voltage controlled oscillator

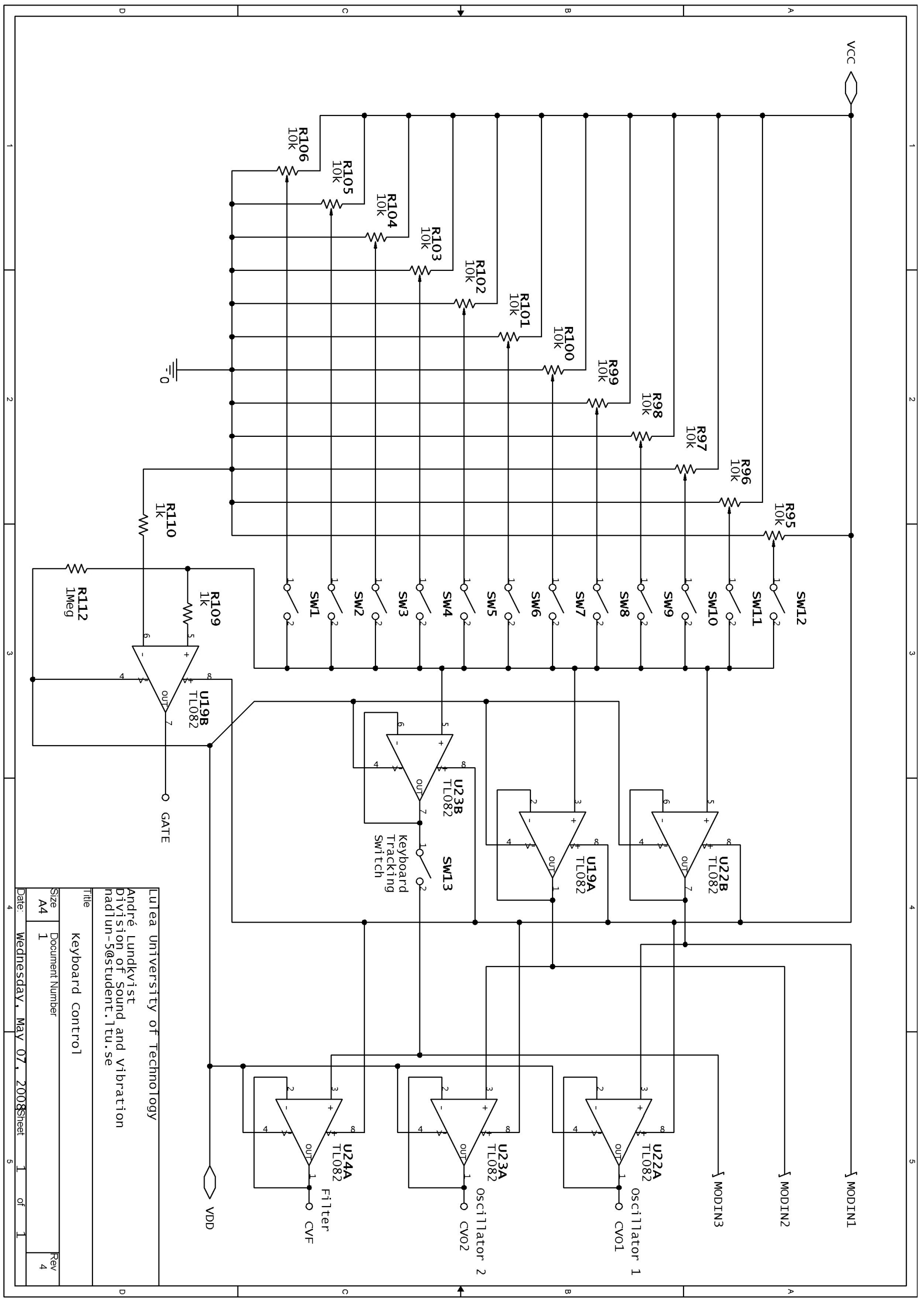

Figure D.5: The keyboard control schematic