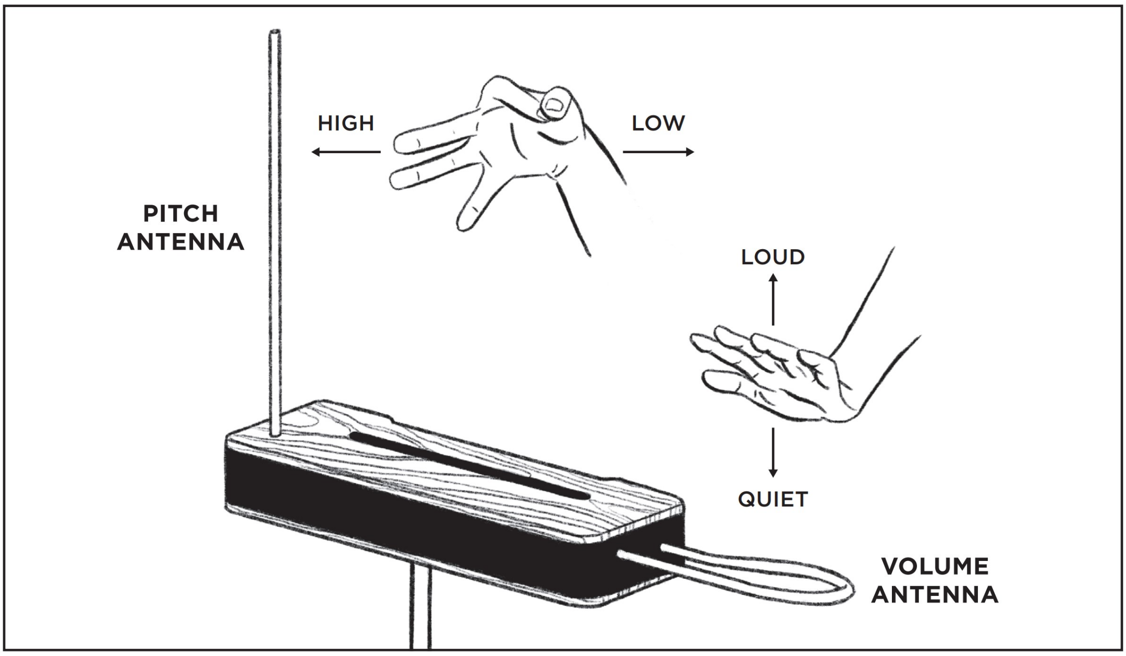


Comprehending the Analog Theremin

P4 Project Report

ES24-ESD4-412

Aalborg University
AAU Electronic systems
Front page photo courtesy of [1]

AALBORG UNIVERSITY
STUDENT REPORT

AALBORG UNIVERSITY
STUDENT REPORT

Electronics and System Design
Aalborg University
http://www.aau.dk

Title:
Comprehending the Analog Theremin

Project:
P4-project

Project Period:
Spring Semester 2024

Project Group:
ES24-ESD4-412

Participants:
Christian Lykke Jørgensen
Ditte Filskov Theilgaard
Johan Guldberg Theil
Marcus Vinicius Hodal Xavier de Oliveira
Mikkel Norre Nielsen

Supervisor:
Fengchun Zhang

Page Numbers: 204

Date of Completion:
May 17, 2024

Abstract:

This report explores the construction of a theremin without integrated circuits, ICs, dividing the project into key components: antennas, DC oscillators, mixing, demodulation, and audio amplification. Each component undergoes research, design, and testing before being integrated into a functional prototype. In this project, quite a few notable problems arose: The mixer has harmonic frequencies that cause modulated signals, the filter has undesired values, and also the system is very vulnerable to small changes in the circuit and surrounding area, because of working with pico-Farads. It has still however been possible to make a theremin that successfully produces sound, between 30Hz and 3kHz, and enables hands-free playability. It does exhibit its limitations attributed to gaps in theoretical documentation and time constraints in design and realization. This project reveals the lack of well-documented theoretical knowledge on the subject and that more time is needed to make a fully fledged theremin.

Contents

Preface

Aalborg University, 17-05-2024

Christian Lykke Jørgensen
cljo22@student.aau.dk

Ditte Filskov Theilgaard
dtheil22@student.aau.dk

Johan Guldberg Theil
jtheil22@student.aau.dk

Marcus Vinicius H. X. de Oliveira
molive22@student.aau.dk

Mikkel Norre Nielsen
mnni22@student.aau.dk

1 | Introduction

In October of 1920, the theremin was invented by Lev Sergeyevich Termen, known in the West as Leon Theremin, who was a Russian physicist. The theremin was invented mostly by accident, as Leon was originally involved in a project to develop a proximity sensor using electromagnetic fields. The proximity sensor should function as a doorman, reacting to a change in capacitance when a person enters the electric field, and then setting off an audible alarm, on a secondary circuit. As this project proved a success, he was assigned to invent a device capable of measuring the density and dielectric constants of gases under a variety of different conditions, such as pressure and temperature.

Lev registered his data by looking at fluctuations on a voltmeter. As the device was incredibly sensitive, Lev noticed fluctuations in his reading based on even the smallest movement, as this interfered with the relative density of surrounding air. In an effort to tune the device to specific gasses, an audion oscillator was used, just as he used it in his proximity sensor. The purpose of adding the oscillator is to eliminate any harmonic noise made by the device itself, creating a single frequency. To monitor this frequency, Lev added a pair of earphones, making the frequency audible. As the frequency continued to change based on minimal gestures made by Lev, he noticed the device could produce music, [2].

In the following years, Lev has been credited as the first creator of an electronic instrument, and essentially every sort of synthesizer that has since been produced stems from his research. To understand the future of electronics and electronic music, this project strives to comprehend the unplanned birth of the theremin, its complexity, and the very fundamentals, of producing sound from thin air. Therefore the initial problem statement can be formulated to:

"How does a theremin work, what are its components and capabilities?"

2 Problem Analysis

2.1 A Brief Introduction to the Theremin

Renowned as the earliest electronic instrument, the theremin is also the first commercially available instrument. The commercial theremin was designed by Leon Theremin in cooperation with Radio Corporation of America, RCA, and patented in 1928 but unfortunately became a commercial flop, most likely because of the simultaneous stock market crash in 1929, no more than 10 days after its public debut. RCA only produced 500 theremins in total, with 138 surviving till today, [3].

Figure 2.1: An original theremin made by RCA, [3].

As can be seen in figure 2.1, the original design for a theremin resembles that of a writing desk, more than an instrument. The body of the theremin is hollow, to hold all of the electronics within. The looped antenna on the left is the volume antenna. The volume is adjusted by moving a hand up and down over this antenna. The upright antenna is the pitch adjustment antenna and allows the user to adjust the pitch, tone, generated by the theremin by moving their hand near the antenna, [3, 4].

When a user gets proficient enough in the use of a theremin, it becomes possible to play entire melodies and even imitate opera singers, [3, 4]. The theremin is, as mentioned in the introduction, regarded as the first electric instrument, but the theremin becomes even more peculiar, as it can be played without contact. The theremin reacts to changes in capacitance, as this changes the oscillating frequency within the pitch circuit. This change results in a frequency difference between two oscillators, and it is this frequency difference that is played as a tone.

As the capacitance perceived by the theremin is in the low pico-Farad range produced by a human, the theremin is very sensitive and requires a variable capacitor so it can be adjusted to fit each user, [5].

2.2 How to Play a Theremin

"Imagine tickling butterflies rather than clutching guitar strings." - Robert Moog, Etherwave Theremin User Manual [1]. That should indicate how sensitive the theremin is as an instrument and what precautions the thereminist (the person playing) should take, but to accentuate it, the following can impact the capacitance between the player and pitch antenna, therein influencing the tone generated by the theremin:

- Who is playing - a difference in players results in a difference of capacitance, as each body has different capacitative capabilities.
- The distance between the theremin and the thereminist.
- Surroundings - devices such as cell phones, laptops, or even large metal objects such as lamps, tables, and the like.
- Tension on clutched fingers, as the difference between an open and closed hand can be up to a full octave.
- The stance of the thereminist, as a slightly unstable stand could displace the playing hands, and therefore change the pitch.
- Temperature, i.e. the Moog Etherwave Theremin can be played from 10-43°C but performs best between 10-35°C, per its user guide, [1].

Nevertheless, the theremin can be played to some degree by almost everyone, at least at the same stage as anyone can play the piano or a guitar. Unlike conventional instruments where notes, keys, and tones played give physical feedback, the theremins only feedback is the tone produced. As the tone/pitch is as sensitive as mentioned above, it results in it being susceptible to differ, depending on who is playing, effectively meaning that the placement yielding a "C" for one person, might not yield a "C" for anyone else.
A general guide for playing the theremin can be divided into three steps: Preparation, playing the first tone, and specialty techniques, based upon [1, 6, 7]:

2.2.1 Preparation/Setup

1. Place the theremin on a microphone stand or similar and remove everything in a radius of approximately one meter from the theremin.
2. Adjust/tune the theremin according to its instructions.
3. Back away from the theremin until an extended arm barely reaches the pitch antenna by the wrist.
4. Get a stable stance with feet slightly apart.
5. Connect yourself to the ground of the circuit if possible - this will help keep a stable connection, thereby improving the performance.

Now the thereminist is ready to start playing music, a more thorough guide can be accessed at either of the following [1, 6, 7], as this section is based upon them.

2.2.2 Playing the First Tone

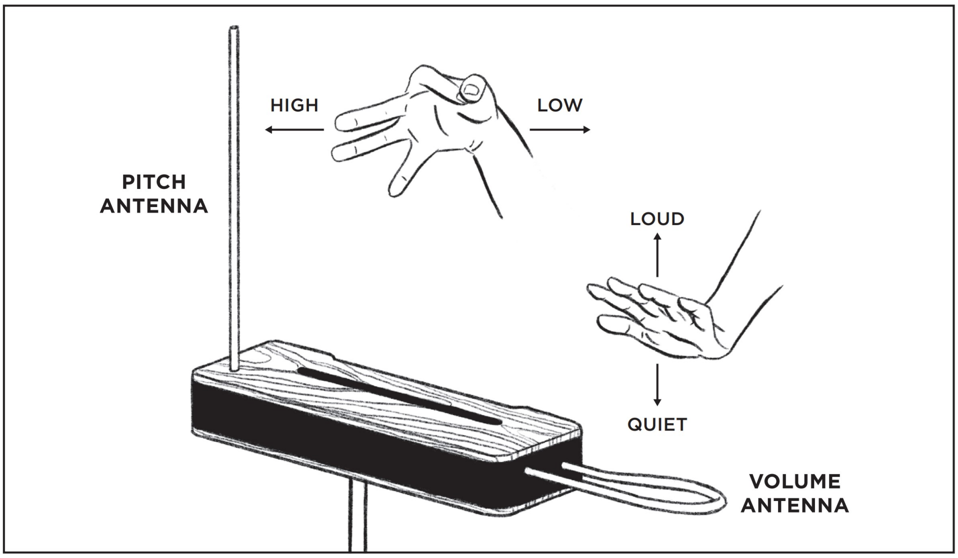


Figure 2.2: Relationship between hand placement and pitch development, [1].

1. Standing as described above, move the left hand towards the volume antenna on the left. Hover the hand approximately 10 cm above the loop.
2. Depending on the specific theremin and its current tuning, a subtle humming should be audible.
3. Move your right hand towards the pitch antenna and observe how the humming tones turn into a pitch.
4. Depending on the thereminist preferences, the theremin can be played either by moving the right hand between the thereminist and the antenna or by moving it from the pitch antenna perpendicularly towards the volume antenna.
5. Make a circle with the index finger and thumb on the right hand, with the other fingers lightly curled into a fist.

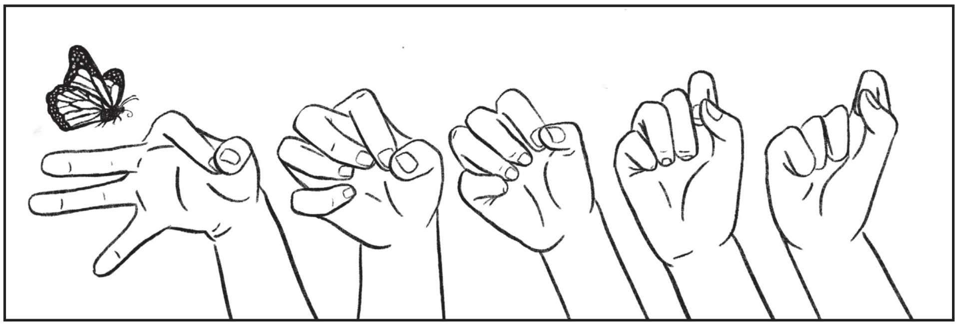


Figure 2.3: Assortment of different fingering techniques. The rightmost is the circle with index and thumb basis technique, [1].

6. To play the theremin, move the right hand away from and towards the theremin to change the pitch. Moving the hand closer toward the pitch antenna results in a higher pitch, and away from the antenna results in a lower pitch.

7. Moving the left hand up and down changes the volume, with lower hand placement resulting in lower volume, and higher placement in higher volume.

8. Moving the right hand up and down could also affect the pitch being played, but that is very dependent on the theremins composition and tuning.

9. From here, find a steady position with the right hand and start playing with fingering positions. Notice how extending, curling, and otherwise manipulating finger positions change the pitch of the theremin. Subtle changes such as knuckle positions can make big differences in the played pitch.

10. When the thereminist has got a decent hang of holding a pitch, and how to manipulate it, they should start "finding" pitches matching tones known from musical theory, such as a "C".

When the thereminist is comfortable with all the above, their technique can be expanded upon. As before a more thorough guide can be accessed at either of the following [1, 6, 7], as this section is based upon them.

2.2.3 Specialty Techniques

As with any other instrument, the theremin has its fair share of specialty techniques. These techniques can be used to mimic other instruments, or simply to make the music more expressive. Like the previous sections, a more thorough guide can be found in these sources: [1, 6, 7].

Glissando
A glissando is a smooth transition from one pitch to another. To perform a glissando, the thereminist should be aware of where the individual notes are. Holding the hand steady at one note, a smooth movement towards a higher note followed by a movement towards yet another higher note is a glissando. Doing it in the other direction is a glissando as well.

Legato
Like a glissando, a legato is a transition from one note to another. The main difference lies within the transition, as the glissando is smooth, and the legato is a sharp snap from one note to another. The execution is similar to the glissando, just sped up.

Vibrato
A vibrato is surprisingly simple to achieve on the theremin, as it only requires the thereminist to shake their hand. However, the shakes should be subtle, as too much movement will result in a change of pitch, rather than a vibrating sound. The vibrato is often used to make the theremin sound more warm and natural, as "flat" pitches otherwise is regarded as extraordinarily eerie.

Volume Manipulation
Manipulating the volume can make the music even more expressive, as the same pitch can "sound different" at varying volumes. Volume manipulation is more reliant on the melody being played, as it can emphasize certain parts of it. It is therefore not a technique per se, but more of a way to make the other techniques particularly expressive.

2.3 Composition of a Theremin

As with anything else, the theremin can be reduced to its bare components. This section will serve as an overview of a theremins main components, and what subcomponents are used to build the main components.

2.3.1 Housing

The theremin and all of its components are stored within a housing. Traditionally this housing is a wooden cabinet, but in more modern theremins it has been exchanged for anything the imagination can fathom, ranging from simple plastic cases to 3D-printed and laser-cut enclosures. Metal enclosures are generally not used, as these could introduce unknown capacitances, making the theremin unplayable. Furthermore, metal housings and shielding are advised against, as they make the theremin "numb" to the subtle capacitance emitted by the player, [5, 8–10].

2.3.2 Antennas

A true no-contact theremin has two antennas, and any kind of theremin has at least one antenna for pitch, as the volume antenna could be substituted with a turn-knob. Even though they will be referred to as antennas throughout this project, the antenna does not behave as a regular antenna, as the "working field" is within half a meter of the antenna. The antennas will behave as one side of a plate capacitor. Therefore it is the surface area that is important, rather than the antennas' possible Radio Frequency, RF, capabilities. It is general consensus across forums and tutorials to use antennae made of high-impedance materials ,such as the ceramic in ceramic capacitors, shielded with aluminum foil, as these will behave as desired, whereas low-impedance antennae might shunt the capacitance resulting in a failing theremin. To increase the surface area of the antennae, most builders use hollow tubing of a diameter between 8 and 22mm. Regarding the length, most commonly the pitch antenna is 40-60cm, as this length enables the player to play across a wider range of tones, pitches. Nevertheless, some make the pitch antenna shorter but maintain the same surface area, leading to higher sensitivity to hand placement, [2, 5, 10–18].

The volume antenna is placed perpendicular to the pitch antenna, so their capacitative fields interact the least. The volume antenna was a byproduct of Leon's desire for the theremin to be completely touchless, as the first version did not have an adjustable volume at all. Furthermore, the volume antenna enables the player to play a wider range of music, as the silence is just as big a part of music, as the tones. The volume antenna is mostly formed as a loop of varying sorts, as this increases surface area while making the antenna susceptible to "reading" changes in hand places from more angles than the straight antenna used for the pitch circuit. This eases playability as the player can fully focus on 3-dimensional placement with their pitch hand, while the volume hand can vary along the x- and y-axis without it changing the volume at a noticeable level, [2, 5, 10, 12, 16–18].

2.3.3 Power

Since the theremin is an electrical instrument, it needs a power source, and it should be noted that this power source only refers to powering the theremin, not any amplifiers, speakers, or other devices. Most theremins are made with a power plug, in which a 220V AC to 12V DC adapter can be used. Commonly theremins operate on 12V or less, but some systems use up to 24V. It is rather important to note that the power supply has to be grounded for any theremin to play properly, just as the player has to be grounded, and a direct connection between the player and the theremin will improve sound quality. Apart from being connected to ground, the adapter has to provide a DC voltage, and preferably not a switch-mode power supply, as this can affect the sound quality as well. In general, a 12V power supply capable of feeding 2A will be sufficient to drive most theremins, but as most theremins are DIY projects, it cannot be stated these parameters are true for every theremin made, [1, 19–22].

2.3.4 Electrical Circuits

To fully understand the electrical composition of the theremin, it has been broken down into smaller subcircuits. These subcircuits and their relation to other parts of the theremin will be explained in the following. In figure 2.4 a block diagram for the EM theremin by Robert Moog is shown. It should be noted that the oscillator/antenna circuits are placed on individual boards to mitigate possible synchronization, as is the front panel circuitry. The rest is placed on a single board. This overview will be used to explain the necessary electrical components of a theremin.

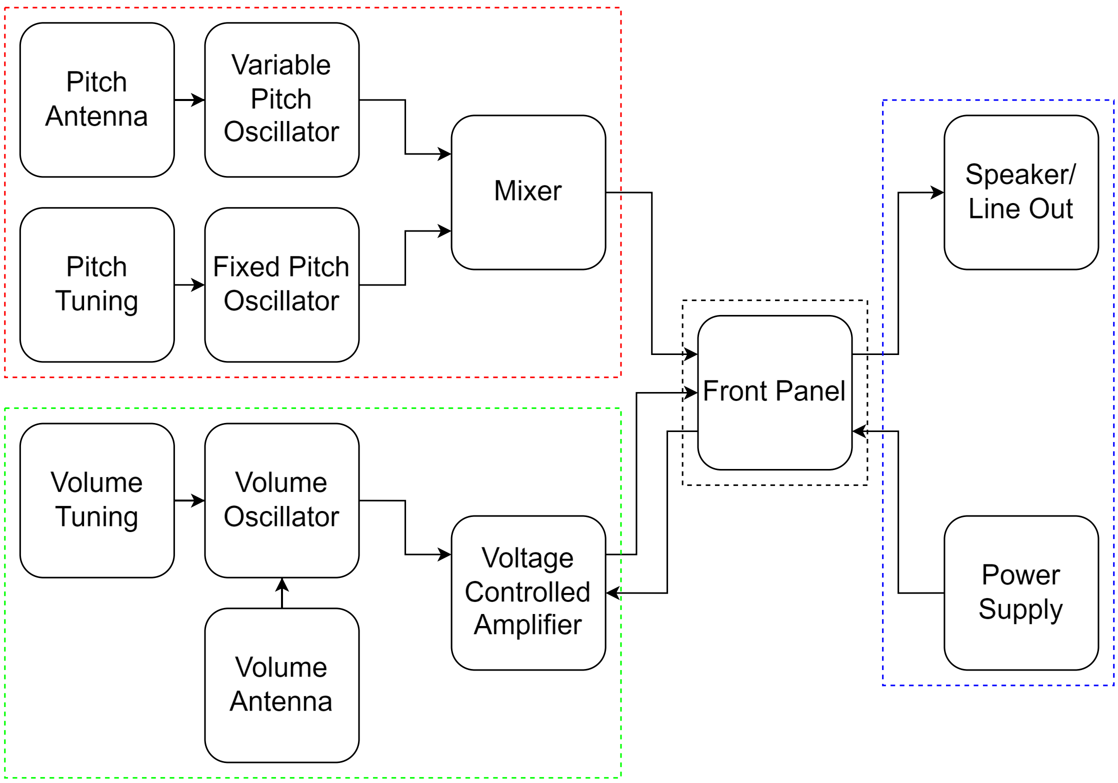


Figure 2.4: The EM theremin explained with a block diagram. The red dashed box denotes the pitch circuit, the green denotes the volume circuit, the blue denotes the auxiliary systems, and the black denotes the front panel. It should be noted that even though there are no lines between the power supply and the oscillator circuits, power is necessary for them to work. The same goes for the front panel to the tuning circuits, as the potentiometers for tuning are placed on the front panel. A schematic for the EM theremin can be found on page 3 here, [5].

As can be seen from figure 2.4, the theremin can be broken into several smaller circuits, and for the theremin to function properly, it also has to be physically divided.

Pitch Circuit

The pitch circuit is related to the straight antenna and is responsible for changing the audible pitch of the theremin. The pitch circuit has several smaller circuits and can be divided into a fixed pitch oscillator, FPO, a variable pitch oscillator, VPO, a pitch tuning, and a pitch antenna circuit. As mentioned in section 2.1 on page 2, the pitch circuit generates a tone by determining the difference between the fixed and variable oscillators. To fully understand their relations, these circuits are further detailed as follows:

- **Fixed Pitch Oscillator Circuit**
  The FPO circuit's main purpose is to generate a stable oscillation at a set frequency. This frequency is most often fixed between 175kHz and 300kHz, but theoretically, it can be any frequency beneath 1MHz if the accompanying precautions are taken, but this will not be discussed in this project. When a frequency has been chosen, the oscillator will have to be built to that spec, which is described in further detail in section 4.1 on page 11. The fixed oscillation frequency creates a "benchmark" around which the VPO circuit will fluctuate. The FPO is generally composed of two transistors connected to a range of resistors, capacitors, and an inductor. The capacitors used are mostly in the picofarad range and have very strict tolerances, as small divergences can result in the FPO oscillating at a wrong frequency. The resistors and inductor are under likewise strict tolerances.

- **Pitch Tuning Circuit**
  To accommodate for component tolerances a pitch tuning circuit is added. With the tuning circuit, it is possible to adjust the FPO's oscillation frequency. This is usually done by connecting the pitch-tuning circuit to a variable capacitor. The pitch tuning circuit itself acts as a variable capacitor and is adjusted with the potentiometer, and therein adjusts the FPO circuit.

- **Variable Pitch Oscillator Circuit**
  The VPO circuit is perhaps the most interesting circuit in the theremin. This is due to the circuit utilizing the pitch antenna and human capacitance. The VPO is identical to the FPO with the exception that the FPO is adjusted to a fixed frequency using the pitch tuning circuit, whereas the VPO is adjusted using the pitch antenna circuit. The VPO is under the same tolerances as the FPO.

- **Pitch Antenna Circuit**
  The pitch antenna circuit is rather simple, as it consists of the antenna and a series of inductors. The antenna itself works as one part of a plate capacitor, with the player's hand being the other part. As the player moves the hand around, the capacitance changes, resulting in a changing oscillation frequency for the VPO circuit.

Volume Circuit

The volume circuit consists of fewer subcircuits, composed of an antenna circuit, a volume oscillator, and a volume tuning circuit. As the name suggests, the volume circuit is responsible for changing the volume of the tone produced by the pitch circuit. As with the pitch circuit, the volume circuit will be divided and further explained in the following:

- **Volume Oscillator circuit**
  The volume oscillator circuit is similar to the pitch oscillators but differs as it does not have the same requirements for precision and stability, as the volume control is more of a smooth dynamic, rather than the high precision placement for pitch control. The volume can be used to emphasize the current pitch being played and enables the player a more forgiving control. Therefore the oscillator itself has more loose requirements for operation, as sharp "cuts" in the volume could produce undesired tones.

- **Volume Tuning Circuit**
  The volume-tuning circuit can be made identical to that of the pitch-tuning circuit, as its function is essentially the same. The volume-tuning circuit acts as a variable capacitor, enabling adjustment apart from hand placement.

- **Volume Antenna Circuit**
  The volume antenna circuit is similar to that of the pitch antenna, with the main difference being the shape of the actual antenna. Other than that, the circuit has a similar series of inductors, but with a capacitor and resistor in series and a diode in parallel, to create another "layer of smoothness" to the volume control.

Mixer

As the VPO and FPO will most likely operate in the 175-300kHz range, any differences will be inaudible to the human ear, as the human hearing range is between 20Hz and 20kHz. The mixer is responsible for converting the oscillation difference between the FPO and VPO to an audible frequency. The mixer is often composed of a variable inductor, a capacitor, and a crystal diode, but can be made as many different circuits.

Amplifier

Strictly speaking, a theremin does not need an amplifier. However, an amplifier is commonly used to amplify the signal sufficiently for playing the theremin to an audience or at least loud enough for the thereminist to hear it without using an anechoic chamber. The type of amplifier to be used with a theremin is not as important, as the frequency range played by the theremin commonly ranges from 20Hz - 3KHz.

2.3.5 Summary

As the theremin has become a hobby project for many electrical engineers across the world, there exist a vast number of tutorials, guides, explanations, and opinions on what makes a good theremin, unfortunately, most of the guides present themselves as "the one true guide" and discards any other versions as inferior. This makes it hard to understand what composes a theremin properly, however, the above repeats itself again and again, and it can therefore be said that this is the bare minimum to build a theremin, [1–5, 8–25].

3 | Problem Statement

Most theremin diagrams are made with some degree of pre-produced parts, and most available for purchase are either kits or pre-assembled theremins. This makes it easier for most to build a theremin of their own, however, it would be interesting to take a deep dive into how important each component is. Therefore, the following problem statement will make ground for the future of this project:

"How can a theremin, composed of a minimum of pre-produced IC circuits, be developed?"

The rest of this project will handle breaking a theremin into its most basic components, to determine their importance, and modify the circuits with the intent of making a theremin completely out of readily available components.

4 | Technical Analysis

4.1 Electronic Oscillator

In order to build a theremin, an electronic oscillator that is able to convert a DC input to a sine wave is needed. An ideal oscillator operates with a DC-input combined with noise, to create a single frequency output as seen in figure 4.1:

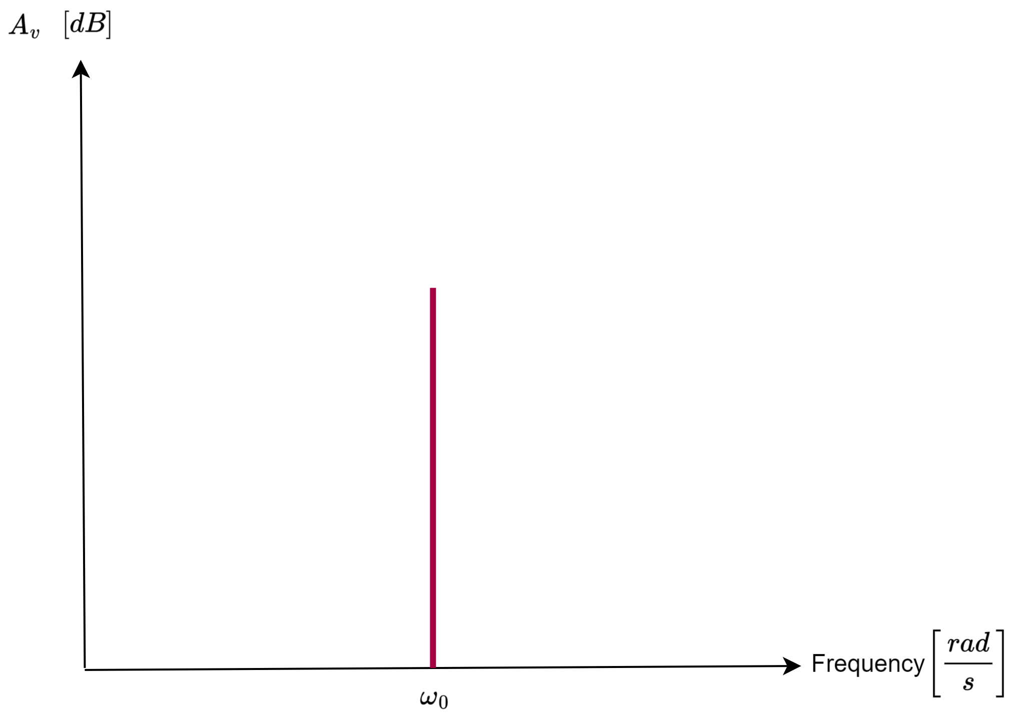


Figure 4.1: A diagram showing the Fourier transform of an ideal oscillator.

Oscillators are a very big subject and over the years a lot of different designs of oscillators have been made. This section will mainly focus on the Colpitts oscillator, as it operates in the analog realm and use no IC's, but also mentions the Wien Bridge oscillator.

4.1.1 General Look at an Oscillator

An oscillator is a rather simple circuit that uses noise and a positive feedback loop to start oscillation. The general block diagram of an oscillator can be seen in figure 4.2.

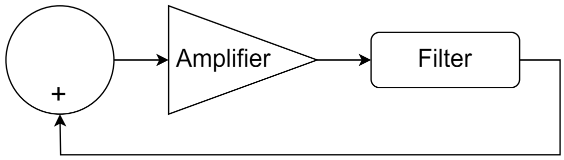


Figure 4.2: A block diagram showing the basic function of an oscillator.

Figure 4.2 shows that an oscillator can be broken down into two main components, a bandpass filter and an amplifier converting the DC signal into a sine wave, [26]. More precisely the filter is an LC-tank circuit, which is a bandpass filter only passing a single frequency. Looking at the Fourier transform for each pass which can be seen in figure 4.3. This figure clearly shows that only one pass over the LC-tank will not result in a single output frequency.

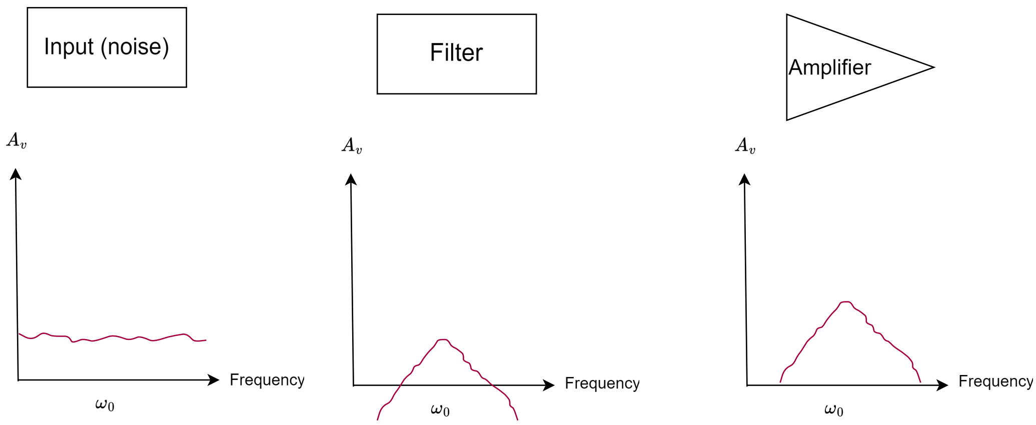


Figure 4.3: A look at what the different components does as the signal passes through the oscillator.

However, this figure also shows that 1 pass over the LC-tank dampens all other frequencies except for the wanted frequency. This is why the positive feedback loop is implemented. This means that the LC-tank gets a much "higher order", as the same LC-tank is passed thousands of times a second. This results in the LC-tank having an order of ~1000, which means that the frequency dropoff will be ~20000$\frac{dB}{\text{decade}}$. This results in a final Fourier transform that looks like the one depicted in figure 4.1.

The amplifier is needed for two reasons: The first is to amplify the noise to ensure, that the oscillation, is a readable signal. The second is to counteract any loss in the system. This is not only what is found in the LC-tank, but also the loss of the wires.

The design of an oscillator can be very simple. Using a non-inverting OPAMP and a first-order RC band-pass filter, a Wien Bridge Oscillator can be constructed. As illustrated by figure 4.4, where R1, C1, R2 and C2 create a bandpass filter, and finally R3 and R4 determine the gain.

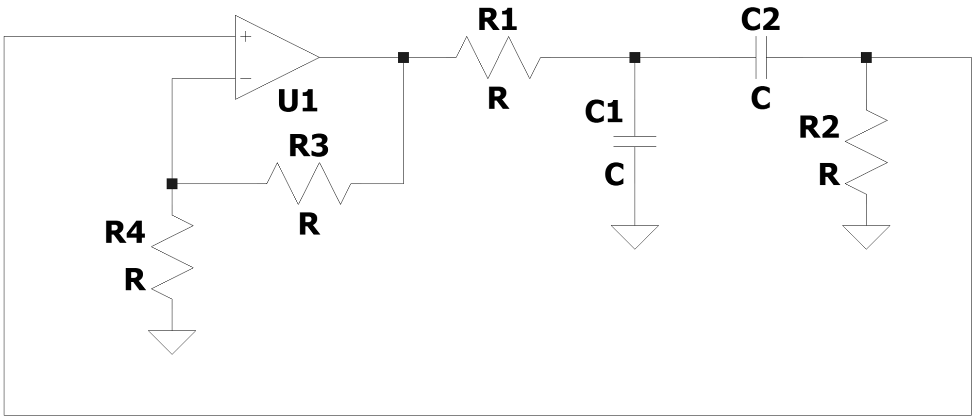


Figure 4.4: A circuit diagram showing the Wien Bridge oscillator. R1, R2, C1, and C2 make up the band-pass filter, and the OPAMP, R3 and R4 make up the amplifier.

This very simple oscillator works very well but is also constricted by the Gain Band Width of the OPAMP chosen.

4.1.2 The Colpitts Oscillator

The Colpitts oscillator works the same way as described in the former section. This oscillator uses an LC-tank circuit as its filter, and a transistor amplifier, rather than an OPAMP to amplify the signal. This expands the operational frequencies of the oscillator all the way up to higher radio frequencies. Transistor amplifiers will be described in more detail in section 4.4. Figure 4.5 shows the circuit of a Colpitts oscillator.

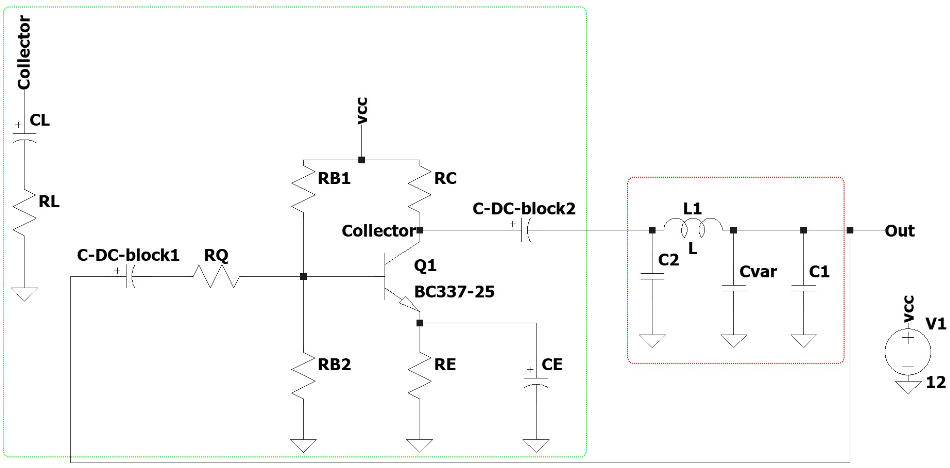


Figure 4.5: A circuit diagram showing the circuit of a Colpitts oscillator. The green area is the amplifier, and the red area is the LC-tank.

Looking at the red part of the circuit it is an LC-tank circuit which will serve as the resonant element that establishes the oscillation frequency. This part of the circuit is what decides what the oscillating frequency will be. Calculating the resonance frequency of this LC-tank can be seen in equation 4.1:

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{4.1}$$

Where C represents the equivalent capacitance of the 2 capacitors which are in series. This means that the frequency will be:

$$f_0 = \frac{1}{\sqrt{L_1 \cdot \left(\frac{C_1 C_2}{C_1 + C_2}\right)}} \tag{4.2}$$

Looking at the green part of the circuit, this is the class A amplifier that will be used to amplify the signal that the circuit loops back. This amplifies the signal from the LC-tank circuit to compensate for losses in the feedback loop and other components of the oscillator. Notice that this is an inverting amplifier, which means that the amplifier shifts the phase 180°. This means that the actual operating frequency will be found at the point where the LC-tank shifts the phase of the signal ±180°, as for all other frequencies the feedback loop means that the phase-shifted signal will eliminate itself. As mentioned earlier this circuit will be described in more detail in section 4.4 on page 30, but the basic overview of the components seen on figure 4.5 is:

- **RB1, RB2:** These resistors decide how much power is going in to the base of the transistor. These resistors should be dimensioned so that the transistor is always in forward bias mode. This varies from what the strength of the signal generated is.

- **RQ:** This resistor is used to move the Q point of the amplifier to prevent either saturation or cutoff issues of the transistor. For more information about the Q point see section 4.3.2.

- **RC, RE, CE:** These components will decide the amplification of the amplifier. Having lower values with these compared to RB1 and RB2 will ensure that more amps will be going into the collector, and will result in more amplification. CE will smooth out the sine wave, and can also help with saturation issues.

- **C-DC-block:** These capacitors both isolate the DC-offsets coming from the collector and base of the transistor.

- **CL, RL:** This is the load capacitor and resistor. These affect how much is amplified and stabilizes the signal. Making the load resistance large makes sure that the load of the following circuit does not affect the amplification, which eases calculations and also stabilizes the amplification.

In summary the electronic oscillator is a circuit that uses a tank circuit, single frequency filter, an amplifier and noise to convert a DC input into a sine wave.

4.2 Superheterodyne Mixing in a Theremin

4.2.1 Basic of Superheterodyne Mixing

Heterodyne mixing, HTD mixing, is a method used for extracting/transforming a signal from a high frequency to a lower frequency, without data loss.

In its simplest explanation, it combines two frequencies, resulting in both the summation and the difference between the two signals. There are two types of mixers, HTD mixing and Superheterodyne mixing, Superhet. HTD mixing has a fixed bandpass filter and a variable Local Oscillator, LO, whilst a Superhet has a fixed LO and a variable input frequency, [27]. A theremin uses a Superhet and is what will be described.

4.2.2 Quick Overview of Super Heterodyne Mixing

An RF filter ensures the desired range of frequencies enters the mixer and a lowpass filter is applied after the mixer to get the desired difference between the two signals. This is then passed through a diode demodulating the signal into the lower desired signal. A block diagram of a Superhet can be seen in figure 4.6.

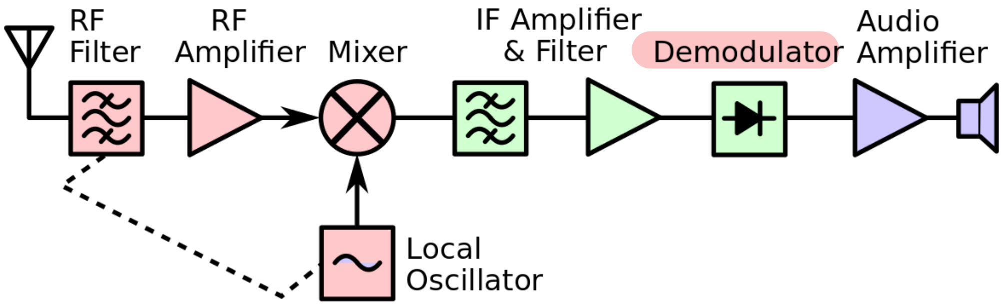


Figure 4.6: Block diagram from Superheter and its application, [28].

As described earlier in section 2.2 the pitch antenna's oscillator frequency is affected as the hand gets closer. The Superhet has a stable, local reference frequency from the LO, which should match the pitch antenna's frequency, when not played on. As the difference between the two signals will be very low, optimal 0, a very deep frequency will play, practically unhearable to the ear. As the hand approaches the antenna, the capacitance will increase, resulting in a lower frequency from the VPO. The difference between the VPO and LO will increase resulting in a larger difference. This means the output from the mixer will be a higher frequency resulting in a higher tone for the human ear, [29], [30].

4.2.3 Breakdown of a Superhet

To better understand the Superhet, a breakdown of the parts will follow. A more thorough block diagram can be seen in figure 4.7.

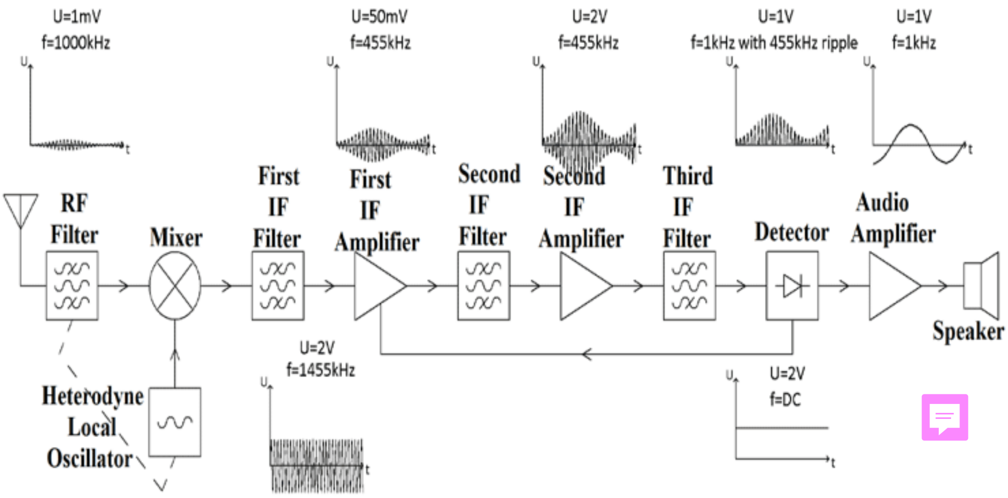


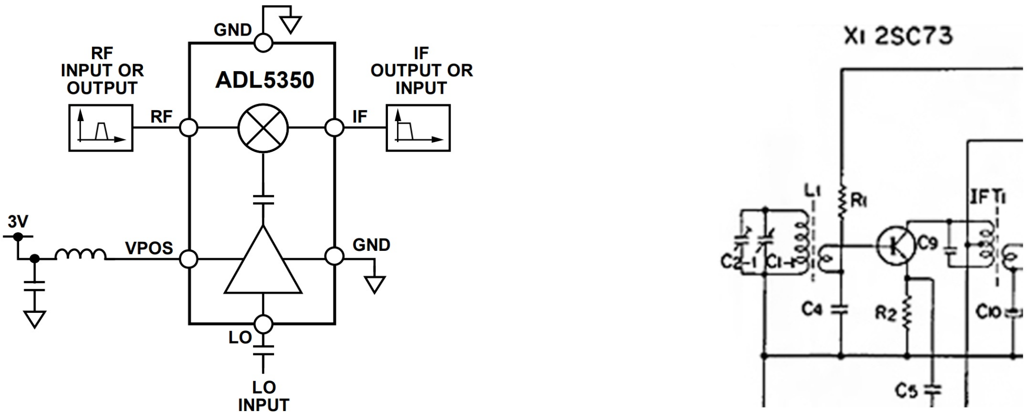
Figure 4.7: Block diagram of aSuperhet and its application. The Superhet can be more or less complicated but the basic principles are the same, [29].

RF Filter and RF Amplifier

As the antenna can pick up a wide variety of signals a hard bandpass is needed to be implemented. The bandpass filter is centered around the LO frequency as the difference between the VPO and LO should be between 20Hz and 20kHz. For the RF filter to be efficient, it should have a very steep roll-off at the frequency of the LO, to not accidentally play if the pitch antenna's frequency is higher than the LOs, as a negative difference still is a difference. The filtered signal can go through an amplifier to boost the signal before entering the mixer.

Mixing of Signals

Mixing is the point where the two signals meet, a collision in simple terms. The mixing happens when two signals is propagating through a nonlinear component. The component could be a diode, transistor, MOSFET, etc.. There are many ways to do this. Figure 4.8a is a chip used by Digi-key in their mixer, whilst figure 4.8b is using a transistor, where L_1 is the antenna, and the LO is C_5, as done by Circuit Digest, [29].



(a) Analog Devices' chip, which can be used as mixer, [31, 32].

(b) Circuit diagram form Circuit Digest Superheterodyne AM Receiver, [29] .

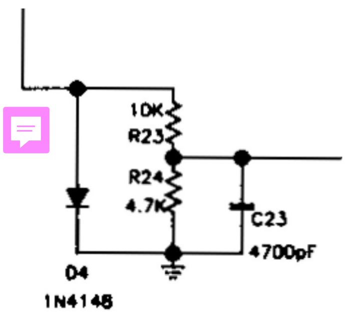
Figure 4.8: Two different ways to build a mixer.

IF Filter and IF Frequency

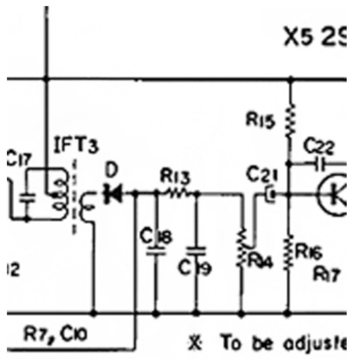
An Intermediate Frequency, IF, filter is essential for the Superhet to only get the difference between the two signals, not the summation. Therefore, it is important to know the desired final frequency. A filter with a steep roll-off and minimal distortion is optimal. The theremin works with sound in the audible spectrum, a lowpass filter with a cutoff frequency around 20kHz or slightly lower would be desired as the average human ear does not hear higher than 20kHz.

Detector/Demodulation and Audio Amplification

The IF is then passed through a detector. This removes all the negative values, and as can be seen in figure 4.7 top right corner, now resembles a lower frequency, which is exactly what is wanted. As with the mixer, there are many ways to do this and levels of complexity. Robert Moog's detector is a rather simple circuit, see figure 4.9a, whilst the Circuit Digest's circuit consists of more parts and is therefore more complex, see figure 4.9b, [5, 29].



(a) Robert Moog's detector from his article "Build the EM Theremin" page 3, [5].



(b) Circuit diagram form Circuit Digest Superheterodyne AM Receiver, circuit of their detector, [29]. Input is D, and output is right before R_4.

Figure 4.9: Two different ways to build a detector.

This can then be sent to a Hi-Fi amplifier and then to the speaker. Hi-Fi amplifiers will be described further in section 4.3 on page 18.

4.2.4 Summary

To summarize this section and the relevance for building a theremin:

- A theremin uses the method called Super Heterodyne mixing
- The mixer block is a collision of the two signals
- The difference between the two signals is the desired output, not the summation. This can be moved by the usage of filters
- In terms of mixer and demodulators/detectors there are a wide range of options.

This section is based on [5, 27, 29–34].

4.3 High Fidelity Amplifier

4.3.1 Quick Breakdown of a High Fidelity Amplifier

As the signal from the theremin is far too low to pass on to a speaker directly, an amplifier is needed. A High Fidelity amplifier, Hi-Fi amplifier, is a high-quality audio amplifier used everywhere in the musical world to amplify a signal i.e. from your phone or an electric guitar to a stereo. To play the theremin and hear it the internal signal output needs to be amplified, before sending it out through the speaker, which creates the sound.

As building a good Hi-Fi amplifier is time-demanding and a project on its own, this section will instead focus on the usages of a Hi-Fi amplifier in this project and the overall concepts and parts of a Hi-Fi amplifier and what is relevant if it should be designed from scratch. The simplest form of an amplifier, is any type of OPAMP, increasing the signal by a fixed amount, and connecting it to a speaker. This is however far from a Hi-Fi amplifier as the output signal would be riddled with noise and imperfections, and not be very close to the desired signal.

Therefore, in order to build a good and proper Hi-Fi amplifier these are the things needed to take into consideration:

- **Strength of the input signal:** This is in order to know how much gain is needed for the speaker, as the range and precision of the volume control should not be out of proportion.
- **Frequency of the input signal:** As there is bound to be noise in the system, a band-pass filter, cutting every frequency except for the desired, should be implemented to minimize noise.
- **Impedance of the speaker:** This is relevant to find the peak voltage, and hence the maximum that the amplifier can output.
- **Desired quality:** This is much more for internal use, as the quality rises, so would the time required, and price for components.

This subsection is based on [35, 36].

4.3.2 Amplifier Classes

Within the amplifier family, there are a couple of different classes which all have their advantages and disadvantages. Classes such as A, B, AB, and D are amplifiers used for audio and linear applications. Class C is used for high-power telecommunications, and classes G and H are variations of the class B amplifier.

Class A

A class A amplifier is a power amplifier, also known as a large signal amplifier, and is used to deliver power to the load, which in this case would be the loudspeaker. When the power increases, so will the voltage. One of the advantages that class A has over the rest of the classes is that it is simple to construct, only needing a few components.

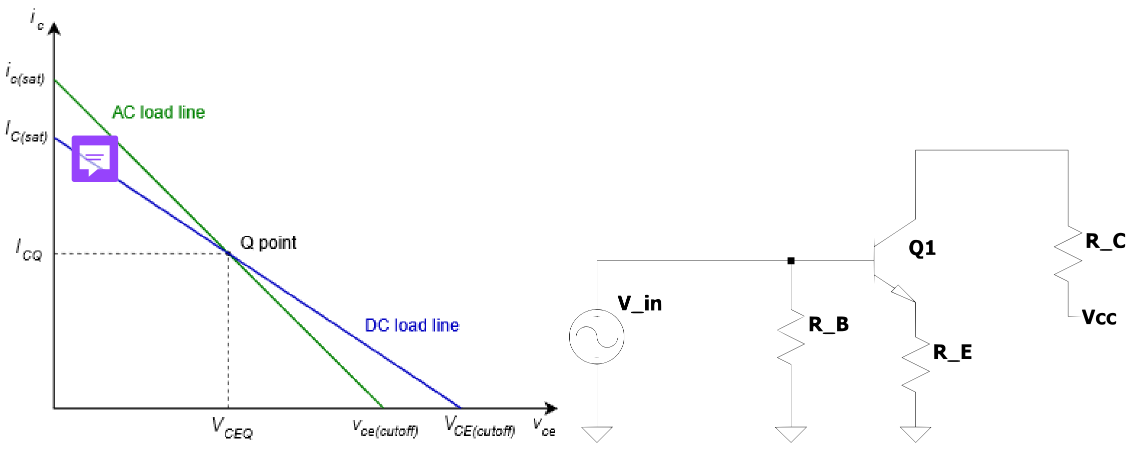
It also has good linearity between the input and output signals, meaning that the distortion is kept to a minimum. Unfortunately, one of the drawbacks of class A is that it consumes a lot of power, given that the theoretical efficiency of the system is 25%. The reason for the low efficiency is that a lot of the power consumed will be dissipated in the transistor, meaning that a lot of the power will be lost in the form of heat. This means that a cooling system is needed to keep the transistor at a stable temperature, typically coming in the form of large and heavy cooling.

The class A amplifier can amplify the whole collector current, i_c, 360° of the flow. This means that it is capable of amplifying the positive and the negative parts of the wave, or in other words, it can amplify the whole waveform. However, there is a limitation in how much it can amplify the signal before it gets clipped and/or distorted. That is why it is important to find the signal size, also known as the compliance, before it gets distorted. This is done by constructing a plot of the AC load line and examining an AC equivalent of the amplifier circuit.

The AC load line is a linear line describing the ratio between the AC voltage and current for the amplifier, which is used to analyze the compliance. To plot the AC load line, it is also necessary to know about the DC load line. The DC load line is similar but describes the ratio between the DC voltage and current, and is used to analyze biasing circuits. To quickly summarize, the AC load line is used to determine the compliance whilst the DC load line determines the quiescent point, also called the Q point of the circuit. The Q point will be described later in this segment on page 20.

As mentioned, both the AC and DC load lines describe a linear line which can be expressed as $y = m \cdot x + b$, as seen in figure 4.10a. For the load lines, the x-intercept, $V_{CE(cutoff)}$, is the largest possible voltage over the collector-emitter when the y-intercept, I_C, is 0. $V_{CE(cutoff)}$ can therefore be seen as V_{CC}. The y-intercept, $I_{C(sat)}$, is the largest possible collector-current when V_{CE} is 0. The endpoints are situated at the saturation and cutoff regions and are labeled as such. Once the x- and y-intercepts are calculated, the linear line can be drawn. The calculations of the intercept points for the AC and DC load line will be shown below in equations 4.3 and 4.4.
A notable difference between the annotations of the intercept points of AC and DC load lines is that AC uses small v and i while DC uses big V and I.

An AC equivalent circuit of a Class A circuit is shown below in figure, 4.10b. It is a very simple circuit, with the base, collector, and emitter of the transistor having a resistor connected to them, and named respectively R_B, R_C, R_E representing the part they are connected to.



(a) AC and DC load lines plotted. **(b)** Simple AC equivalent circuit of a class A amplifier.

Figure 4.10: Class A circuit and load lines,[37].

Now it's possible to move on and calculate the intercept points of the DC load line.

$$V_{CE} = V_{CC} - I_C \cdot (R_C + R_E) \tag{4.3}$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C + R_E} \tag{4.4}$$

Where:

$$\begin{aligned} V_{CC} &= \text{Supply voltage} \\ V_{CE} &= \text{Common emitter voltage} \\ I_C &= \text{Collector current (current through collector terminal)} \\ R_C &= \text{Resistor connected to the collector} \\ R_E &= \text{Resistor connected to the emitter} \end{aligned}$$

As mentioned before, to find the interception points at either V_{CE} or I_C, the other must then be equal to 0, resulting in the $V_{CE(cutoff)}$ and $I_{C(sat)}$ values.

$$V_{CE(off)} = V_{CC} - 0 \cdot (R_C + R_E) \tag{4.5}$$

$$I_{C(sat)} = \frac{V_{CC} - 0}{R_C + R_E} \tag{4.6}$$

The AC and DC load lines must share one point. The point where they cross each other is the Q point. The Q point is the steady state where no signal is applied. The Q point is dependent on a whole heap of factors and also depends on the transistor used. Factors such as the V_{CC} supplied, biasing resistors, temperature, and amplification, β or h_{FE}, as given in the datasheet. All these factors can move the Q point up and down on the DC load line, depending on their values. If the Q point gets too close to either the saturation or the cutoff points, then the incoming signal will be clipped and the output signal will be distorted. To calculate where the Q point is, the following equations are needed to be found:

$$I_{BQ} = \frac{V_{BB} - V_{BEQ}}{R_B} \tag{4.7}$$

$$\beta_F = \frac{I_C}{I_B} \tag{4.8}$$

$$I_{CQ} = \beta_F \cdot I_{BQ} \tag{4.9}$$

$$V_{CEQ} = V_{CC} - I_{CQ} \cdot (R_C + R_E) \tag{4.10}$$

Where:

$$\begin{aligned}
V_{BB} &= \text{Applied signal (0 when no signal is applied)} \\
V_{BEQ} &= \text{Voltage difference between base and emitter (typically 0.7V)} \\
I_B &= \text{Base current} \\
I_{BQ} &= \text{The base-current at Q point} \\
\beta_F &= \text{The current gain operating in forward active mode} \\
I_{CQ} &= \text{The collector current at the Q point} \\
V_{CEQ} &= \text{The voltage drop over the collector-emitter junction at the Q point}
\end{aligned}$$

Crucially now that the I_{CQ} and V_{CEQ} have been determined, the interception points $v_{CE(cutoff)}$ and $i_{C(sat)}$ of the AC load line can be calculated:

$$i_{C(sat)} = I_{CQ} + \frac{V_{CEQ}}{R_C + R_E} \tag{4.11}$$

$$v_{CE(cutoff)} = V_{CEQ} + I_{CQ}(R_C + R_E) \tag{4.12}$$

Where:

$$\frac{V_{CEQ}}{R_C \cdot R_E} = \text{maximum increase when collector current drops to 0V}$$

Once the AC load line, DC load line, and Q point are known, they can be plotted just like in figure 4.10a. Once the AC load line have been determined, the maximum compliance can be determined. To do so the V_{CEQ} and $I_{CQ} \cdot (R_E \cdot R_C)$ values need to be examined. Whichever of these values is the smallest, is the maximum compliance.

$$Compliance = \begin{cases} V_{CEQ}, & \text{if } V_{CEQ} < I_{CQ} \cdot (R_E + R_C) \\ I_{CQ} \cdot (R_E + R_C), & \text{if } V_{CEQ} > I_{CQ} \cdot (R_E + R_C) \end{cases}$$

Now that the compliance and load lines have been determined, it could be interesting to know the efficiency of the amplifier. This is done by finding the maximum power load. Since power is determined with Root Mean Square, RMS, the RMS of the compliance needs to be determined before moving on. R_L is the characteristic impedance of the connected speaker.

$$Compliance_{RMS} = \frac{Compliance}{\sqrt{2}} \approx 0.707 \cdot Compliance \tag{4.13}$$

$$P_{load(max)} = \frac{{Compliance_{RMS}}^2}{R_L} \tag{4.14}$$

To determine the efficiency, the average power drawn from the supply needs to be found:

$$P_{DC} = V_{CC} \cdot I_{CQ} \tag{4.15}$$

Finally using $P_{load(max)}$ and P_{DC} the efficiency of the amplifier can be found:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{load(max)}}{P_{DC}} \cdot 100 \tag{4.16}$$

Depending on where the Q point is located on the AC load line, the efficiency may be better or worse. The best case scenario for the efficiency is if the Q point is centered on the AC load line. The theoretical efficiency of the Class A amplifier is 25%, [37]. To achieve a centered Q point, the sum of R_E and R_C needs to be equal to V_{CEQ} divided by I_{CQ}.

$$\frac{V_{CEQ}}{I_{CQ}} = R_C + R_E \tag{4.17}$$

The reason for the class A amplifier having such a low efficiency is that the system pulls full current from the power supply, even when there is no signal applied. When powered, the transistor will dissipate a large amount of energy, and the theoretical efficiency is therefore 25%, coming in the form of heat. This causes the transistor to run hot and potentially burn. When a signal is applied, some of the power coming into the transistor will be shifted over to the load, meaning that less energy is dissipated in the transistor. This means that the transistor will run hottest when no signal is applied. To combat this, heatsinks are used, which help with distributing the heat elsewhere from the transistor. The problem with heatsinks is that they are rather large and heavy, which can make a circuit quite bulky.

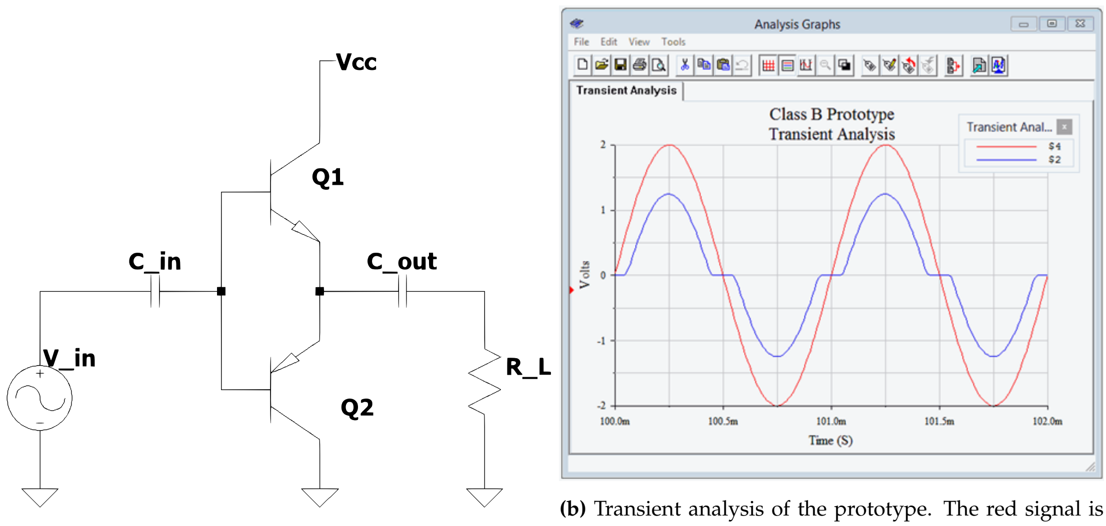
The analysis of the load lines helps to determine the Q-point and compliance of the amplifier class, and the power efficiency calculation helps to determine the amount of power lost in the transistor, which is also applicable to the other classes. The less power that is lost in the transistor, the smaller the heatsink will need to be.

Class B

The idea of a class B amplifier is to improve the power efficiency of a class A amplifier. That is done by having the transistor not draw any power when no signal is applied. This means that there isn't as great of a power dissipation in the transistor, and a higher percentage of the power will be delivered to the load. When the system runs idle, the transistor is at its coolest temperature, which means that heatsinks do not need to be as large. The theoretical power efficiency of the class B amplifier is therefore 78.5 %. The drawback of the class B amplifier comes in the form of complexity. It requires two transistors for the linearization and the biasing is more complex.

The problem with the class A amplifier is that the Q point is centered to ensure that the applied signal is not clipped. But this unfortunately means that the transistor will pull half of the max current. The idea for the class B amplifier is therefore to push the Q point down to the cutoff of the AC load line. This will mean that virtually no current is drawn when no signal is applied. This does come at a cost though. The transistor will no longer be able to amplify the whole waveform, but will instead amplify half of the waveform, 180°. This means that the transistor will clip the negative part of the wave, only leaving the positive part of the wave, assuming it is an NPN transistor. It is therefore necessary to have a mirror counterpart that will clip the positive part and leave the negative part of the wave. The circuit for this is seen in figure 4.11a using an NPN and PNP transistor.

In the circuit, the two transistors have been connected. When no signal is applied to the circuit both Q_1 and Q_2 will be off. When a signal is applied, V_{B1} and V_{B2} will be raised $\frac{1}{2}V_{CC}$. When the signal swings in the positive part, Q_1 will switch on, Q_2 will switch off, and the current will run through Q_1 and down to the load R_L. The opposite happens with the negative part of the wave, with the only difference being the current running up through ground, into the load, and down Q_2. This is possible because there has already been established a DC voltage across C_{out}, which is $\frac{1}{2}V_{CC}$. There is no need for biasing components connected to the base because I_{CQ} is wished to be zero. There is a need to have input and output capacitors, to DC block and avoid the source and load accidentally shorting. The nature of the transistors acting as pushing and pulling forces gives them the name push-pull amplifiers.



(a) Prototype Circuit of a Class B amplifier, [37].

(b) Transient analysis of the prototype. The red signal is the input, the blue signal is the output, [37].

Figure 4.11: Class B prototype with transient analysis, [37].

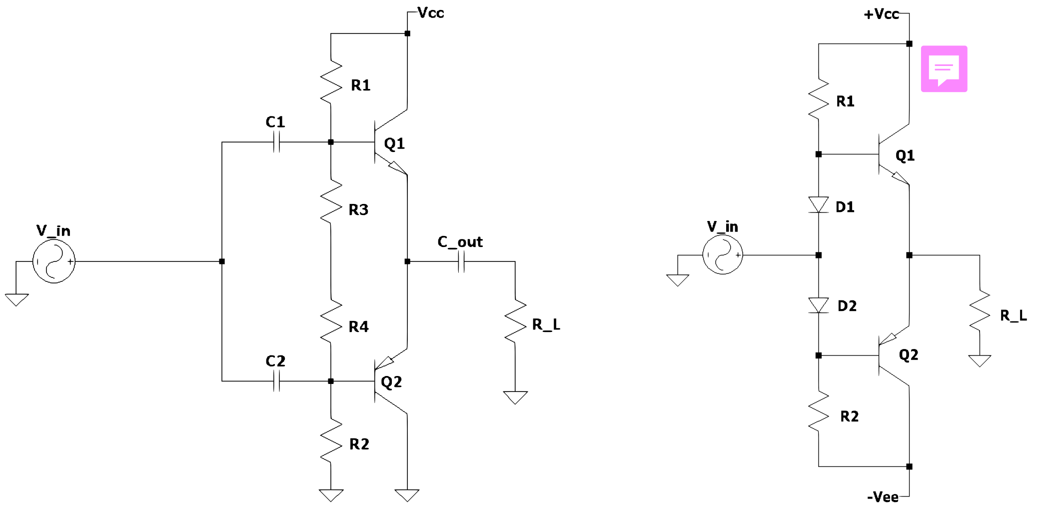
As seen in figure 4.11b a transient analysis has been made of the circuit seen in figure 4.11a. The red signal is the original signal whereas the blue signal is the amplified signal. As evident, the amplified signal has some "flat spotting" near zero. The reason for this is that the NPN transistor needs $0.7V$ to turn on, and the PNP transistor needs $-0.7V$ to turn on. So the amplifier will not react to any signal between $\pm 0.7V$, resulting in a "dead zone". This type of distortion is also known as notch distortion or crossover distortion.

The compliance of the class B amplifier is determined by the power supplies connected, with the peak-to-peak being the difference between the two power supplies. The class B has a better power dissipation than the class A, being one-fifth of the maximum load power. This means that the power efficiency of class B is much greater than that of class A, with a theoretical efficiency of 78.5%, [37]. The class B amplifier, with its variations, is quite a good balance between complexity and efficiency.

Class AB

The class AB amplifier is a variation of the class A and B amplifiers. The idea of the class AB amplifier is to solve the flat spotting of the class B amplifier. This is done by supplying the transistor with a small idle current so that the transistor is almost on. This means that the Q point will be biased to be just above the cutoff point, hence the power efficiency is slightly less than the class B amplifier. There are a couple of different ways this can be achieved, but in this example, a basic solution with a voltage divider will be shown.

The circuit seen in figure 4.12a, shows that both Q_1 and Q_2 have a voltage divider connected to them. Since it is the AC signal that needs to be amplified, capacitors are connected, acting as DC blockers. The circuit is therefore symmetrical, and the components are then equal to their counterpart, $R_1 = R_2, R_3 = R_4, C_1 = C_2$. The voltage dividers are configured to have just around 0.7V over R_3 and R_4 so that the transistors are almost on. If done properly, the crossover distortion of figure 4.11b, will be eliminated and the signal will be clean and continuous instead of having the flat spotting.



(a) Circuit of a class AB, [37]. **(b)** Class B amplifier biased with diodes, [37].

Figure 4.12: Biasing circuits of class AB and B, [37].

A problem with this type of circuit is the stability and biasing of the Q point. Resistors have a linear current-voltage characteristic, I-V curve, while Bipolar Junction Transistors, BJT, have an exponential I-V curve. This creates a problem where it is very difficult to try and match the I-V curves of BJT's and resistors. This problem worsens when the temperature varies. When the temperature of the transistor and resistor varies, the I-V curves of the components will drift in different directions. It is therefore very important to keep the circuits cooled so the I-V curves do not drift.

The I-V curve problem can be solved by replacing R_3 and R_4 with two diodes and placing them in parallel with the base-emitter junctions, as seen in figure 4.12b. This makes the I-V curve matching much easier since they both have an exponential I-V curve. In theory, if the I-V curve of the transistor matches that of the parallel diode, then the emitter current must be the same. It can be quite difficult to match a transistor and diode together exactly, but as long as the transistor and diode are quite similar, then the bias will be quite stable. There are a number of other class B configurations that offer current gain, power gain, and voltage gain, but these won't be examined in the report.

Using either the resistors or the diodes to try and match their I-V curve with the transistor, and the addition of an extra transistor lends the class B and AB amplifiers to be more complex. Class AB is an attempt to mix class A and B, by having the Q point situated just above the cutoff. This means that it is more efficient than the class A amplifier, and has less distortion than the class B amplifier. This unfortunately does come with a slight drawback, in that the class AB amplifier is slightly less efficient than that of the class B amplifier.

Class D

The idea of the class D amplifier is to have high power efficiency, essentially having no power dissipated in the device and no heat in the device. The Metal-Oxide-Semiconductor Field-Effect Transistor, MOSFET, has become the norm in class D applications, but a BJT could also be used. To have high power efficiency, the output devices are used as switches, where they are either at cutoff or saturation. Theoretically, the class D amplifier has a power efficiency of 100%. As mentioned before, by having higher power efficiency, less power is wasted in the device as heat. The advantage to having a higher power efficiency is that less power would be wasted, which in turn makes it cheaper to drive. If there also is not any power being dissipated, then there is no need to have a heatsink. That would mean the amplifier would be smaller compared to the other classes, and more reliable since the device would not be as worn.

A class D amplifier is constructed similarly to the class B amplifier. It uses the push-pull topology to alternate between Q_1 and Q_2 to allow the current to flow to and from the load. As seen in figure 4.13, a driver receiving Pulse Width Modulation, PWM, signals are connected to Q_1 and Q_2. The driver takes the PWM signal and produces a bipolar pulse train that swings from negative to positive, instead of the typical ground to positive like PWM. The circuit shows that the NMOS connected to the drain, V_{CC}, will supply the positive part of the wave, while the PMOS connected to the source, V_{EE}, will supply the negative part.

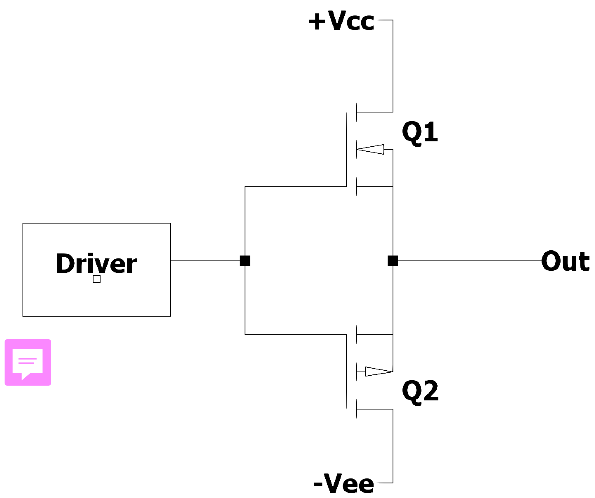


Figure 4.13: Basic Push-Pull Switching topology, [37].

In figure 4.14 a 2-device half bridge is presented. This configuration helps the amplifier with higher performance with a lower distortion. The difference is that the MOSFETs must be identical. A problem that arises with this configuration is that the gates can't be driven with the same signal. It therefore needs unique signals to be able to drive the terminals of the gates.

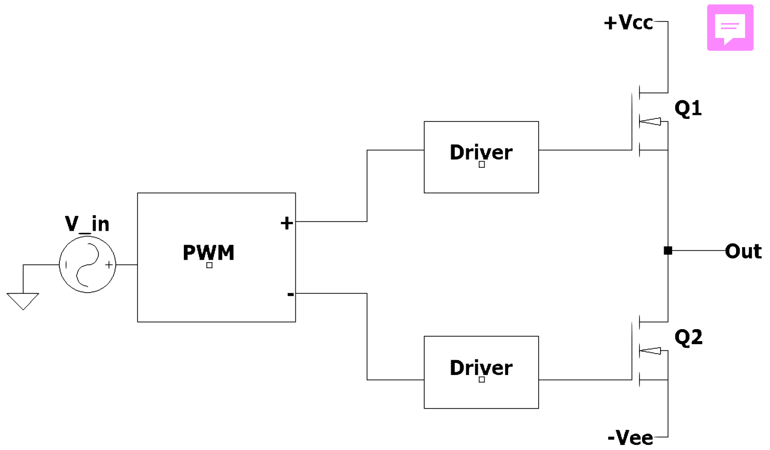


Figure 4.14: 2 device half bridge, [37].

To drive the load at both ends, the circuit must be configured in a differential fashion. This is where the 4-device full bridge comes into play, as shown in figure 4.15. This configuration drives the MOSFETs in diagonal pairs, so when Q_1 and Q_4 are on, then Q_2 and Q_3 will be off, and vice versa. When one of the diagonal pairs is on, a path for the current is created which will run over the load and down to ground. When this happens the amplitude of the current will double and the power will quadruple. There has also been added a passive low-pass LC filter for both halves, to eliminate any unwanted high-frequency components.

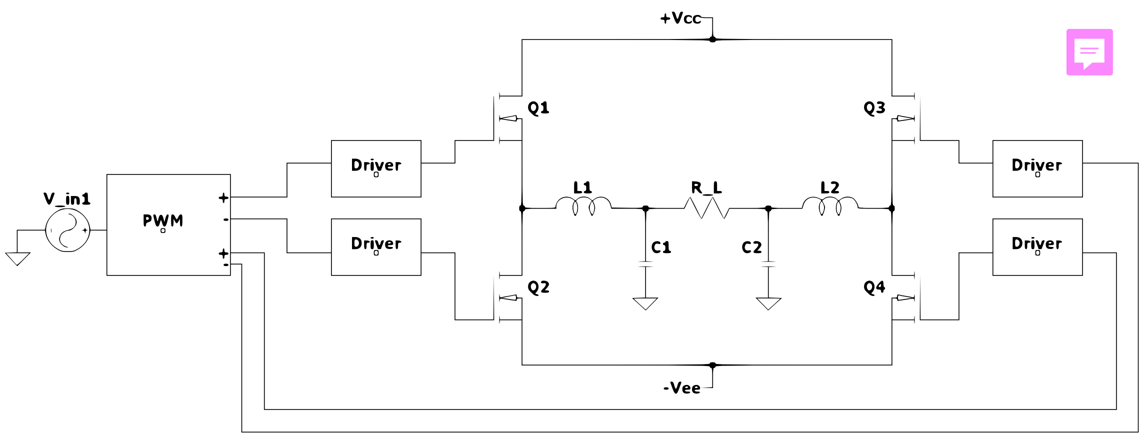
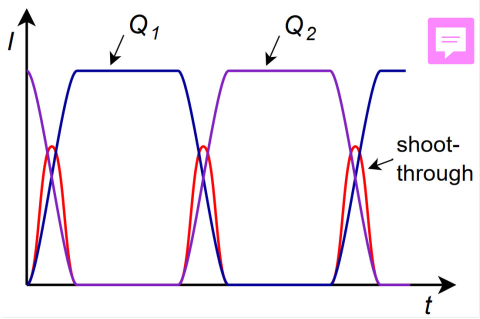


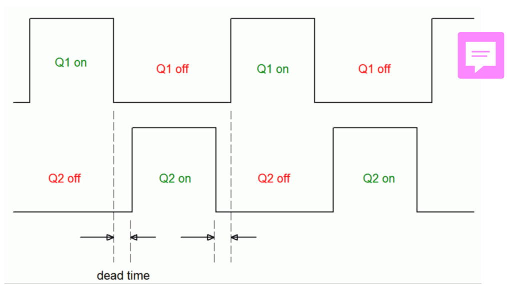
Figure 4.15: 4 device full bridge, [37].

A concern that comes with the class D amplifier is device capacitance. MOSFETs may have high device capacitance at the input and output gates. This can cause some problems with the switching frequency. If the current is large or if the capacitor is small, then the rate of change for the voltage will increase. If this isn't taken into consideration the switching frequency may be too low for signals with high switching frequencies.

Figure 4.16a shows another concern that can arise when one of the MOSFETs turns off whilst another is turning on. This problem is known as shoot-through. It would arise if the rise and fall times of the two switches of Q_1 and Q_2, or Q_3 and Q_4, were to overlap and be in the ON state at the same time. This would lead to a very large current flowing through the system and likely damaging it in the process. To combat this problem, a built-in dead time would be implemented, as shown in figure 4.16b. The dead time is used as a buffer between the switch states, ensuring that the first switch has fully turned OFF before allowing the second switch to turn ON.



(a) Shoot through, [37].



(b) Dead time.

Figure 4.16: Shoot through concern, [37].

To summarize, a table below has been constructed showcasing the pros and cons of the different classes.

Class A

Pros	Cons
Simplicity	Theoretical efficiency: 25%
Good linearity	High heat dissipation
Very low distortion	Large and heavy

Table 4.1: Pros and cons of class A amplifiers.

Class A amplifiers are used for applications such as outdoor musical systems.

Class B

Pros	Cons
Theoretical efficiency: 78.5%	Crossover distortion
	Difficult to characteristic match

Table 4.2: Pros and cons of class B amplifiers.

Class B amplifiers are used for applications such as Hi-Fi amplifier for loudspeakers and radio frequency amplification.

Class AB

Pros	Cons
Eliminates crossover distortion	Complexity
More efficient than class A	Slightly less efficient than class B
Less distortion than class B	

Table 4.3: Pros and cons of class AB amplifiers.

Class AB amplifiers combine the advantages of class A and B amplifiers. Typical applications are such as high-end home audio systems, home theaters, and digital audio players.

Class D	
Pros	Cons
Theoretical efficiency: 100%	Complexity
Small size	Potential shoot through
Strong reliability	Device capacitance

Table 4.4: Pros and cons of class D amplifiers.

Class D amplifiers are used in applications such as home theaters, car audio systems, wireless communication devices, and portable media players.

Section 4.3.2 is based on [37].

4.3.3 Total Harmonic Distortion

A system might have some unwanted frequency components also known as harmonic distortions. The total harmonic distortion, THD, shows the amount of deviation there is in the waveform of the system compared to a desired pure sinusoidal wave. To calculate the THD the following equation is used:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + ... + V_n^2}}{V_1} \tag{4.18}$$

Where V is the voltage amplitude of the nth frequency component.

$$\begin{aligned} V_1 &= \text{Fundamental frequency voltage} \\ V_n, n \geq 2 &= \text{Voltage of harmonic distortions} \end{aligned}$$

To find the voltage amplitude of the harmonic distortions, a Fast Fourier Transform, FFT, is needed. The FFT will show the harmonic distortions as peaks, with the first and largest peak being the original pure sinusoidal, and the subsequent peaks being the harmonic distortions. If done in simulation programs such as LTspice, there are a couple of ways to find the THD. To calculate the THD based on the FFT in LTspice, the voltage amplitude of the harmonic distortions must be noted. An example of this can be seen in figure 4.17, where the FFT is represented linearly instead of in decibels. As can be seen in the figure, the fundamental frequency has a voltage amplitude of around 3.8V, while the subsequent harmonic frequencies have a voltage amplitude of around 400mV or less.

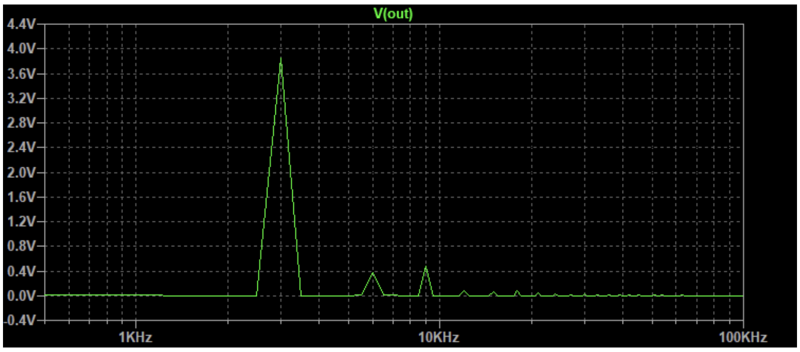


Figure 4.17: Linear representation of the FFT. The 30Hz signal is the fundamental frequency component, anything after it are the harmonic distortion frequency components.

If the voltage amplitudes of the frequencies is then inserted into equation 4.18, then the following THD of the example circuit is:

$$THD = \frac{\sqrt{(376.57mV)^2 + (475.74mV)^2 + ... + (26.72mV)^2}}{3.852V} \cdot 100 = 16.14\%$$

LTspice is also capable of calculating the THD with the *.four <frequency> [N Harmonics] [N Periods] <Data Trace>* spice directive, [38]. Using the spice directive will open the spice error log as can be seen in figure 4.18.

```
Warning: Multiple definitions of model "2scr375p" Type: BJT
Warning: Multiple definitions of model "bc857b" Type: BJT
Warning: Multiple definitions of model "bc847c" Type: BJT
Warning: Multiple definitions of model "bc847b" Type: BJT
WARNING: Node OUT is floating.

WARNING: Less than two connections to node out.  This node is used by c6.
Direct Newton iteration for .op point succeeded.
N-Period=6.00
Fourier components of V(out)
DC component:1.03528

Harmonic    Frequency    Fourier     Normalized   Phase       Normalized
 Number       [Hz]      Component    Component   [degree]     Phase [deg]
    1       3.000e+3    5.448e+0     1.000e+0     -90.00□       0.00□
    2       6.000e+3    5.326e-1     9.775e-2     179.99□     270.00□
    3       9.000e+3    6.728e-1     1.235e-1     -90.19□      -0.18□
    4       1.200e+4    1.161e-1     2.132e-2      -0.55□      89.45□
    5       1.500e+4    7.976e-2     1.464e-2      90.90□     180.90□
    6       1.800e+4    1.077e-1     1.976e-2      -0.54□      89.46□
    7       2.100e+4    6.799e-2     1.248e-2      90.25□     180.25□
Partial Harmonic Distortion: 16.130274%
Total Harmonic Distortion:   16.187821%
```

Figure 4.18: THD calculated by LTspice.

As can be seen from the calculation and the LTspice directive, the THD of the circuit in question is quite poor. For a normal circuit, a good typical THD percentage is around 0.5% - 1%, while for HIFI amplifiers a good THD is typically around 0.1%, [39].

There are a couple of different solutions to improve the THD. One solution is to optimize the biasing and feedback circuits. Another solution could be implementing filtering or equalizing. If there are any unwanted frequencies, a low-pass or high-pass filter can be implemented to remove or attenuate the unwanted frequencies. The equalizer can be used to move the frequency response so that the signal will be enhanced or reduced. Another solution is also to choose another amplifier class, but this of course comes with its advantages and disadvantages, [40].

4.4 Common Emitter Amplifier

As this project is in need of an amplifier, a Common Emitter Amplifier, CEA, has been chosen to further analyze in depth, to use later in the project. In order to design a CEA there are a few things to know:

- Frequency of the input signal
- Amplitude of the input signal
- Desired amplification
- Specifications and abilities of the chosen transistor

The transistor can be broken down into 3 different stages, low, mid, and high frequencies, as can be seen in figure 4.19. The desired frequency has to be within the borders of your F_L and F_H, to not attenuate the desired frequency, that is to be amplified. The F_L is affected by the capacitors, while F_H is by the transistor and its stray capacitance.

There are several methods to design and calculate for a transistor, and the method that has been chosen here is just one of many. It has has been chosen as it is relatively straightforward, compared to many other methods.

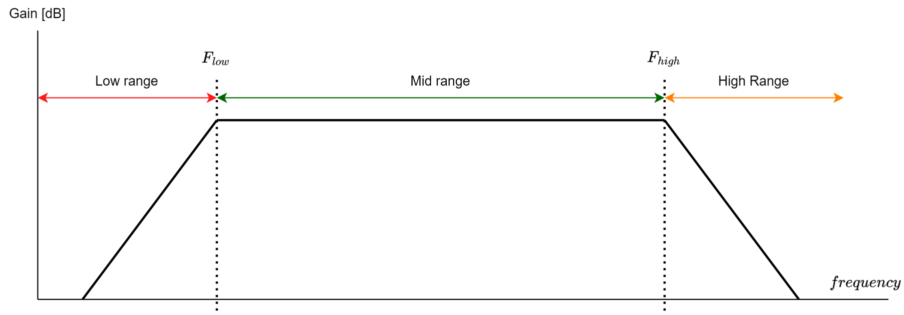


Figure 4.19: Frequency response for a CEA.

The analyzed design example will be based upon figure 4.20. R_{sig} can be seen as the resistance from the signal/source and R_{load} as the load from the output. What is important to note here is R_{E2} and C_e which is added to reduce distortion. Furthermore, C_b and C_c are capacitors used to remove the DC-offset introduced by R_{B1} and R_{B2}.

Besides the components seen in figure 4.20, there is an internal resistance in the transistor, which is important to remember as the transistor is not ideal. The different component values that vary from transistor to transistor are: $\beta, re, ro, V_{CE}, V_T, V_A, C_{cb}, C_{be}$ and most can be found in the datasheet, but it varies. These components will be introduced later on, in

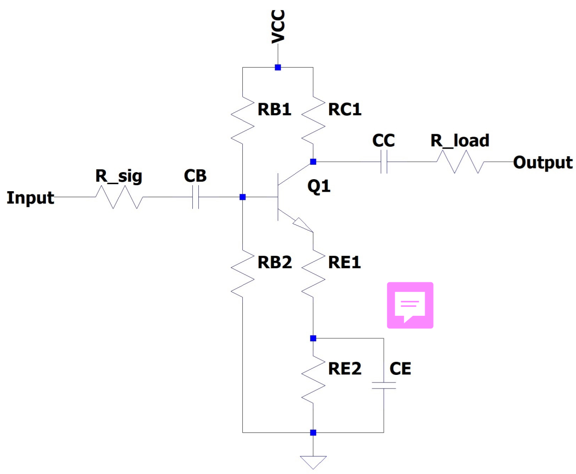


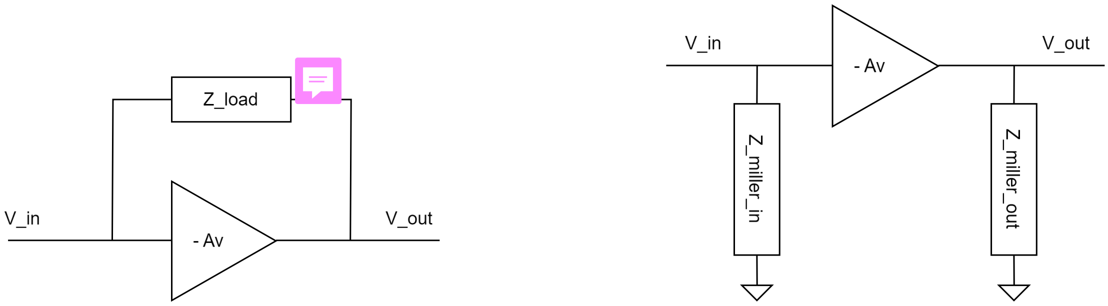
Figure 4.20: Chosen components and circuit for the CEA. Do note, that this is without internal components.

subsection 4.4.2, 4.4.3, 4.4.4 as they become relevant to introduce.

There are also several other phenomenons, that has to learn in order to do the proper calculations and they will be described before going further into the BJT.

4.4.1 The Miller Theorem

The Miller theorem states that an impedance over an inverting amplifier, in this case the transistor, can be made into an equivalent circuit, with two impedances to ground, one on either side. This can be seen in figure 4.21, where figure 4.21a is the circuit, while figure 4.21b is the equivalent circuit afterward. This is particularly important further on, when looking into the BJT and high-frequency analysis and finding the F_H.



(a) A load over an amplifier. **(b)** Miller equivalent circuit.

Figure 4.21: The Miller theorem.

Finding the values for Z_{miller}, is relatively easy. The first thing to remember:

$$V_{out} = V_{in} \cdot A_v \tag{4.19}$$

From here, due to the current running through is the same, the equation for Z_{in} can be written as:

$$\frac{V_{in} - V_{out}}{Z_f} = \frac{V_{in}}{Z_{in}} \rightarrow Z_{in} = Z_f \cdot \frac{V_{in}}{V_{in} - v_{out}} = Z_f \frac{1}{1 - A_v} \tag{4.20}$$

with Z_f being the floating component, Z_{load} on figure 4.21a.

Same method for Z_{out}:

$$\frac{V_{in} - V_{out}}{Z_f} = \frac{V_{out}}{Z_{out}} \rightarrow Z_{out} = Z_f \cdot \frac{V_{out}}{V_{in} - V_{out}} = Z_f \cdot \frac{1}{1 - \frac{1}{A_v}} \tag{4.21}$$

It's important to remember when using capacitors that $Z = \frac{1}{sC}$ and therefore when finding the component values for capacitors it become:

$$\frac{1}{C_{in}} = \frac{1}{C_f} \frac{1}{1 - A_v} \leftrightarrow C_{in} = C_f \cdot (1 - A_v) \tag{4.22}$$

$$\frac{1}{C_{out}} = \frac{1}{C_f} \frac{1}{1 - \frac{1}{A_v}} \leftrightarrow C_{out} = C_f \cdot \left(1 - \frac{1}{A_v}\right) \tag{4.23}$$

4.4.2 Midband Frequency Calculations

The midrange section should encapsulate all the frequencies needed to be amplified. In this section implication and Gain Bandwith Product, GBP, will be introduced.

V_b is the bias, which needs to ensure the signal doesn't clip, due to V_{CE}, and is a simple voltage divider between R_{B1} and R_{B2} and can be found by the following equation:

$$V_b = \frac{R_{B2}}{R_{B2} + R_{B1}} \cdot V_{cc} \tag{4.24}$$

The current on the collector is I_c. It's particularly important to find the internal resistance, re in the transistor. I_c can be found by:

$$I_c = \frac{V_b - V_{BE}}{R_{E1} + R_{E2}} \tag{4.25}$$

Where re can be found by:

$$re = \frac{V_T}{I_c} \tag{4.26}$$

Where V_T is the temperature coefficient for the transistor, usually 26mV at 27°C and can otherwise be found by:

$$V_T = \frac{K \cdot T_K}{q} \tag{4.27}$$

Where:

$K = 1.38 \cdot 10^{-23}[\mathrm{J/K}]$, which is the Boltzmann's constant
T_K, which is the absolute temperature in Kelvin
$q = 1.6 \cdot 10^{-19}$

As an CEA is an inverting amplifier, the amplification can then be written as:

$$A_v = \frac{RC1}{R_{E1} + re}[\cdot] \tag{4.28}$$

Where $[\cdot]$ denotes unitless, $R_{E1} + re$ is the only resistance, and not $R_{E1} + re + R_{E2}||C_e$ as it otherwise could have been expected. This is because C_e can be seen as short, bypassing R_{E2} entirely. Do remember that A_v is phase shifted 180° as it is an inverting amplifier.

GBP should also be considered, especially at high frequencies, as it should not be surpassed. If so, the amplification of the signal will decrease, or clip. Most transistors have a GBP of 100MHz, where the maximum output voltage, V_{gain}, is much more varying from transistor to transistor. The formula for GBP is:

$$GBP = f \cdot A_v \tag{4.29}$$

Where f = frequency bandwidth.

For example, with a GBP of 100MHz, an A_v = 100, a f = 100kHz, GBP would be $100 \cdot 100\text{kHz} = 10\text{MHz}$, which would not be problematic. But when working with a frequency bandwidth of 1MHz and above, it's something that has to be take more notice of, as an $A_v > 100$, would be above GBP and the signal would not be amplified as desired.

4.4.3 Lower Cutoff Frequencies

The lower cutoff frequencies, F_L, are largely decided by the values of the capacitors in the CEA. There will be three individual F_L poles, and the largest pole will be the dominant F_L pole. Remember, the formula for finding cutoff frequencies are:

$$f_{cutoff} = \frac{1}{2\pi RC} \tag{4.30}$$

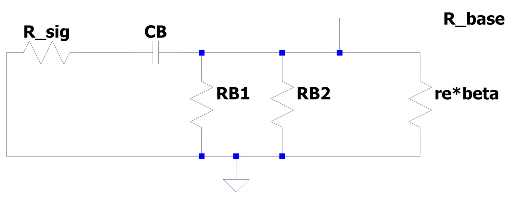
As this will be used for finding both F_L but also F_H.

Finding F_L for C_b

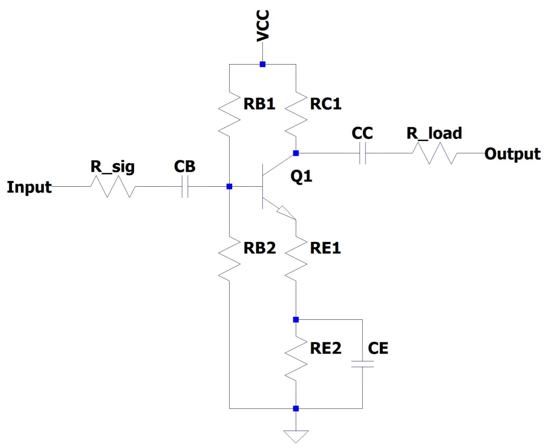
C_b is the capacitor at the base of the collector. The resistance on the base can be seen in figure 4.22a, as the capacitors can be seen as shorts.

$$R_{base} = R_{B1}||R_{B2}||\beta \cdot re = \frac{1}{\frac{1}{R_{B1}} + \frac{1}{R_{B2}} + \frac{1}{\beta \cdot re}} \tag{4.31}$$

An equivalent of the circuit can be seen in figure 4.22a.



(a) Equivalent circuit for the resistance at the base.



(b) The original diagram for the CEA.

Figure 4.22: The equivalent circuit and the original diagram, side by side.

Where R_{base} can be seen as what solely affects the base. From this F_L for C_b can be found:

$$F_{L_{base}} = \frac{1}{2\pi(R_{sig} + R_{base}) \cdot C_b} \tag{4.32}$$

Finding F_L for C_c

To find F_L at the collector, the internal output resistance at the collector ro, has to be found. To do this, the early voltage effect, V_A, is required. In simple terms, the early voltage effect describes how changing the voltage across certain parts of the transistor can affect how efficiently it operates. V_A is therefore dependent on the transistor. A figure describing it can be seen in figure 4.23.

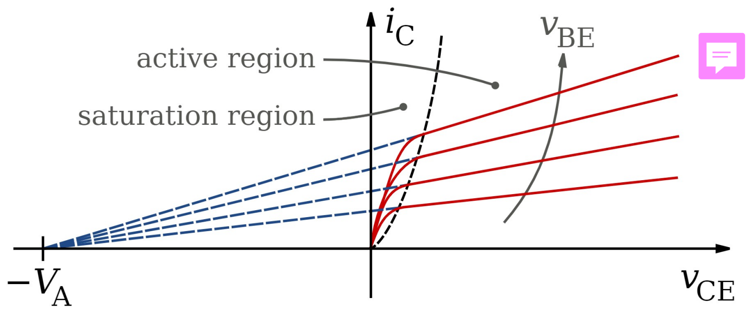


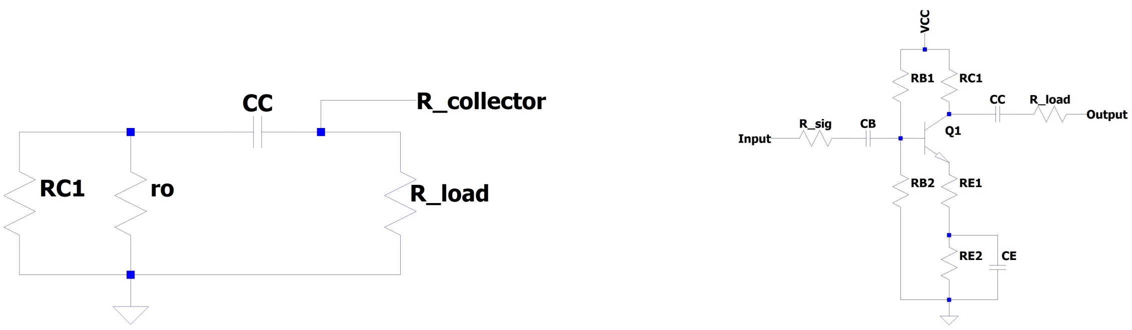
Figure 4.23: Figure of how to understand V_A, [41].

$$ro = \frac{V_A}{I_c} \tag{4.33}$$

With this, the resistance at the collector can be found, and following a similar approach. Where for the resistance at the collector, without R_{load} as it is "after", can be written as:

$$R_{collector} = RC1||ro = \frac{1}{\frac{1}{RC1} + \frac{1}{ro}} \tag{4.34}$$

And can be seen as the equivalent circuit in figure 4.22a and the original in figure 4.24b.



(a) Equivalent circuit for the resistance at the collector.

(b) The original diagram for the CEA.

Figure 4.24: The equivalent circuit and the original diagram, side by side.

Therefore the F_L for C_c is:

$$F_{L_{collecor}} = \frac{1}{2\pi(R_{collector} + R_{load}) \cdot C_c} \tag{4.35}$$

Finding F_L for C_e

The same principle applies to finding the $R_{emitter}$, with an equivalent circuit seen in figure 4.24a. With R_{sub} being $(R_{B1}||R_{B2}||R_{sig})/\beta$. It's important to note that C_e here is considered as open.

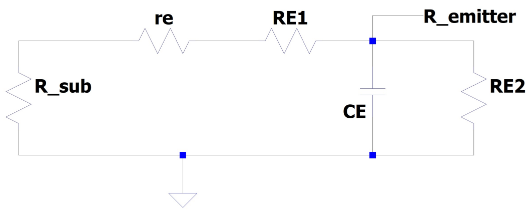


Figure 4.25: Equivalent circuit for the resistance at the emitter.

As $R_{emitter}$ is at the emitter leg, the resistance $R_{emitter_{final}}$ will be:

$$R_{emitter_{final}} = R_{E2}||R_{emitter} = R_{E2}||\left(R_{E1} + re + \frac{R_{B1}||R_{B2}||R_{sub}}{\beta}\right) =$$

$$\frac{R_{E2} \cdot \left(R_{E1} + re + \frac{1}{\frac{1}{R_{B1}} + \frac{1}{R_{B2}} + \frac{1}{rs}}\right)}{R_{E2} + \left(R_{E1} + re + \frac{1}{\frac{1}{R_{B1}} + \frac{1}{R_{B2}} + \frac{1}{rs}}\right)} \tag{4.36}$$

Which means the $F_{L_{emitter}}$ can be written as:

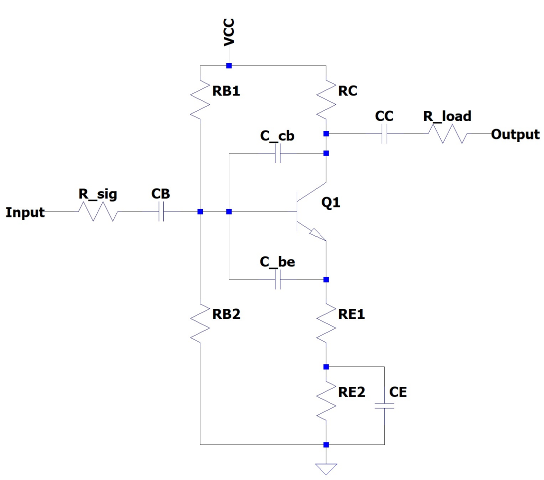
$$F_{L_{emitter}} = \frac{1}{2\pi \cdot R_{emitter_{final}} \cdot C_e} \tag{4.37}$$

Dominating F_L and Its Effect

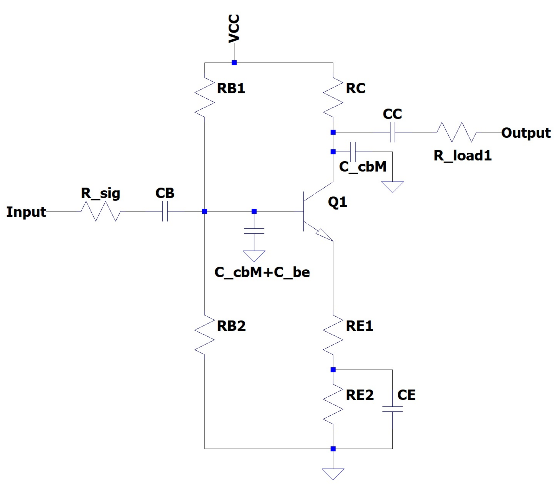
When all of the F_L poles are found, the highest is the dominant F_L pole. Higher capacitor values means a lower F_L.

4.4.4 High Cutoff Frequency

When doing high-frequency calculations on the CEA the primary factors determining the F_H poles are the stray capacitance that occurs inside the transistor, as shown in figure 4.26a, where C_{bc} and C_{be} are the capacitors that effects our circuit when doing high-frequency analysis. By applying Miller's theorem on C_{bc} C_{be}, the new circuit can be seen in figure 4.26b:



(a) Stray capacitance on the BJT at high frequencies, before Miller's theorem.



(b) After applying Miller's theorem to the circuit for stray capacitance at high frequencies.

Figure 4.26: Before and after applying Miller's theorem to stray capacitance on a BJT.

As each of the normal capacitors can be seen as shorts, a new equivalent circuit can be seen in figure 4.27:

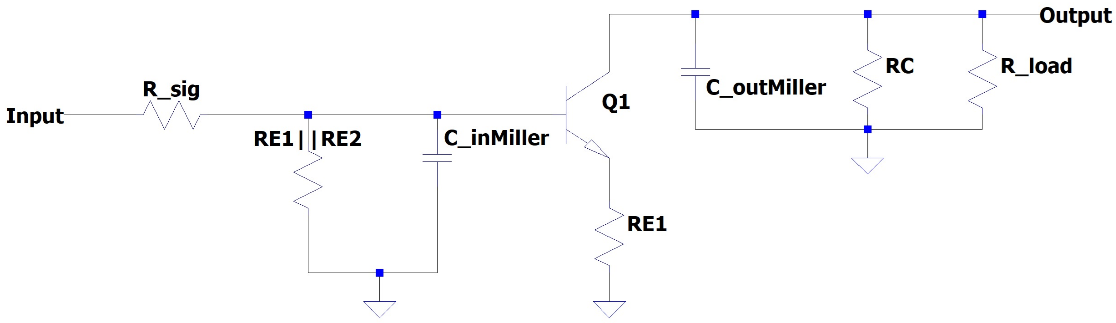


Figure 4.27: Equivalent circuit when doing high-frequency analysis.

When doing high-frequency analysis, it is only the capacitors at the input and output that affect the F_H poles.

Finding F_H for $F_{H_{in}}$

Once again, remember the formula for finding the cut-off frequency, the resistance R, and the capacitance C are needed. The resistance at the base can be seen as:

$$R_{in} = R_{sig}||R_{B1}||R_{B2}||\beta(re||R_{E1}) = \frac{1}{\frac{1}{R_{sig}} + \frac{1}{R_{B1}} + \frac{1}{R_{B2}} + \frac{1}{\beta(re||R_{E1})}} \tag{4.38}$$

And by following the application of Millers theorem, as mentioned previously in subsection 4.4.1, $C_{inMiller}$ is:

$$C_{inMiller} = C_{bc}(1 - A_v) + C_{be} \tag{4.39}$$

C_{bc} and C_{be} are usually around 2pF - 8pF but vary on the chosen transistor. With $C_{inMiller}$ found, the equation for $F_{H_{in}}$ is:

$$F_{H_{in}} = \frac{1}{2\pi \cdot R_{in} \cdot C_{in_{Miller}}} \tag{4.40}$$

Finding F_H for $F_{H_{out}}$

The resistance at the collector can be seen as:

$$R_{out} = RC||R_{load}||ro = \frac{1}{\frac{1}{RC} + \frac{1}{R\,load} + \frac{1}{ro}} \tag{4.41}$$

And the $C_{out_{Miller}}$ is:

$$C_{out_{Miller}} = C_{cb}\left(1 - \frac{1}{A_v}\right) \tag{4.42}$$

Which gives the $F_{H_{out}}$:

$$F_{H_{out}} = \frac{1}{2\pi \cdot R_{out} \cdot C_{out_{Miller}}} \tag{4.43}$$

Dominating F_H Pole and Its Effect

When all of the F_H poles are found, the lowest is the dominant F_H pole. Unfortunately, as F_H is decided by the stray capacitance internally in the transistor, and is therefore much harder to manipulate and design as with the F_L poles. But as C_{bc} and C_{be} are around 2pF - 8pF, it usually means an F_H pole is in the GHz range. Of course the resistor values, the equivalent R_{out} and R_{in}, affect it as well, but C_{bc} and C_{be} are the dominating components.

4.4.5 Summary

To summarize, there are a lot of things to be careful of and take into account when designing the CEA. If done correctly and thoroughly the CEA can be designed to precision, almost acting as a bandpass filter, if F_L and F_H are done correctly. As F_H is more set by internal component values, but luckily also quite high, it will rarely affect your amplification. However, F_L is very important, as it accidentally could choose a very low-value capacitor, and therefore end up attenuating the desired frequencies, getting an uneven output signal.

Furthermore, the unknown transistor-dependent components and values can be a bit more complicated to find, and calculating them could be a problem. So while in theory it could be done to precision, it may not be possible to do in real life.

This section is based upon, [42–44] and the "Analog Electronics" course held at AAU, in spring of 2024.

4.5 Modelling of a Loudspeaker

The study order states that a physical system should be able to be modeled as an electromechanical model. Therefore this section functions as an explanation of a loudspeaker, and how it can be electromechanically modeled.

A loudspeaker is a very common load connected to amplifiers. The loudspeaker takes electrical energy and converts it into mechanical energy which then causes sound. Figure 4.28 shows a cutaway view of how a typical loudspeaker driver looks like. At the heart of the loudspeaker is the voice coil. The voice coil is a wire wound around something called a former, which is a lightweight, non-ferromagnetic cylinder. The voice coil is connected to some lead wires which will terminate on the frame of the loudspeaker. The voice coil is also connected to the diaphragm which will generate sound waves when pushed. The loudspeaker has two suspensions, the outer suspension is simply called suspension, and the inner suspension is called spider. The voice coil is placed in a magnetic field which is created by the magnet.

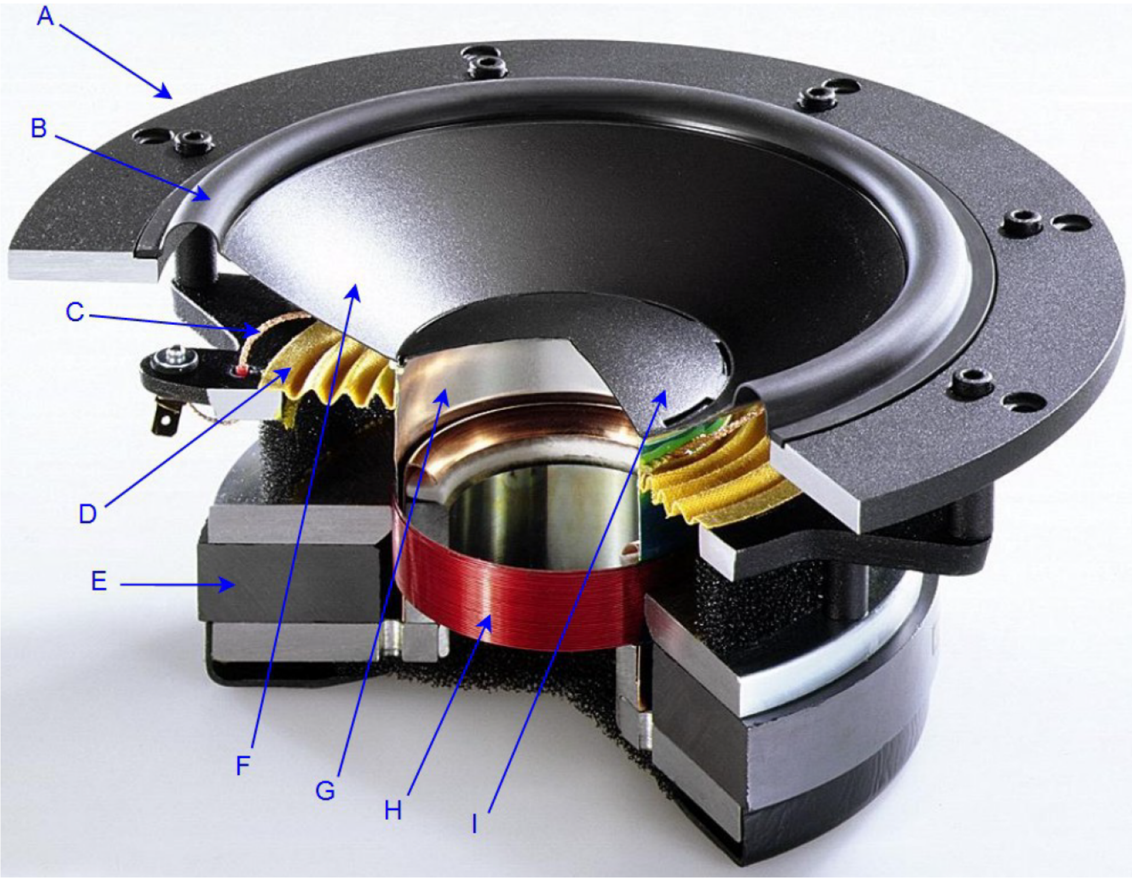


Figure 4.28: Cutaway view of a loudspeaker driver; A: Frame, B: Suspension, C: Lead wire, D: Spider, E: Magnet, F: Diaphragm, G: Voice coil former, H: Voice Coil, I: Dust cap, [37].

When a current runs through the voice coil, a magnetic field is induced, and this is exactly what Ampere's Law states, see equation 4.44.

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \cdot I_{enc} \tag{4.44}$$

Where:

$$\oint \vec{B} \cdot d\vec{l} = \text{Line integral of magnetic field, } \vec{B}\text{, around a closed loop}$$

$$\mu_0 = \text{Permeability of free space, given as } 4 \cdot \pi \cdot 10^{-7} \left[\frac{H}{m}\right]$$

$$I_{enc} = \text{Electric current passing through the loop}$$

Depending on the direction of the current, the magnetic field will either aid or oppose the permanent magnetic field and move the voice coil and diaphragm, which then creates sound. Unfortunately, it is very difficult for the loudspeaker driver to play within the audio spectrum without introducing distortions. This is because it is very difficult to have a diaphragm whose size and weight work for all frequencies. It is much easier to have a lighter and smaller diaphragm for the higher frequencies while having a larger and heavier diaphragm for the lower frequencies. The loudspeaker driver is therefore divided into three different drivers: woofer, midrange, and tweeter. The woofer is a larger driver that can play the lower frequencies, the midrange driver can play within the midrange frequencies, and the tweeter is a smaller driver that can play within the higher frequencies.

The loudspeaker commonly has a nominal impedance between 4Ω - 16Ω, with 8Ω normally for home sound systems. An electromechanical model of a loudspeaker can be seen in figure 4.29, modeling the relevant components of the loudspeaker. R_{VC} and L_{VC} are the resistance and inductance of the voice coil, while R_{ES} is the resistance of the suspension, L_{CES} is the inductance of suspension compliance, and C_{mes} is the moving mass capacitance.

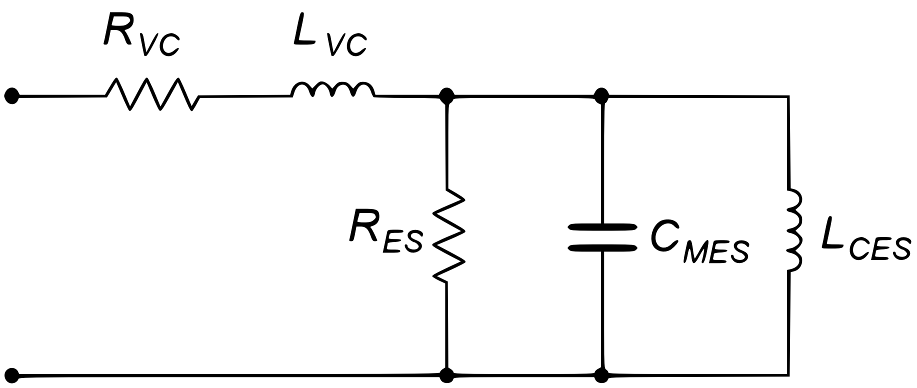


Figure 4.29: Electrical equivalent of a loudspeaker, [37].

4.6 Antenna Analysis

As the antennas are the real unknown element of a theremin, these need a thorough analysis, converting the unknown elements into scientific terms and notations. A side note about the theremin antennas would be that they have a primary function as one part of a capacitor, but can also act as actual antennas. This is rather unfortunate as the theremin is not intended to receive radio signals, and will be addressed in section 4.6.3 on page 43. This entire section is based upon the following citations: [11–17, 45–77].

4.6.1 Antennas as Capacitors

As mentioned several times, the key operation is directly related to capacitance, and the use of antennas as part of a capacitor and humans as the other. This subsection searches to describe this relationship in more depth and instantiate equations for it.

Human Capacitance

Human capacitance is rather abstract, as it depends on many physical aspects (bodyfat, muscle mass, water retention, weight, height, etc.) that cannot be determined without either testing it or measuring accurate body composition. Nevertheless, an average human based upon the "human body model", is assumed to have a body capacitance of 100pF in series with a 1.5kΩ resistor, [59, 61]. This capacitance should be negligible by connecting the thereminist to the ground plane of the theremin, but this will have to be tested to confirm it, which can be read in section 6.2.4 on page 60. It is beneficial to "remove" the general human capacitance to minimize its impact on the pitch/hand capacitance, as this otherwise would be a capacitance in series with the capacitance between the thereminist's hand and the pitch antenna. Regarding the hand/antenna capacitance, which from now on will be referred to as mutual capacitance, the most thorough data for their relation is derived by "dewster" on the forum theremin world. He has made a rather large Excel sheet containing data for 7 types of antennas, with hand placement 5-50cm away in 5cm intervals. From his tests, it is evident that the mutual capacitance relation is far from linear, which can be seen in figure 4.30.

The 7 types of antennas are described in table 4.5. The antennas are made of the following: column 1-3 is aluminum tape applied to the outer diameter of 3/8" PEX pipe. Column 4 is aluminum tape on the outer diameter of a Schedule 40 PVC pipe. Columns 5 and 6 is a telescoping antenna from Radio Shack - part number 270-1405 - at different extension levels. In column 7, the antenna is a plate antenna, measuring 235x115mm. Despite the rather large difference between the sizes of antennas, they all show similar behavior, in that they show an exponential increase in capacitance as the distance between hand and antenna is minimized. Furthermore, it can be seen from the data shown in figure 4.30 and table 4.6, that the mutual capacitance is directly related to the size of the antenna. A longer or wider antenna yields larger capacitance, especially close to the antenna. This fits general knowledge about capacitors and their capabilities.

Antenna	1	2	3	4	5	6	7
Antenna Length	250	330	450	450	450	710	235 (plate)
Antenna Diameter	9.9	9.9	9.9	21.7	3.61	3.61	115 (plate)

Table 4.5: Table of antennas used for "dewster"'s tests. All measurements are in mm, [45].

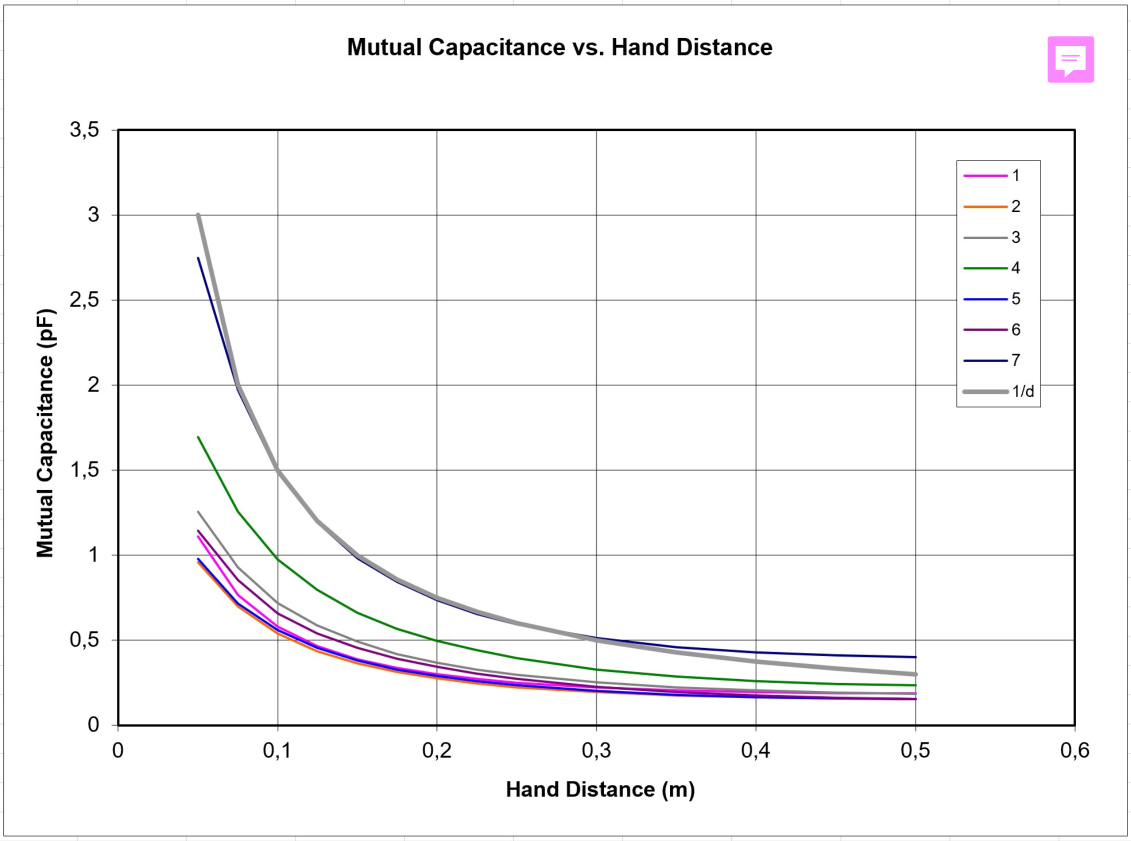


Figure 4.30: Graph showing the relation between hand placement in meters on the x-axis and mutual capacitance between the hand and pitch antenna inpF on the y-axis. The data shows the 7 different antenna capabilities while showing an approximate relation of C=1/d, with d being distance and C capacitance. Unfortunately, the approximation is mostly a "spherical cow" in a toy model, and not relevant for understanding the relation, but merely a first-order approximation, based on trace slopes, [45].

Antenna:			1	2	3	4	5	6	7	1/d
Antenna Length (m):			0,25	0,33	0,45	0,45	0,45	0,71	0,235	
Antenna Diameter (m):			0,0099	0,0099	0,0099	0,0217	0,00361	0,00361	0,115	
Antenna Self C (pF):			6,01	6,78	8,35	10,52	7,04	9,34	9,13	
Stray C (pF):			1,77	1,98	2,06	2,15	1,99	2,29	2,65	
Mutual C:	distance (m)	1/d	C (pF)	C (pF)	C (pF)	C (pF)	C (pF)	C (pF)	C (pF)	1/d
	0,05	20	1,110097	0,956585	1,255964	1,6947	0,97916	1,14383	2,74598	3
	0,075	13,33333	0,7657	0,69802	0,926309	1,25411	0,7164	0,85256	1,97024	2
	0,1	10	0,581604	0,539462	0,720017	0,97651	0,55816	0,65691	1,48997	1,5
	0,125	8	0,465643	0,435725	0,585751	0,79654	0,45655	0,54064	1,19429	1,2
	0,15	6,666667	0,389003	0,363191	0,490843	0,6621	0,38013	0,45637	0,98321	1
	0,175	5,714286	0,335636	0,313447	0,418077	0,56679	0,32624	0,39206	0,8429	0,85714
	0,2	5	0,299651	0,276138	0,367631	0,49632	0,28818	0,34295	0,73604	0,75
	0,225	4,444444	0,271706	0,247457	0,327055	0,44134	0,2584	0,30415	0,65522	0,66667
	0,25	4	0,250542	0,223636	0,295947	0,39277	0,23431	0,27224	0,59443	0,6
	0,3	3,333333	0,222611	0,193889	0,250915	0,32846	0,20133	0,22693	0,51184	0,5
	0,35	2,857143	0,205604	0,175433	0,222848	0,2858	0,17958	0,19519	0,45883	0,42857
	0,4	2,5	0,195659	0,164157	0,204146	0,25864	0,16562	0,17419	0,42823	0,375
	0,45	2,222222	0,189808	0,157568	0,191985	0,24245	0,15719	0,16056	0,40987	0,33333
	0,5	2	0,187214	0,154726	0,185967	0,23549	0,15277	0,15373	0,40004	0,3

Table 4.6: Table of "dewster"'s findings. The 1/d relation is a proposed approximation derived by dewster, where the first 1/d column is his constant and the last column is the result using a trace slope found somewhere else in his Excel sheet. Stray C is capacitance found in the environment, i.e. "noise" perceived by the antenna. Notice how the self-capacitance rises with the diameter and length, as this affects the mutual capacitance, [45].

As shown in the above graph and table, the mutual capacitance appears to be representable with an inverse exponential function. This is especially evident looking at the plate antenna, column 7, in the table, and comparing the mutual capacitance change from 5-7.5cm being 0.77pF and the change from 45-50cm being 0.009pF. Similar comparisons can be made across the table or read from the graph. What is noticeable from this information is the range of mutual capacitance to expect from different antennas i.e. the range for the plate antenna is approximately 2.34pF and for a 10x450mm rod antenna 1.07pF, which is close to negligible amounts. Nevertheless, this is the range to expect when the theremin will be designed in section 6.2.2 on page 58.

Linearity of Antenna-Capacitors

Obtaining the linearity of "antenna capacitors" is a bold task. This comes down to capacitors' general characteristics, but that can be mitigated if the attention is oriented towards a different "linearity". As proven by the Fletcher-Munson curves, human hearing perceives frequencies and loudness logarithmically and not in the least linear. A mix of this logarithm and the exponential capacitance increase could make it seem as if the antenna capacitors are linear. However, as the logarithm and exponential functions are not completely inverse, the result is still not perfectly linear. There exist several attempts to mend this conundrum, but as with everything else theremin-related, it becomes a matter of "it works for me" rather than scientific data showing actual benefits. In spite of that, the most common "solutions" deserves a mention: changing the shape of the antenna to lightning bolts, curving the antenna, adding a CD on top of the antenna, adding an adjustable coil at the top of the antenna, changing the antenna to an adjustable screen door spring, adding one-transistor LC oscillators to the circuit, digital filters, equalizers, after-effects, and a host of other manipulation, of which none achieves making a linear pitch or volume field. Other theories state that longer antennas exhibit better linearity than shorter antennas.

Pitch Drift

Pitch drift is a phenomenon in which a stationary hand placement to the antenna results in a change in pitch produced. The phenomenon is rarely described scientifically but has been noted/produced by several thereminists across different forums. It is often described as a change in pitch when a thereminist tries holding a specific pitch much more than fractions of a second. The only way to counter the phenomenon is to add a vibrato or a constant glissando between pitches, see section 2.2.3 on page 5. Attempts have been made to alter the theremin construction to mitigate possible pitch drifts, but none has shown significant reduction. This is theorized to be because of the capabilities inherent in any capacitor, specifically the charging capabilities. As the mutual capacitance relation is best described as an actual capacitor, the ability to charge small voltages must follow. The theory relies on the time-changing characteristics inherent to capacitors, and the fact that a theremin is sensitive to even the smallest changes derived by the pitch antenna circuit. Therefore, it is possible that a small voltage across the mutual capacitance could result in pitch drift. However, such a claim must be tested thoroughly to support itself. Such a test and setup can be read in section 6.2.4 on page 60.

Circuit and Ground Connections

As the thereminist acts as the grounded side of the capacitative relations C_{Mutual} for both pitch and volume, it is integral that the thereminist is grounded. To enhance this effect, a line similar to the ESD bracelets should be connected between the thereminist and ground on the theremin, just without the 1MΩ resistor embedded in them. Furthermore, it is of utmost importance that the antennas are not grounded anywhere else and are only connected to the positive sides of the capacitor that they're emulating.

4.6.2 Dimensioning Theremin Antennas

When it comes to dimensioning theremin antennas, there isn't much research on what effects certain characteristics impose on the antenna. Therefore, the following two subsections will be mostly based on statements from various forums, books, guides, etc. put together with "dewster"'s data.

Pitch Antenna

A general rule of thumb is that the pitch antenna should have a diameter of 10mm and a length between 40cm and 50cm, as this resembles that of Leon Theremin the most. Furthermore, most DIY guides and "professional" guides give similar measurements. An increase in either diameter or length yields higher capacitance, with the diameter being the most prominent, which can also be seen in table 4.6 on page 41 across antennas in column 3, 4, and 5. Beyond the capacitive abilities, the size (width and length, both respectively and separately) could also affect linearity, but there simply does not exist enough data to support this.

Volume Antenna

The volume antenna is rarely spoken about in technical detail, other than it should be 600mm-900mm in total length, have a diameter of 10mm, and then bent around itself. Other than this, most guides only show pictures of what it should look like when done, without specifications regarding bent length, curvature, or the like. Generally, the volume antenna is either U-shaped or shaped like the outer boundary of a $\mathbb{P}$.

4.6.3 Actual Antenna Capabilities and Their Relation to Theremins

All of this information may not matter without mentioning actual antenna capabilities. As the pitch antenna is what most resembles an actual antenna, that will be the subject of this subsection. In general, antennas either receive or transmit electromagnetic waves or use a transceiver to handle both operations. Furthermore, antennas are constructed in various forms and sizes, fitting a wider variety of tasks. As antenna and wavelengths can be matched by making the antenna length divisive by 2, 4, or sometimes 8, this becomes a factor to keep in mind when designing the pitch antenna. A typical length of the pitch antenna is 40cm-50cm. A length of 40cm corresponds to 1/8 wavelength at a frequency of 93.685MHz and 42.779cm corresponds to 1/8 wavelength at 87.6MHz, which would make the antenna "ideal" for receiving either of the local radio stations "Mariagerfjord Lokalradio" or "ANR". While this is mostly theoretical, it is a detail to keep in mind when designing a theremin, as it might introduce noise in some cases, although it is mostly discussed regarding digital theremins. This will not be tested, as it does not fit the scope of the project.

4.6.4 Setting up Mathematical Equations Describing Antennas Capacitor Capabilities

To ease into the thought pattern of using antennas as capacitors, some basic ideas and relations will be described before turning to the abstract version related to theremins.
The most basic capacitor relations applicable to theremins can be described with the following equation:

$$C = \frac{\varepsilon \cdot A}{d} \tag{4.45}$$

Where ε is the absolute permittivity found by multiplying the relative (air in the case of theremins) permittivity with ε_0, A is the area in m^2 of the plates used in the capacitor, and d is the distance between plates in meters. A is more specifically denoted as the overlapping area between the two plates, as a capacitative effect can only exist here.

Considering the design of a theremin antenna, the surface is omnidirectional due to using rods rather than directed as when using plates. This introduces stray capacitance to the antenna, as everything around the antenna adds a capacitance in minuscule amounts, and will be referred to as C_{Stray} from now. As mentioned in 4.6.1 on page 40 the capacitance between the player's hand and pitch antenna is named "mutual capacitance" and will be denoted C_{Mutual} in future equations. The first step towards approximating the antenna relations is determining the intrinsic capacitance, which is capacitance present in PCBs, breadboards, components, etc., of the antenna according to Skeldon K et al, [78]. To determine the intrinsic capacitance, the formula for capacitance per unit length of a coaxial cable could be used:

$$C = \frac{2\pi \cdot \varepsilon}{ln(\frac{R_2}{R_1})} \left[\frac{F}{m}\right] \tag{4.46}$$

Where ε is given by $\varepsilon_0 \cdot \varepsilon_r$ with ε_0 being vacuum permittivity ($\frac{1}{36\pi} \cdot 10^{-9}$) and ε_r being the relative permittivity between the positive and negative sides of the capacitor. R_2 is outer diameter and R_1 inner diameter in meters. The result is in F/m. For demonstration purposes, a common antenna size of 10mmx500mm with 1mm wall thickness is used for all following calculations. Adding these measurements to the formula yields:

$$C = \frac{2 \cdot \pi \cdot ((\frac{1}{36\pi} \cdot 10^{-9}) \cdot 1.00059)}{ln(10 \cdot 10^{-3}/8 \cdot 10^{-3})} \rightarrow C = 249.12 \cdot 10^{-12} \left[\frac{F}{m}\right] \tag{4.47}$$

As known from equation 4.46 the result of 4.47 is in Farad per meter, and can therefore be multiplied by the length of the antenna (50cm):

$$C = 249.12 \cdot 10^{-12} \cdot 0.5 \Rightarrow 124.56 \cdot 10^{-12} \, [F] \tag{4.48}$$

Comparing it to "dewster"'s findings, as he has provided the most thorough data set available, the result is very similar. In his data, an antenna with the same diameters and a length of 0.45m has an intrinsic capacitance of $108.35 \cdot 10^{-12}$ F. Substituting the length of 0.5m with 0.45m in the above equation yields:

$$C = 249.12 \cdot 10^{-12} \cdot 0.45 \rightarrow 112.10 \cdot 10^{-12} \, [F] \tag{4.49}$$

With "dewster"'s data being measured, it verifies that equation 4.46 is applicable for calculating intrinsic capacitance, as the difference can be accounted to measurement methods and common differences between calculations and real life.

However, this calculation implies that the full length of the antenna is used at all times. Theoretically, this is not necessarily true as the thereminist would not have their hand perpendicular to the top of the antenna, at least not looking at common playing techniques. Therefore, depending on the sensitivity of the theremin, the antenna might "produce" a different capacitance, depending on the height of the thereminist's hand. In figure 4.31 three different hand placements can be seen, where the theoretical approach would imply that the different hand placements could shorten/lengthen the perceived size of the antenna. Nevertheless, this is rather theoretical and only implied to have relevance by a few forum members, and must therefore be tested before any conclusions can be made to say if there is a direct relation, or if it is only perceived by some thereminists much the same way as audiophiles proclaim a difference across similar high-end coaxial cables.

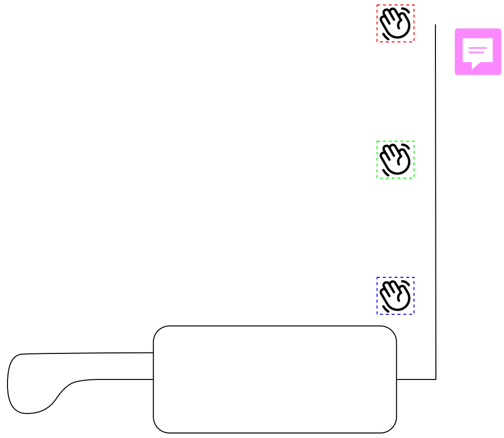


Figure 4.31: Illustration of different hand placements w.r.t. the pitch antenna.

Now that the antenna's intrinsic capacitance has been found, the capacitance relation between the antenna and the thereminist's hand can be found. To calculate the capacitance, equation 4.45 will be used. Unfortunately, neither the tube area nor the hand area can be easily determined. Looking at the tube first in figure 4.32, the different color combinations showcase different area relations. In a traditional capacitor, the only area relevant is that of the side of the plate overlapping with another plate. In the case of a tube, at least two surfaces are faced towards the hand, but as there is no dielectric material forcing the relation in one direction, it could be theorized that either all surfaces of the tube or only the surface faced directly towards the hand should count. To showcase how much the different variations impact the capacitance, the following equations will describe the relations. All equations operate with a flat hand area 10cm in height and 1cm wide ,as the copper tube is 1cm wide. However this area cannot be added to equation 4.46, as the equations shown in appendix A.2.1 already account for the area. The results can be seen in table 4.7:

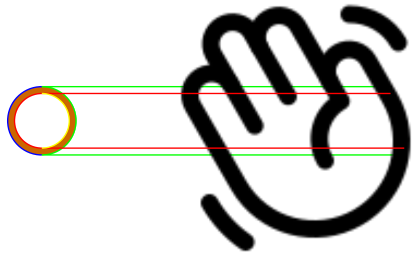


Figure 4.32: Illustration showing different possible "area" definitions regarding the hand-antenna overlapping area. The different color areas could all be considered areas for which the capacitance is related.

A_{Hand}	A_{D_1}	A_{D_2}	$Crescent_{Inner}$	$Crescent_{Outer}$
0.001 $[m^2]$	0.0008 $[m^2]$	0.001 $[m^2]$	0.01256 $[m^2]$	0.01571 $[m^2]$

$A_{CrescentInner}$	$A_{crescentOuter}$	$A_{HalfMoon}$	$A_{FullMoon}$
0.001571 $[m^2]$	0.001571 $[m^2]$	0.002827 $[m^2]$	0.005655 $[m^2]$

Table 4.7: Results of calculating different area possibilities of overlapping hand/rod area. Calculations can be found in appendix A.2.1 on page 148.

In figure 4.32 several different area configurations are shown by different colour combinations. These area definitions are used again in table 4.8. Explanations for the various names are: D_1 and D_2 are based upon the inner and outer diameter of the tube (8 and 10mm). $Crescent_{Inner}$ and $Crescent_{Outer}$ is based upon the the inner and outer half of the circumference of the tube. The $A_{Halfmoon}$ area is the two crescent areas put together and $A_{Fullmoon}$ is the full inner and outer circumference of the tube. As mentioned in the table, calculations are available in appendix A.2.1 on page 148. Substituting the A in equation 4.45 with these areas and a distance of 0.5m yields:

A_{D_1}	A_{D_2}	$A_{CrescentInner}$	$A_{CrescentOuter}$	$A_{HalfMoon}$	$A_{FullMoon}$
$14.155[fF]$	$17.694[fF]$	$22.235[fF]$	$27.794[fF]$	$50.030[fF]$	$100.059[fF]$

Table 4.8: Overview of different results yielded by implementing values from table 4.7 into equation 4.45. Calculations can be found in appendix A.2.2 on page 148.

All of these results are unfortunately about 10-100 times smaller than the capacitances measured by "dewster" shown in table 4.6 on page 41. This would imply that the capacitance relations are far off from being this simple. Another way the antenna might perceive the thereminist's hand is shown in figure 4.33. In this version, the area perceived by the antenna is close to being omnidirectional, as the antenna reacts in all directions, and not directional as shown in the previous equations. This omnidirectionality would also better fit the narrative that theremins are sensitive to everything in their proximity. Unfortunately, it also complicates any equations related to explaining the possible capacitance.

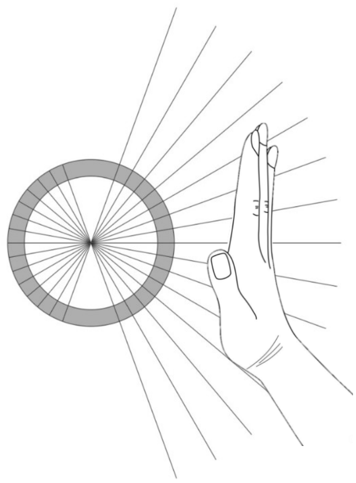


Figure 4.33: Possible relations showing the antenna being capable of perceiving the entire hand, arm, and other capacitative elements in the vicinity.

The first step towards defining omnidirectional capacitance is determining stray capacitances, C_{Stray}. Instead of calculating C_{Stray}, "dewster"'s data will be used for antenna 3, having a C_{Stray} of 2.06pF. This leaves C_{Mutual} to be calculated as the only variable. To ease the calculations, the following boundaries will be made:

- The hand will only be "2 dimensional" - a given area at a given distance.
- The entire hand will be at the same distance from the tube, meaning the area follows the curvature at the chosen distance.
- The area calculated for the hand is a rough estimate, as some hand positions are harder to calculate the exact areas of.
- The accompanying arm area perceived by the antenna will be set to $15cm \cdot 8cm = 0.012m^2$ and will be added to the area of the hand.
- The tube will be capable of mirroring the area at all times, effectively using the full area of the hand/arm.

With the above boundaries in place, the hand postures shown in figure 2.3 on page 4 will be calculated/measured. A sixth posture using a flat hand will be calculated as well. To ease the calculations, AutoCAD 2024 will be used to trace the silhouettes of each hand, and then the "AREA" function gives the area in mm^2. The postures will be named 1-6 from left to right in figure 4.34. Using AutoCAD the following areas have been found for postures 1-6:

Figure 4.34: The 6 different postures drawn in AutoCAD.

Posture 1	Posture 2	Posture 3	Posture 4	Posture 5	Posture 6
$0.012748705m^2$	$0.012235360m^2$	$0.011093810m^2$	$0.012570834m^2$	$0.010729653m^2$	$0.014195711m^2$

Table 4.9: Area results for the 6 different postures. Calculations can be seen in appendix A.2.3 on page 149.

Adding the new areas and a version with the arm area of $0.012m^2$ to formula 4.45 yields the capacitative capabilities shown in figure 4.35 and 4.36 for posture 5. All other postures and their capabilities can be seen in appendix A.3 on page 150 with raw data available in appendix A.1 on page 147.

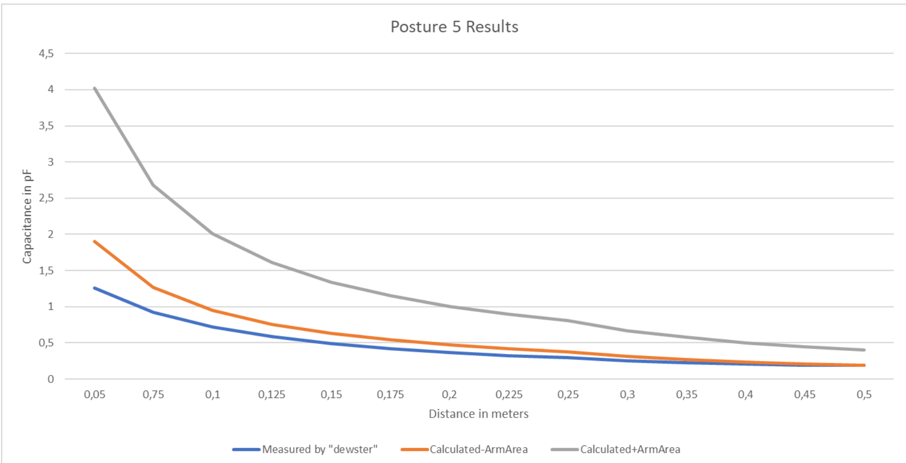


Figure 4.35: Line graph showing that equation 4.45 used on posture 5 is relatively far off in close distances, but at 0.5 meters, the equation almost matches "dewster"'s data. The blue line is "dewster"'s data, orange is without the "ArmArea" added and grey is with "ArmArea" added.

As can be seen from figure 4.35 the theory of adding "ArmArea" certainly did not give the desired result. Without the added "ArmArea" though, the calculated data comes within 30% deviation at 12.5cm and within 2.1% at 50cm, which is better than "dewster"'s proposed 1/d relation. In figure 4.36 the percentwise deviation can be seen for both with and without "ArmArea". The figure underlines that the "ArmArea" adds too much capacitance to the calculation, and will therefore be scrapped in search of approximating "dewster"'s results better.

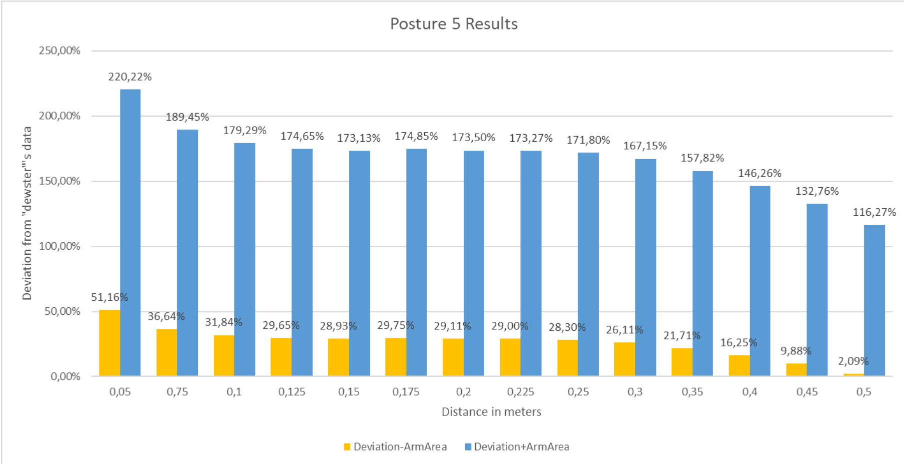


Figure 4.36: Bar graph showing the deviation from "dewster"'s data in percent. The orange bars are without the "ArmArea" added and blue is with "ArmArea" added.

To produce a better approximation, it is clear that some constant has to be multiplied by the capacitance. The constant should, in this very specific instance, be near 1 at a distance of 50cm and about 2/3 at a distance of 5cm. Adding a constant of $distance + 0.6$, found by acknowledging the constant should change according to the distance, while still having minimum and maximum around 2/3 and 1, and multiplying it with the calculated capacitance ($C = \frac{A \cdot \varepsilon}{d}$) yields an average deviation of 4.7%, in comparison with an average deviation of 26.46% without it. This result is used with the data for posture 5, as this was the posture with values most resembling "dewster"'s. When adding the constant to the remaining 5 postures, it yields similar results, ranging from 8.26% to 38.52% deviation, compared with 30.75% to 67.31% without the constant added. It should be noted that generally, the formula is a better fit at small distances, which is beneficial, as a majority of theremin playing is done close to the antenna. The full tables can be seen in figure 4.37.

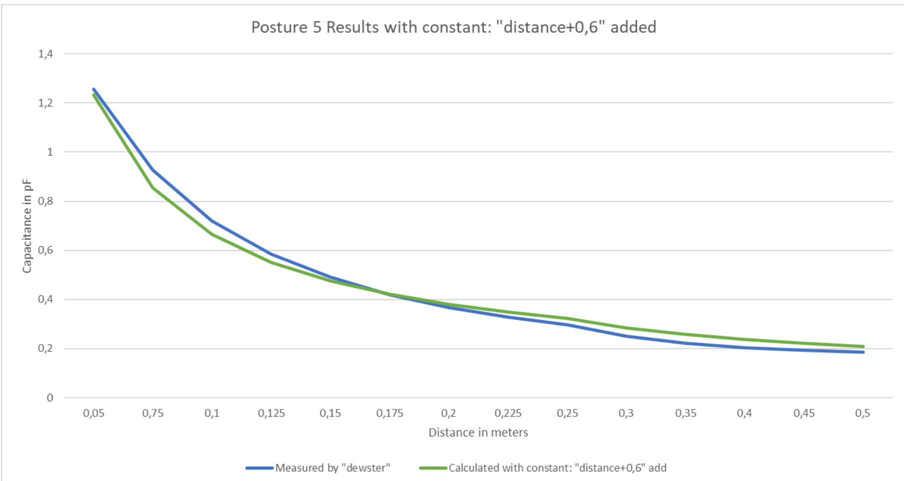


Figure 4.37: Line graph showing that the addition of a constant $distance + 0.6$ yields a far better approximation for the 5th posture. The blue line is "dewsters" measurements, and the green line is with the constant $distance + 0.6$. Similar line graphs and results can be seen in appendix A.4 starting on page 156.

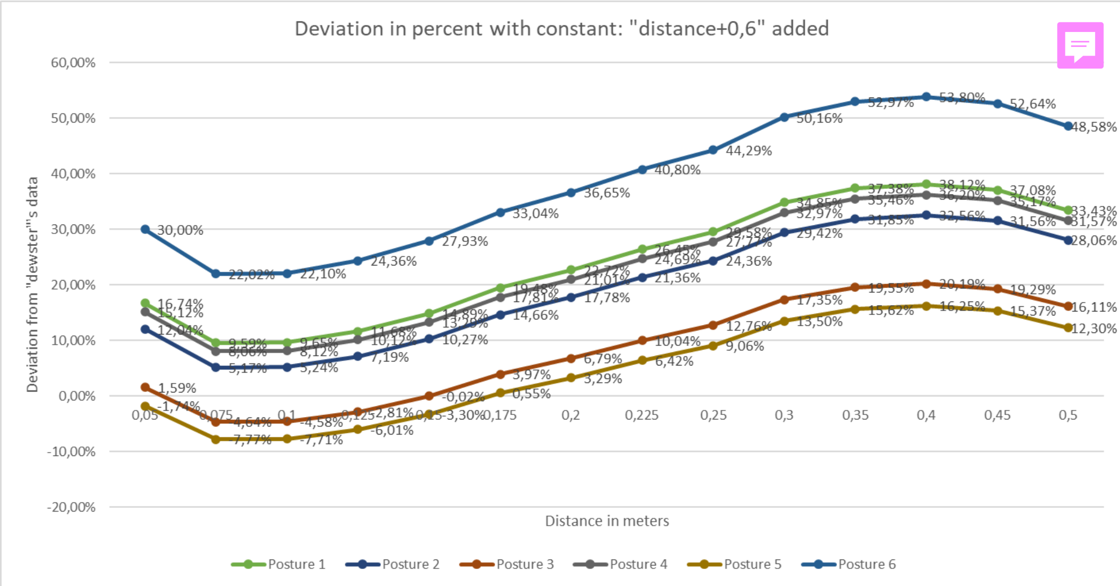


Figure 4.38: Line graph showing that the addition of a constant *distance* + 0.6 yields a far better approximation across all postures. A bar graph showing the same data can be found in appendix A.4 in figure A.19 on page 159. Similar line graphs and results can be seen in appendix A.4 starting on page 156.

Due to time constraints, there will not be spent any more energy trying to instantiate an equation describing the relation. When searching different forums for help, it is clear that no one else has been capable of determining a formula, that can be used at every instance of a theremin antenna. Neither can this formula, but it closely resembles "dewster"'s data, and is acceptable for some postures in this very specific setup with constructed boundaries. As several forum posts have been discussing this formula spanning back 12 years, as of writing this, the following formula will be used to describe the relation of C_{Mutual}, instead of instantiating finite element analysis:

$$C_{Mutual} = \left(\frac{A \cdot \varepsilon}{d}\right) \cdot (d + 0.6) \tag{4.50}$$

4.6.5 Summary

This section set out to de-mystify some of the unknown elements surrounding the antennas of a theremin but has not been able to do it sufficiently. There still exist several cloudy patches regarding their relations, but some of them have cleared. The proposed linearity between pitch and the antenna-hand distance is describable using Fletcher-Munson curves and related knowledge about human hearing. An approximative relation formula has been found in equation 4.50, which fits the measured data by "dewster" within a deviation of 4.7%. Last but not least, a heap of theories has been introduced, making ground for a thorough analysis in the testing phase. As mentioned at the beginning of this section, it is based upon the following citations: [11–17, 45–77].

4.7 Component Tolerance

Component tolerance can be incredibly important when building a system comprised of purely analog components. Especially if you have a very sensitive system. The easiest way to mitigate it would be to use components with smaller tolerances, but these components are more expensive and harder to come by. In most cases, this would also be unnecessary with such high precision, but it should always be considered.

4.7.1 Errors Effect on Systems

It is no secret that component tolerances can make or break a project if they're not managed correctly. In the case of oscillators, amplifiers, and similar circuits used in this project, the component tolerance effect can be diminished by incorporating variable components. Without variable components, the system specification must either be loose or the component tolerances strict. In the case of an oscillator, just a single capacitor with tolerances of $\pm 10\%$ set to oscillate at 390kHz could result in the oscillator shifting significantly. Using equation 4.51 first introduced as equation 4.2 in section 4.1.2 on page 14 we adjust C_1 & C_2 with a value of 330pF $\pm$ 10%:

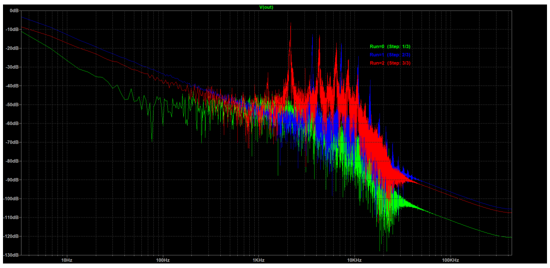
$$\omega_0 = \frac{1}{\sqrt{L_1 \cdot \left(\frac{C_1 C_2}{C_1 + C_2}\right)}} \tag{4.51}$$

This yields a frequency of 385kHz at plus 10% ,363pF, and 404kHz at minus 10%, 297pF. If C_1 is set to minus 10% and C_2 to plus 10% the frequency yielded is 396kHz, while if both capacitors are set at the upper bound the frequency yielded is 375kHz and set at the lower bound the frequency yielded is 415kHz.

4.7.2 Error Accumulation

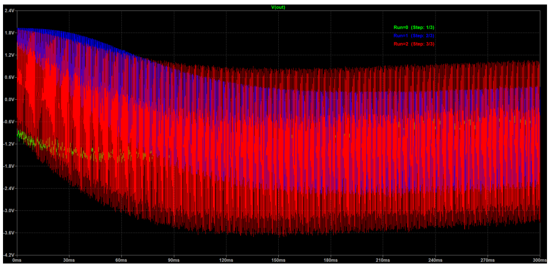
Considering that the above fluctuations are based upon a single component deviating from the specified value, error accumulation throughout the entire system could be disastrous. If the entire system is fixated with no variable components, any system will be prone to irregular behavior, unless component tolerances are strict. Encompassing filters as well as amplifiers to the mixture, specific amplifications and bandpasses will be impossible to reach, as both subsystems are reliant on specific components. Adding a wrong oscillating frequency to an amplifier that does not amplify within specs, before sending the resulting signal through a bandpass that is askew of desired values, could lead to several hours of futile debugging in an effort to get the desired output.

To test error accumulation the entire finished theremin circuit has been simulated. Any circuit could have been used, but the fully designed theremin was used to show error accumulation on theremin. As can be seen in figure 4.39 accumulating errors could lead to disastrous results. A similar simulation has been made with a tolerance of 1% for the resistors, which is the tolerance available at the university. Those simulations are available in appendix A.58 on page 198. The 5% tolerance has been used to emphasize the importance of strict component tolerances or loose specifications.

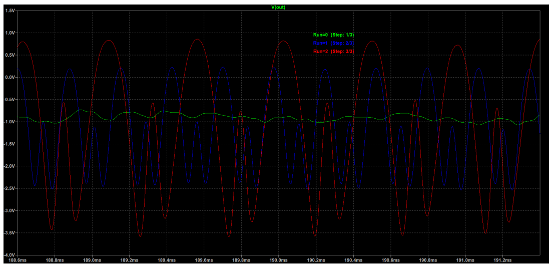


(a) Full FFT showing that either the system does not function at all, or has shifted severely.

(b) Closeup of the same FFT as in figure 4.39a.



(c) Transient analysis of the complete system.



(d) Closeup of the transient analysis of the complete system, showcasing the far from ideal sinus waves.

Figure 4.39: LTspice analysis showing deviances in the final system, with capacitor tolerances of 10%, resistors of 5%, and inductors of 5%. Run 0 (green) is with positive deviance for all components, run 1 (blue) is with negative deviance, and run 2 (red) is with ideal values. These simulations were made at the end of the project, as a complete system was constructed in LTspice at that time.

4.7.3 Relation of Error to a Theremin

When building a theremin, errors, and different components are heavily embedded in every aspect. Especially as the person playing it, is the "component" with the largest error. Simple things such as moving, breathing, and width between one's legs can affect it, but this you cannot tune for, as it varies constantly.

Things such as the weather conditions that day, your clothes, and the playing environment, should therefore be tuneable. Besides, each person has a different capacitance, and if several people would play the theremin properly, it should be tuneable for each person to play it.

5 Specification

This chapter outlines and describes the specifications of the product. Firstly, as high-level specification,HLS, determined from the problem statement. Secondly, as functional specifications and technical specifications, determined by the choice of solution in section 5.4. The functional specifications have the purpose of outlining how each of the HLS's can be answered. Technical specification has the purpose of specifying from a developers view point and setting further internal requirements.

5.1 High Level Specification

This section describes the HLS's overview of the functionality desired from the product. The specifications below are described from a thereminist's perspective. More detailed specifications on how to meet criteria set by these specifications are described in the next section 5.2 on page 53.
As a thereminist I want:

1. *A theremin where I can play a broad range of tunes and adjust the volume of them simultaneously with ease*

2. *A theremin where I can play the entire range without over- or under-exaggerating my movements to change the pitch and volume*

3. *A theremin where I can tune it to allow different players and other conditions to become irrelevant*

4. *A theremin with a simple interface, allowing me to control the tuning, power, ground, and output from the theremin safely*

5. *A theremin where I can replace or change broken parts to increase the life span of my theremin*

5.2 Functional Specification

This section describes the functional criteria of the product. The criteria are seen from an end-user perspective and made as user stories, where all acceptance criteria, AC, must be fulfilled for a story to be considered fulfilled. A test of the functional specification is made in section 8. Each of the functional specifications is linked directly to an HLS, where each of the AC's must be fulfilled for the HLS to be fulfilled.

5.2.1 HLS 1) Pitch and Volume

"As a thereminist I want a theremin where I can play a broad range of tunes and adjust the volume of them simultaneously with ease"
Accept Criteria:

1. I want the opportunity to play from 30Hz to 3kHz as this is the range a piano roughly plays within
2. I want the distance between my hand and the pitch antenna to determine the pitch
3. I want to easily and simultaneously adjust the volume of the pitch while playing
4. The theremin should be playable without any physical contact

5.2.2 HLS 2) Movement to Play the Theremin

"A theremin where I can play the entire range without over- or under-exaggerating my movements to change the pitch and volume"
Accept Criteria:

1. When my hand is $\geq$50cm away from the pitch antenna, there should be a frequency between 0 Hz and 15Hz, zero beat frequency, generated by the theremin
2. When my hand is 5cm $\pm$2.5cm away from the pitch antenna, the highest specified frequency, 3kHz, should be outputted
3. Adjust the entire volume range of the pitch by vertically moving my hand between 2cm and 50cm above the volume antenna
4. When I'm in neutral playing position, the placement of my hands should be slightly wider than my body's width, in line with my elbows and arms down/slightly out the side of my body

5.2.3 HLS 3) Control and Tuning

"A theremin where I can tune it to allow different players and other conditions to become irrelevant"
Accept Criteria:

1. I want a way to tune the theremin pitch circuit so 50cm $\pm$2.5cm is where zero beat frequency is
2. I want a way to tune the theremin volume so that when my hand is 5cm $\pm$2.5cm away from the antenna it will result in no output voltage, and when my hand is $\geq 50cm\pm$2.5cm away from the antenna the output voltage will not increase further.

5.2.4 HLS 4) Interface with the Theremin

"A theremin with a simple interface, allowing me to control the tuning, power, ground, and output from the theremin safely"
Accept Criteria:

1. There should be an interface which allows me to tune the theremin
2. The output should be a single phono connector where I can choose to attach an active loudspeaker or directly digitally record my music
3. A simple yet effective way to ground myself to the theremin

5.2.5 HLS 5) Structure and composition of the theremin

"A theremin where I can replace or change broken parts to increase the lifespan of my theremin"
Accept Criteria:

1. The theremin should be built as subsystems to increase the overview of the theremin and subsystems should be easy to replace. There should therefore be a clear interface between them
2. Each internal component should be leaded to enable replacement with basic soldering skills

5.3 Technical Specification

The technical specification contains the electrical and physical specifications for the product. A test of the technical specification is made in the acceptance test, section 8.

5.3.1 Electrical Specification

1. The theremin should be supplied by a single 12V DC barrel jack adapter
2. The theremin should not contain any pre-brought circuits or IC's
3. The phono connector should output $\geq 900mV_{pp}$

5.3.2 Physical Specification

1. The interface between the modules should be BNC connectors
2. The theremin should be approximately the same size as the Moog Etherwave (450x160x85mm without antennas, [79])

5.3.3 Hardware Specification

1. At steady state, the output should not vary more than ±10Hz
2. At steady state the final peak-to-peak of the signal should not vary more than ±5%

5.4 Chosen Solution

This section outlines the final thoughts and overall concept of the theremins build based upon the specifications set in the previous chapter 5 starting on page 52. Figure 5.1 depicts the final system block diagram, and below is an explanation of the modules.

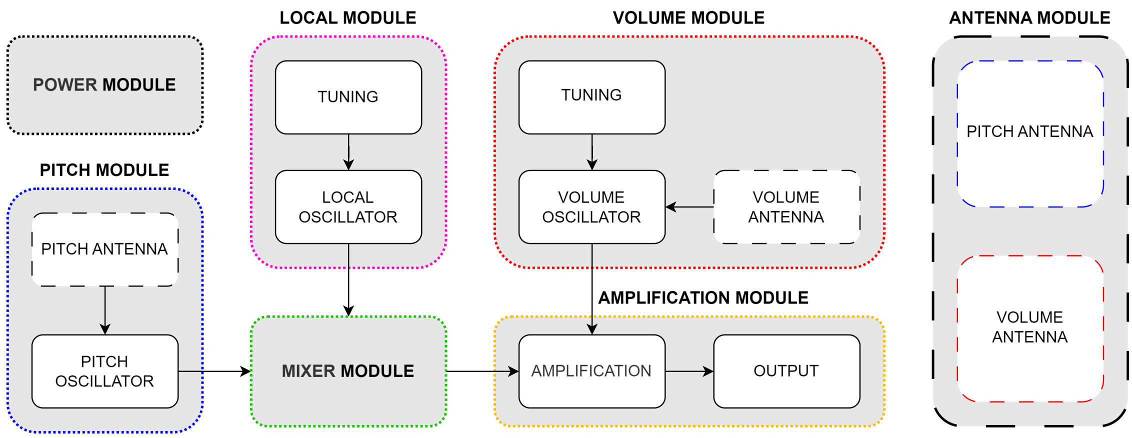


Figure 5.1: Block diagram of the final design of the theremin. The antennas have been given a module section of their own, as design and test of these are individual from the pitch/volume module.

1. **POWER MODULE:** This is the module that will ensure the correct stable power to all the different modules of the system, as the theremin should only be supplied by a 12V DC 500mA, barrel jack. Whilst it is not connected on the block diagram, it will supply every module and has been left out for readability.

2. **ANTENNA MODULE:** The antenna module is not a module per se, but as the antennas would constitute a significant part of both the PITCH and VOLUME module while presenting similar information, they have been joined together in a single module, to present the knowledge once. Furthermore, to modularize even more, the antennas are designed and tested as is, yielding valuable information about how to design adjacent modules.

3. **LOCAL MODULE:** This module is the local oscillator and the tuning circuit the user can adjust to get the exact desired frequency.

4. **PITCH MODULE:** This module contains the variable pitch oscillator and the antenna, used to make it variable in its frequency.

5. **MIXER MODULE:** This is the Superhet and detector, responsible for mixing the signals generated by the local and pitch module into the desired audio signal.

6. **VOLUME MODULE:** This is the volume of the pitch, controlled by the volume antenna. The module contains a tuneable oscillator and the volume antenna, used to determine volume of the theremin.

7. **AMPLIFICATION MODULE:** This module will apply the amplification from the VOLUME module to get the desired final volume generated by the theremin.

Each of the modules contains several submodules and will have its own section with specification, design, test, and conclusion before each part is integrated into the final product, which then will be tested in chapter 8 on page 123.

6 System Design

6.1 Power Module

The power module will largely only be described as a formality, as this project's purpose isn't to create and monitor power distribution.

6.1.1 Specification

As this power module is the general power supply for the whole theremin, it only has to yield to these two demands:

- Be supplied via a 12V DC barrel jack
- Be able to distribute power to all modules at their specified input voltage and current

To meet this demand, the power module will consist of a HAMEG HM7042-2 lab bench power supply (Serial no. 30B0).

6.1.2 Design

To save time at the current stage of development and maintain focus on the actual project, the specification has been modified to enable use of banana plugs. Therefore, design consists of connecting appropriate lengths banana-ended wires to the HAMEG HM7042-2 lab bench power supply.

6.1.3 Implementation

The power supply will simply be connected to the theremin by female banana plugs screwed to all PCB's.

6.1.4 Test

As the HAMEG HM7042-2 lab bench power supply (Serial no. 30B0) is widely used at the university, it has been deemed redundant to test its capabilities. Furthermore, all capabilities can be found in its datasheet, found at [80].

6.1.5 Summary

The specification requiring the use of a barrel jack for power supply has been revoked for the current iteration of the theremin, as decreased development time has been prioritized. Therefore, the theremin will instead be supplied by banana plugs connected straight to a HAMEG HM7042-2 bench power supply.

6.2 Antennas

This section will be strictly about the physical antenna, and will **not** regard how to integrate them into the final system, see chapter 7 section 7.2 on page 120 for the integration. However, the antennas will be tested by themselves and their capabilities will be explored in this section. As there will be two antennas in the final iteration of the system - pitch and volume - this section will be "split" in each subsection to design both antennas. This is done as much theory will be applicable for both antennas, to avoid repeating it unnecessarily. The system design will have its theory in section 4.6 starting page 40.

6.2.1 Specification

Based upon section 4.6 the specifications will be made to enable comparison of data with the data provided by "dewster", see figure 4.6 on page 41, using data from [45]. As shown in section 4.6, the antenna size greatly influences capabilities. Another factor to consider is what is available from the university. Using the knowledge already acquired, the following specifications can be made:

Pitch Antenna

- Must be made of copper tubing (chromed or not is not important)
- Diameter of 10mm
- Length of 450mm (to match "dewster"'s antenna number 3
- Must be straight
- Must be attachable to the rest of the system using a BNC connector or similar

Volume Antenna

- Must be made of copper tubing (chromed or not is not important)
- Diameter of 10mm
- Must resemble a $\mathbb{P}$ in shape
- Must be attachable to the rest of the system using a BNC connector or similar
- Must have a total length of 600mm-900mm before being bent into shape

Apart from these specifications, it should be noted that both antennas should behave as the positive part of a capacitor.

6.2.2 Design

The actual design is rather simple, as it falls back to bending the copper tube into the specified shapes and adding connectors.

Pitch Antenna
As mentioned in the specification, the pitch antenna will simply be a straight pipe with a length of 450mm, with an added connector. See figure 6.1 for the final result.

Volume Antenna
The volume antenna is a little more complicated to design than the pitch antenna. To design it, AutoCAD 2024 has been used, and the functionality to measure the length of

Figure 6.1: The pitch antenna with a BNC-connector added.

each part has been used to ensure the two designs are 600mm and 900mm respectively. Measurements have been added to the drawing for easier manipulation of the actual copper tubing. The design can be seen in figure 6.2 and the actual tubing can be seen in figure 6.3.

Figure 6.2: The design has been made to resemble a $\mathbb{P}$, while also resembling common volume antenna designs. The leftmost version will be constructed in real life, having a total length of 600 mm. All measurements are in mm.

Figure 6.3: The volume antenna with a BNC-connector soldered on.

As both antennas have been bent/straightened into shape, they can be connected to a testbench wherein all antenna tests will be conducted, see section 6.2.4 for further information. Testing will be conducted without the connectors soldered on, to fully isolate the antennas as a single component of the system.

6.2.3 Implementation

As the antennas will act as common capacitors, implementation into the final system will only consist of plugging them into their respective BNC connectors.

6.2.4 Test

Testing the antenna will consist of testing its capacitative capabilities and testing previously stated capabilities mentioned in 4.6, such as pitch drift, linearity, and the like. Testing the antennas will be divided into the following subtests:

A Actual capacitance of the antennas

B Capacitance in a "clean" environment

C Capacitance in a "noisy" environment

D Linearity of capacitance relationship, including size comparisons of 5-45cm lengths of antennas

E Pitch drift - in a clean environment

F Omnidirectionality of the antennas - in a clean environment

By "clean" environment, an environment with little to no capacitative elements present is meant, meaning a bare room with only test equipment present, the testee should also remove jewelry, their phone, and similar that could introduce stray capacitances. A "noisy" environment is an environment with noise present, such as interior, phones, computers, and the like. All tests will be conducted for both types of antenna, as their shape/size is anticipated to have relevance.

Test Setup

The goal of putting the antennas through a set of stand-alone tests it to possibly gain deeper knowledge of how the antennas "perceive" the world. Furthermore, testing the antennas as stand-alone components yields data that could ease development of all affiliated modules, while also enabling testing different theories introduced in 4.6. All tests will utilize a similar setup and have in common that the following materials should be used:

- Antenna - Pitch and volume
- Power source
- Fluke RCL meter PM6306 set at 400 kHz (anticipated stable oscillation from our own designs)
- Ground connection between testee and antenna
- Wooden jig with markings and microphone stands to hold it
- Tape (for marking distances)
- Clamps
- Wiring

In figure 6.5 on page 63 final test-setups can be seen. However, some tests will have minor differences described per test below:

Test A - Intrinsic Capacitance
Test A will consist of attaching a clamp at each end of the antennas, and measuring their intrinsic capacitance with a multimeter. The test should be conducted in a "clean" environment. Apart from testing the full length of each antenna, it could be interesting to see if their capacitative abilities change depending on where the clamps are attached, to see if the theory of different "connection positions" would change the capacitance of the antenna. Data must be logged.

Test B - Measuring C_{Mutual} In a Clean Environment

To test the capacitance, C_{Mutual} in a clean environment, the capacitance should be measured at 1cm intervals from 1cm - 5cm and 2.5cm intervals from 5cm - 50cm. The testee will stand 50cm from the antenna, with the antenna perpendicular to their right shoulder. The right arm must be raised into a semi-straight position until the back of the hand is approximately halfway up the antenna. The hand should be in a loosely closed fist, to mimic the setup used by "dewster". The antenna should be placed 100cm from the floor on a microphone stand. The testee's left hand should be connected to ground. As the environment should be clean, all measurements must be written on a piece of paper. To authenticate the data, all distances should be tested a minimum of 5 times, to calculate an average value. The test must be conducted for both the pitch and volume antenna. Before each test series, the testee should take a step back, then approach the setup again and then conduct a new series. Data must be logged.

Test C - Measuring C_{Mutual} In a Noisy Environment
Test C will be the same as test B, performed in a noisy environment instead of a clean one. Data must be logged.

Test D - Size and Shape Relations
Test D will in broad terms be the same as test B. However, the test must be conducted with different lengths and widths. This test will only be conducted using the pitch antenna. If time allows, testing of using CDs, adjustable coils, and other proclaimed solutions to achieving linearity should be done as well. Data must be logged.

Test E - Pitch Drift
Test E will follow a similar setup as test B, adding voltage to the circuit as well. 12V will be added, and instead of taking one capacitance measurement at a given distance, the difference will be found, if any is present. The purpose is to test whether or not the capacitance changes over time, effectively changing the pitch in a final design. If no change can be found, it could effectively mean that vibrato is unnecessary for playing a theremin. Data must be logged.

Test F - Omnidirectionality
To test the omnidirectionality of the antenna, a setup similar to that of test B will be used. The setup will be replicated in 15° intervals around the antenna and will be done for the volume antenna, as the pitch antenna should be identical all the way around. Data must be logged.

Test Jig
At first glance creating a PCB was thought to constitute the test jig. However, after discussing possible solutions, a wooden jig was chosen instead. The jig can be seen in figure 6.4. The jig consists of two lengths with markings per the description in 6.2.4, where one of the lengths has been placed 5cm below the middle of the antenna. There have been made notches into this length to ease making consistent measurements. The diagonal piece acts as an angle strut to keep the jig perpendicular. As there is no longer a PCB present in the test jig, the antenna will be connected to the positive side of the RCL meter by a cable wound around the base. The testee will be connected to the negative side by a wire wound around the middle finger. This eliminates as much noise as possible, as the only components present are the RCL meter, antenna, testee, and wiring between them.

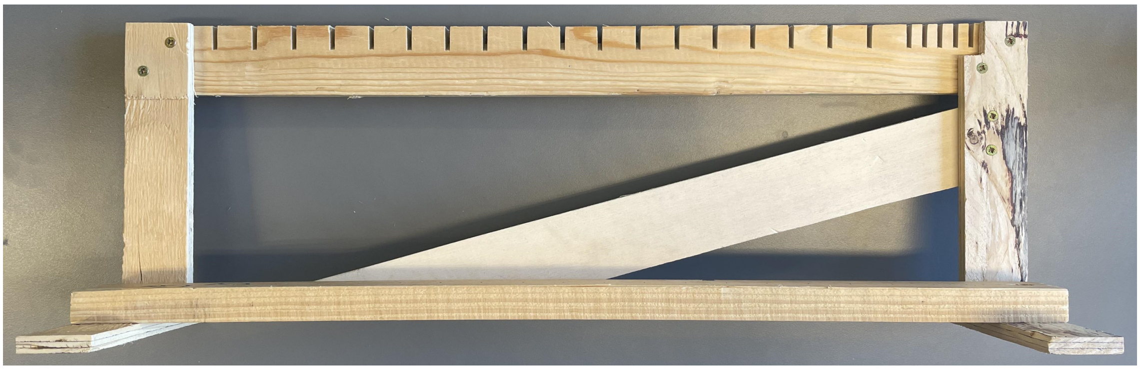


Figure 6.4: The wooden jig with markings every 1cm for the first 5cm and every 2.5cm up till 50cm. The jig is made of scrap wood from MakerSpace and therefore does not have specified dimensions, apart from the markings along the length.

Actual Testing

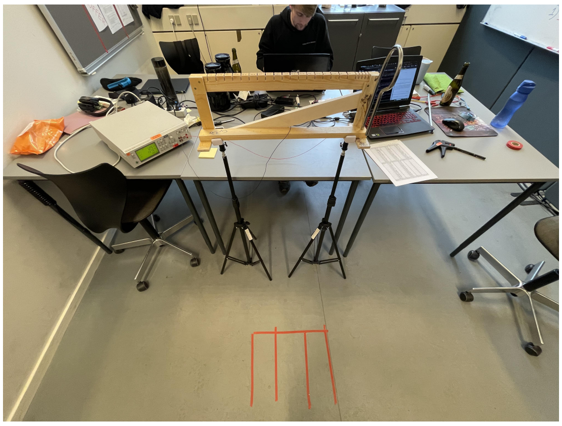
The main testee was Christian, and according to an InBody 270 scan performed during testing, his data is:

- 25 year old Male
- 181cm tall
- 96.5kg
- 28.8% body fat (27.8kg)
- 40.5% musclemass (39.1kg)
- 52.3% water (50.47kg)

During testing in a noisy environment, he was wearing a G-Shock 3420 watch on his left wrist, a silver necklace around the neck, a keyfob for his car, wallet and house keys in the left pocket, and an iPhone 12 Pro in the right. Clothing consisted of shorts and a t-shirt, with ESD-approved safety shoes (Cofra Burst S3). In clean environment, everything other than clothing and shoes was removed. Apart from Christian, Johan (197cm/66kg) and Mikkel (173cm/63kg) also conducted tests for the pitch and volume antenna in a clean environment, to establish the relevance of testee dimensions. There have not been made InBody scans of Johan and Mikkel.

As testing commenced, it became apparent that the posture described by "dewster" was hard to make consistent replications of. Therefore, it was substituted with a flat hand similar to posture 6 shown in figure 4.34 on page 47, as this posture was easily replicated. The pinky finger was placed into the respective notch in the jig, having the knuckles parallel and facing towards the antenna at each measurement.

The chosen noisy environment was the group room, wherein three laptops, three cell phones, a TV, two oscilloscopes, two bench power supplies, and a host of other noisy equipment/interior was present. The cleanest environment available was the reverberation room, consisting purely of concrete walls, lamps high above, and fields of wood and plexiglass that increase reverberation. The noisy testing environment can be seen in figure 6.5a and the clean testing environment in figure 6.5b. More pictures of the setups are available in appendix A.5 on page 159.



(a) Noisy test environment. The RCL meter is at the left of the setup and the red tape markings on the ground are feet placements of the testee, to ensure similar placement.

(b) Clean test environment. The RCL meter is at the left of the setup and the red tape markings on the ground are feet placements of the testee, to ensure similar placement.

Figure 6.5: Test environments/setups.

Observations Made During Testing

Going into testing it was expected that both antennas would be sensitive to even the slightest things, but during testing, especially in the clean environment, it became apparent that the capacitance measured could change upwards of 0.1pF (more than 35cm from the antenna) by a thing as negligent as breathing. Depending on how deep a breath the testee took, it would affect the reading.

When measuring more than 35cm from the antenna, the technique for reaching that far out also influenced the measurements, as almost 0.5pF of change could be measured, depending if the testee twisted the entire torso, just the top of the torso, threw the shoulder forward (without twisting the torso), or straightened the arm more. During testing it therefore became procedure to focus on doing the exact same thing for all measurements.

Furthermore, it was clearly visible that varying finger positions could change the capacitance by over 1pF at the same distance from the antenna. Apart from the "obvious" observations, it became apparent that clenching the left hand (which during testing was down by the side of the testee) could also change the capacitance by approximately 0.5pF. There was even a difference between clenching the fist hard or loose, just as there was also a difference depending on foot placement, how close the left hand was to the body etc. effectively showing that a rod used as one part of a capacitor is far more sensitive to its vicinity, than first foreseen. Moreover, a "weird spot" has been spotted across all testees around the 30cm mark, where the capacitance stagnates or even rises even though the distance is increased. There is no obvious explanation as of now, but the phenomenon is present in about 25% of the tests.

Test Results

To display the results as condensed as possible, the two graphs in figure 6.6 and 6.7 show the average for both environments tested by Christian, and the results from clean environment tests with Johan and Mikkel. The last graph shown in figure 6.8 shows the omnidirectionality of the volume antenna. It should be noted that the clean environment is referred to as CE in the result sheets, and the noisy environment as NE, and that all tests denoted with CE or NE, are with Christian as the testee.

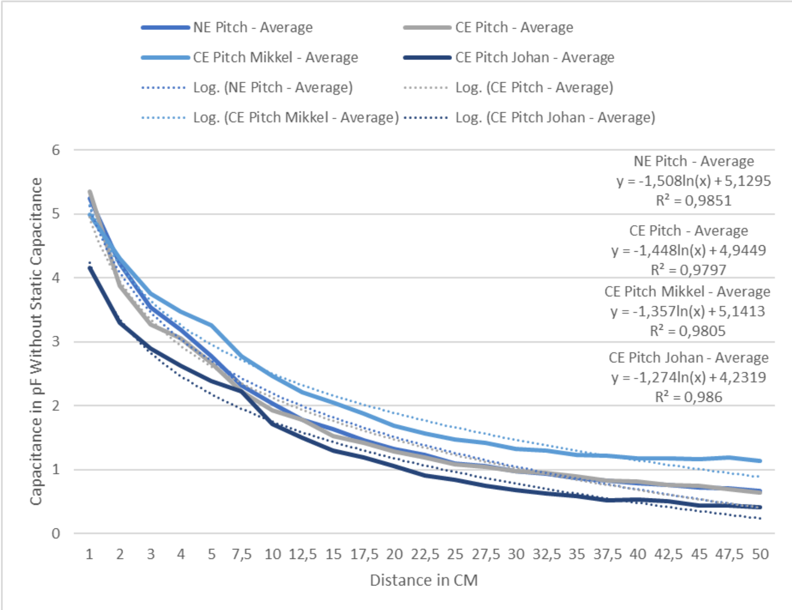


Figure 6.6: General capacitance relation of the pitch antenna. Note that the capacitance range is more than twice that of "dewster". Functions on the right describe logarithmic approximations of each dataset.

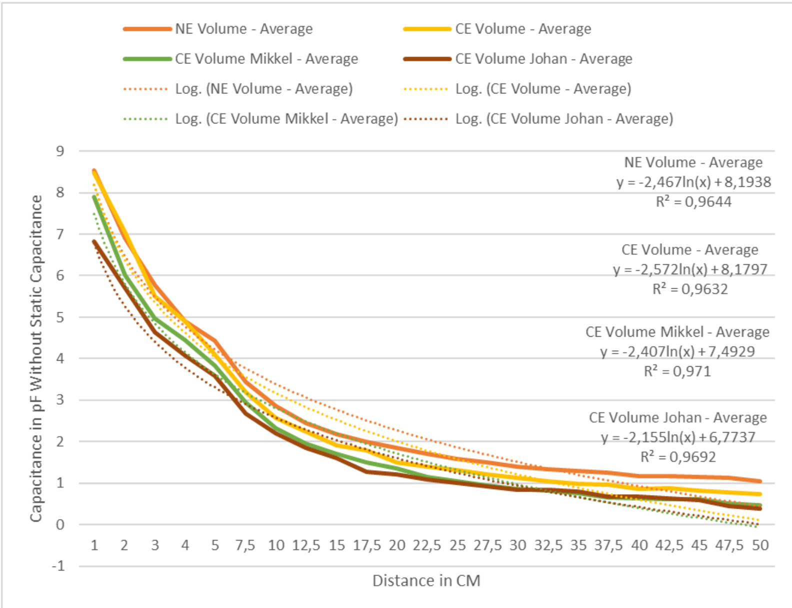


Figure 6.7: General capacitance relation of the volume antenna. Functions on the right describe logarithmic approximations of each dataset.

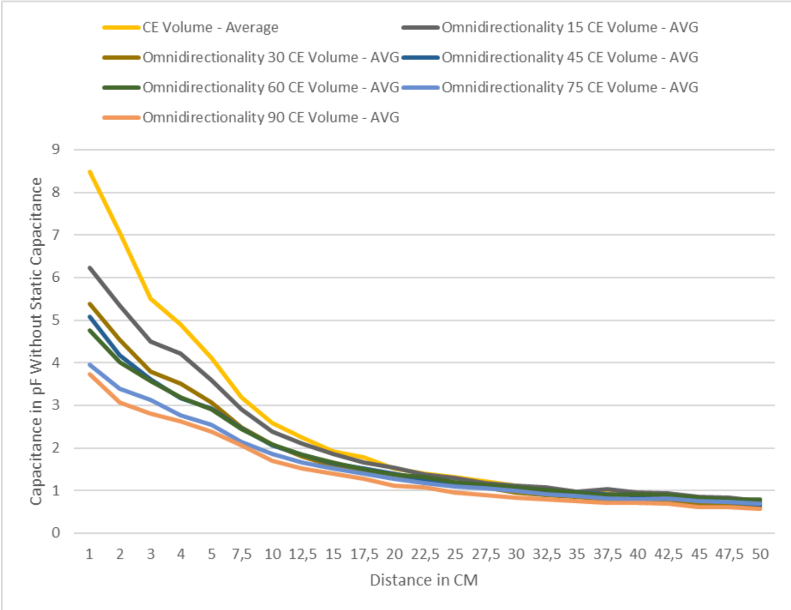


Figure 6.8: Graph showing possible omnidirectionality present in the volume antenna, to support the claim that it is not as sensitive to precise hand positions as the pitch antenna. The claim has not been proven.

From these graphs, the following facts can be stated:

- The intrinsic capacitance could not be tested, as the RCL meter viewed the antennas as resistors rather than capacitors
- All capacitance relations are best approximated by logarithmic functions
- The noisy environment, in general, produced higher capacitances, but not dramatically
- The datasets are almost identical and could be said to be "offset" only by the testee and environment
- In general, Johan showed smaller capacitances, despite his height being incomparable and his weight being somewhat comparable to Mikkels
- Despite a rather large weight difference between Christian and the others, his testing did not show noteworthy increases in capacitance
- The volume antenna is omnidirectional to a degree, as the biggest difference is seen from 0-15° while a similar difference is only seen from 15-90°
- The volume antenna showed significantly higher capacitative capabilities than the pitch antenna, especially within the first 15cm
- Despite the volume antenna being $1\frac{1}{3}$ longer than the pitch antenna, the capacitance is not $1\frac{1}{3}$ times higher
- Approximately 15cm from the antenna, both antennas show similar capacitative capabilities
- Approximately 20cm from the antenna, both antennas' capacitance relations could be approximated best with a linear function

Full test results and corresponding graphs can be seen in appendix A.6 starting on page 162.
On a more test-specific summary the results are:

Test A - Intrinsic Capacitance
The intrinsic capacitance could not be found, as all tested methods have either yielded non-repeating results or viewed the antennas as wires and/or resistors.

Test B - Measuring C_{Mutual} In a Clean Environment
Shows promise of strong logarithmic relations between distance and capacitance. Moreover, testing in a clean environment substantiates that both antennas are sensitive to anything in their vicinity, as small differences in stance or surroundings was visible in measured capacitance.

Test C - Measuring C_{Mutual} In a Noisy Environment
Also shows promise of a strong logarithmic relation between distance and capacitance. However, in a noisy environment, the antennas generally took longer to stabilise at a value, while being less sensitive to the stance of the testee.

Test D - Size and Shape Relations
Has yet to be tested.

Test E - Pitch Drift
Will be tested in pitch module as it requires a voltage, which is not present at current time. Tests will be available in section 6.4.4 on page 77.

Test F - Omnidirectionality
The volume antenna was the main focus of this test, as its shape is not identical all the way round. During the omnidirectional testing, it was visible that in spite of the odd shape, the volume antenna is relatively omnidirectional, but a difference is still present depending on the angle.

6.2.5 Summary

Despite many hours of testing, there still is a lot to test and try with a theremin antenna. Phenomenons such as pitch drift, linearity with different shapes, and other manipulations of the capacitative effects are still yet to be tested. Pitch drift will be tested in section 6.4, as a proper test requires the antenna to be connected to the entire system, not just as a standalone component. However, the tests that have been conducted show strong logarithmic tendencies in the behavior of both antennas' capacitative capabilities. Furthermore, it gives a completely different pF spectrum than that found by "dewster", which could be attributed to differences in testing techniques and equipment. Nevertheless, the new pF range yields changes to the oscillator as well, as the current version is adapted to a range of 0.2pF - 2pF rather than 0.5pF - 5pF. Integration of the antenna into the final system can be found in chapter 7 section 7.2 on page 120.

6.3 Local module

As described in section 4.1 the local module describes the local oscillator needed to mix the signal from the pitch antenna down to the audible range. The local module needs to output a fixed frequency, that can be tuned to match the frequency coming from the pitch module. The chosen oscillator design is the Colpitt's oscillator, as this circuit uses no IC's and is operable in a wide frequency range.

6.3.1 Specification

- The frequency must be between 200kHz - 800kHz
- The local module's frequency needs to be tuneable within a 20kHz band
- When untouched, the frequency of the circuit must vary <10Hz over the course of a minute

6.3.2 Design

The design of the oscillator was described in section 4.1. As mentioned in that section the following diagram is shown in figure 6.9.

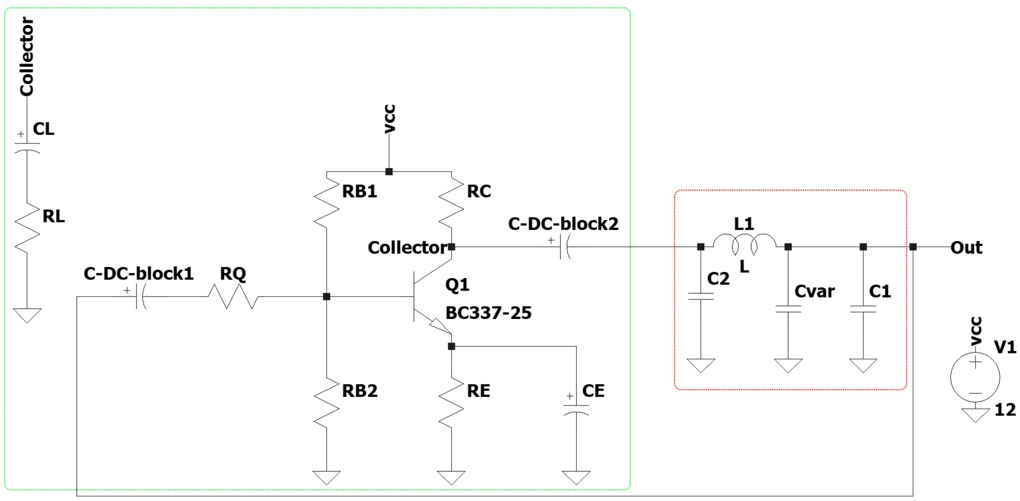


Figure 6.9: The circuit of a Colpitts oscillator. The green area marks the amplifier circuit, and the red area marks the tank circuit.

Actually designing the oscillator requires choosing a lot of component values, as this circuit only has 2 describing equations:

$$f = \frac{1}{2 \cdot \pi \left(\sqrt{L \cdot \left(\frac{C_1 C_2}{C_1 + C_2} \right)} \right)} \tag{6.1}$$

$$|A_v| \approx \frac{RC}{RE} \tag{6.2}$$

When the load resistance is very large, the load of the following circuit is negligible. These 2 equations can only realistically determine 2 of the 12 components, so a lot of the components needs to have a chosen value.

Choice of Frequency

The frequency range that this oscillator can operate in is very large. This is because it does not make much of a difference in what the operating frequency is, the only thing that matters is the difference between the frequency of the local oscillator and the antenna oscillator. This operating frequency normally resonates around 250kHz, see section 2.3.4 on page 8. However, the actual operating frequency can lie between 200kHz - 800kHz. A higher frequency may potentially result in problems with the actual antenna, as this is where the frequency begins to touch radio frequency, and the group has no desire to try and find out what the implications of this may be. A lower frequency makes the actual design of the antenna oscillator difficult, as the capacitance of the antenna is very low, which means that the inductor either needs to be very large, or the difference of capacitance ends up being so large that the amplification of the tank ends up being very large and difficult to work with. The chosen frequency of this project is around 330kHz.

Design of Tank Circuit

The tank circuit is mostly what decides what the actual resonating frequency will be. However, the tank is not the only part of the circuit that has an impact on the final resonance frequency, as the rest of the components also has an impact. Calculating this could be possible but requires a very deep and complicated circuit analysis, so it will not be conducted in this report but will be simulated using LTspice. When designing the wanted frequency, just keep in mind that the calculated frequency will be higher than the simulated frequency by about 60kHz[1]. With this in mind, the resonating frequency of the tank circuit will be designed to resonate around 390kHz. From here a variable capacitor can be set in parallel with the C_1 capacitor to tune the final frequency. This capacitor will also help lower the final frequency down to the desired 330kHz. The tank circuit has been made with the following pre-chosen values:

- $L = 990\mu H$, as this was a value for the inductor that was available in the lab for the group
- $C_1 = C_2$ to ensure that the amplification needed is not too high, and to also reduce the self-amplification of the filter
- $f = 390kHz = 2.47 \cdot 10^6 \frac{rad}{s}$

Solving equation 6.1 with respect to C means that the capacitance will be:

$$C = \frac{2}{L \cdot (2 \cdot \pi \cdot f)^2} = \frac{2}{990\mu[H] \cdot \left(2.47 \cdot 10^6 \left[\frac{rad}{s}\right]\right)^2} = 336pF \tag{6.3}$$

This is a non-standard capacitance, so the chosen capacitance will be: $C = 330pF$. This will result in a slightly higher resonance frequency, but this will be offset with the use of a variable capacitor.

[1]This is what was found with the chosen values for the amplifier-circuit. Results may vary for different chosen components.

Design of amplifier

The design of the amplifier used components with chosen values:

RB1 and RB2: RB1 have been chosen to be $309k\Omega$ and RB2 have been chosen to be $110k\Omega$. With a DC blocking capacitor going in to this voltage divider, this results in the base voltage being: $12V \cdot \frac{110k\Omega}{419K\Omega} = 3.1V$. This will help the transistor always being in the forward bias mode, but the large resistor values means that the current will be low. This is desirable as the current runs from the base node through the RQ resistor. This can negatively impact the output current, so minimizing this is desirable.

RC, RE and CE: RC have been chosen to be $6.98k\Omega$. This value ensures that more current will go into the collector. The emitter resistor has been chosen to be $4.75k\Omega$, as this ensures an amplification slightly larger than 1, which means that the circuit can be started from noise, and the losses in the circuit will be accounted for. CE has been chosen to be $10\mu F$, by recommendation of Aaron Danner, [26].

C-DC-block and RQ: C-DC-block have both been chosen to be $1\mu F$. These values just need to be large enough to not have an impact on the tank. RQ have been found to be $15k\Omega$. This was found through testing the simulation, as without this resistor the signal clips at the bottom. A large resistor value ensures that the signal does not clip at the bottom, but making this too large means that the signal might clip at the top.

Load: CL was chosen to be $1\mu F$ and RL was chosen to be $294k\Omega$. These values need to be so big that the load of the filter and the rest of the circuit does not have a big impact on the amplification.

Final Circuit

The final circuit can be seen in figure 6.10:

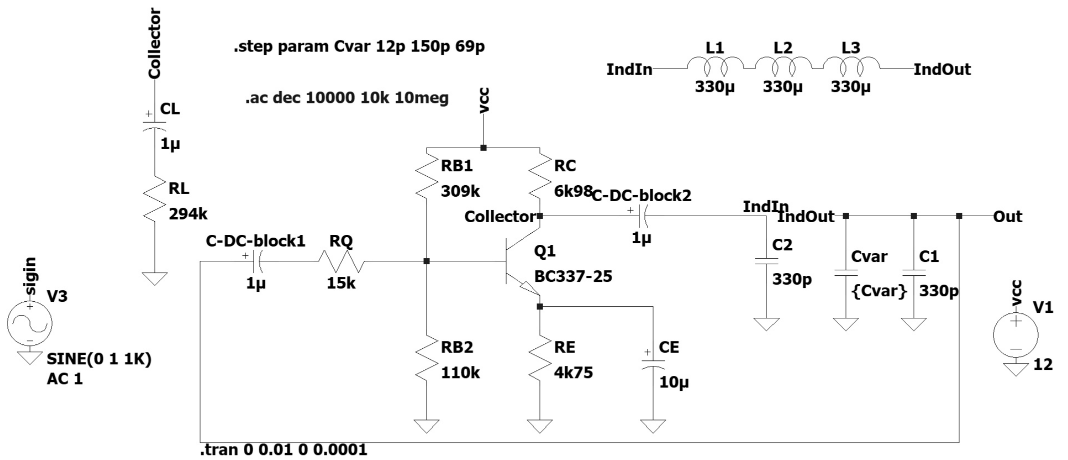


Figure 6.10: The final circuit used as the local oscillator. Notice the Cvar capacitor does not have a set value, as this is the variable capacitor that will be used to tune the signal, and account for component tolerances of the rest of the circuit. The range is from 12pF - 150pF.

Simulations of the Circuit

To encompass all possible relations of the circuit, various simulations will test the expected output frequency. First, a sweep testing of the circuit without the feedback was done, to see the frequency response of the circuit. This can be seen in figure 6.11. Keep in mind that the feedback also influences the final frequency of oscillation, but doing this sweep can give an idea of what the oscillating frequency will be by checking where the phase shift is $= 0°$.

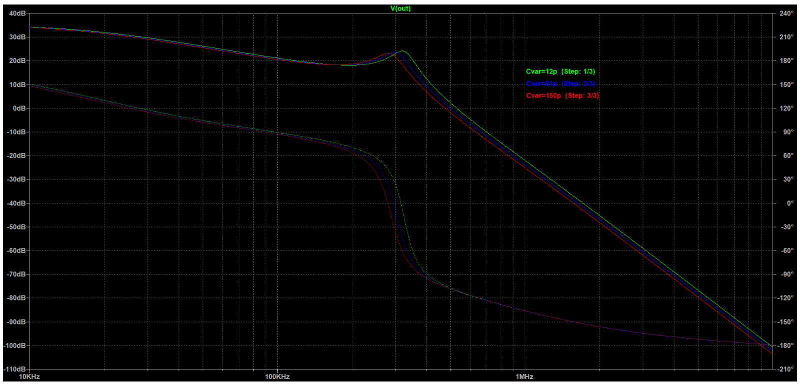


Figure 6.11: The frequency sweep done without the feedback. The frequencies where the phase shift $= 0°$ are between 275kHz-315kHz.

Another simulation is a transient analysis of the circuit, where the FFT of the output is observed. This can be seen in figures 6.12 and 6.13.

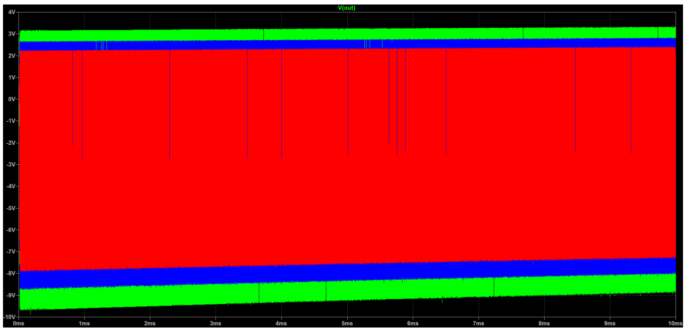


Figure 6.12: The transient analysis showing the peak-to-peak output of the local oscillator. Green is low, blue is middle, and red is high capacitance.

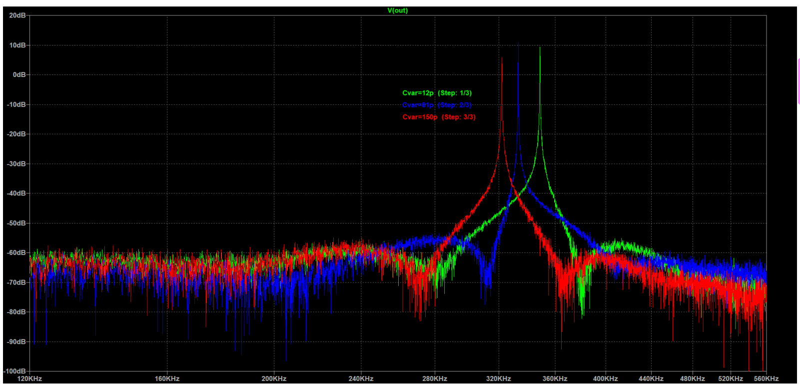
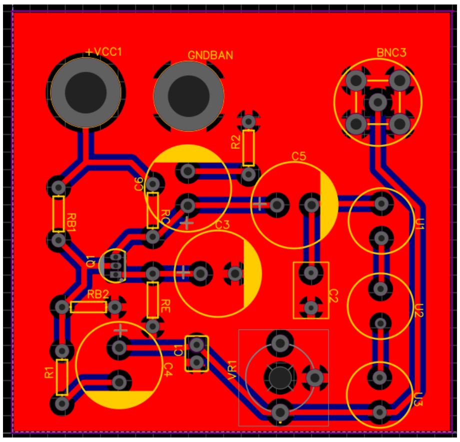


Figure 6.13: The FFT of the local oscillator. This shows that the oscillator is tuneable within the 20kHz range.

6.3.3 Implementation

Implementing this circuit is done on a PCB. The only thing added in the implementation that is not depicted in figure 6.10 is a BNC connector which will be used as the output port of the circuit, and two banana plugs that will be used as V_{CC} and ground. The print layout and printed circuit can be seen in figure 6.14:



(a) The final print layout of the local oscillator.

(b) A picture of the final local oscillator board, after being printed and soldered.

Figure 6.14: The print layout and milled and soldered board for the LOCAL module.

6.3.4 Test

Testing the implementation, is done by testing the requirements setup at the beginning of this section. The requirements that needs to be tested are:

- **Test A:** The frequency must be between 200kHz - 800kHz
- **Test B:** The local module's frequency needs to be tuneable within a 20kHz band
- **Test C:** When untouched, the frequency of the circuit must vary <10Hz within a minute
- **Test D:** Test of the amplitude of the output signal

Test Setup

The test setup for test A, B and C is the same and can be done at the same time. The test setup for frequency analysis can be seen in figures 6.15 and 6.16. The full list of used components are:

- 1x Frequency analyzer (PM6668), serial number: SM 5916
- 2x Test cables with banana plugs
- 1x BNC-Coax cable
- 1x Small screwdriver to adjust the variable capacitor

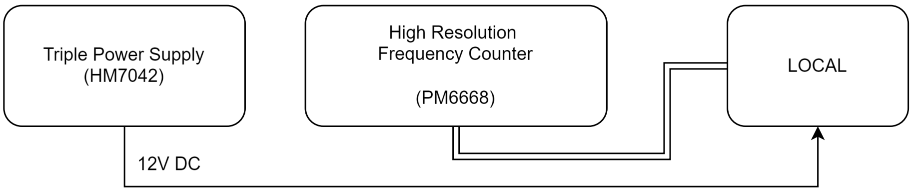


Figure 6.15: The test setup used for frequency analysis of the oscillator.

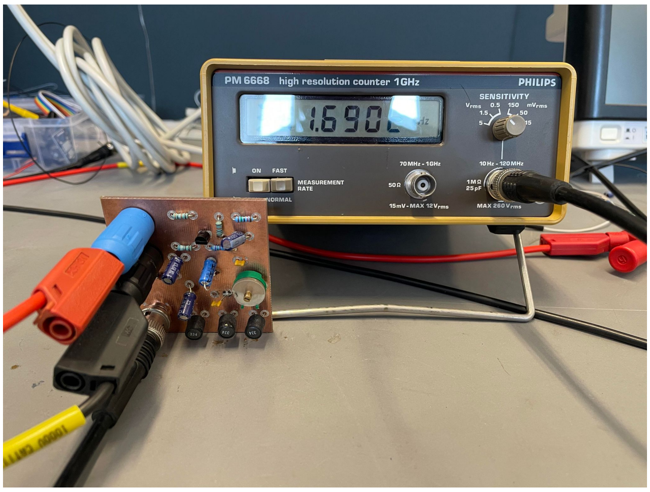


Figure 6.16: A picture showing the test setup in the real world.

The test setup used for test D can be seen in figure 6.17. The full list of components are:

- 1x Oscilloscope (Keysight DSOX1102G), serial number: CN57266298
- 2x Banana cables
- 1x BNC-Coax cable
- 1x Small screwdriver to adjust the variable capacitor

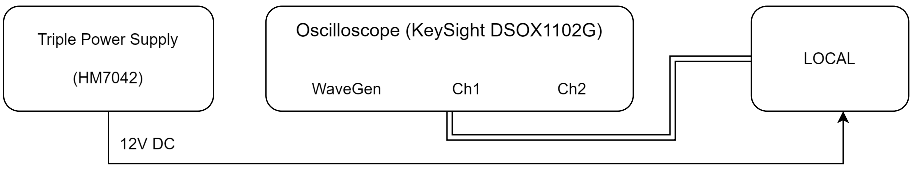


Figure 6.17: The test setup used for amplitude analysis of the oscillator.

Actual Testing

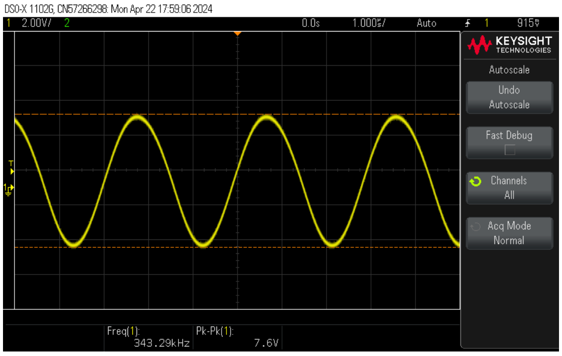
Test A: This test uses the frequency analysis setup. Give the circuit power, and observe the output on the frequency analyzer.
Test B: This test uses the frequency analysis setup. By setting the variable capacitor the lowest, middle, and highest capacitance gives the frequency span that the oscillator can output.
Test C: This test uses the frequency analysis setup. Observing the output frequency over the course of a minute gives the span of output frequencies of the oscillator.
Test D: This test uses the amplitude test setup. Using channel 1 on the oscilloscope, the output peak-to-peak voltage can be observed. This is done at the lowest, middle and highest capacitance.

Test Results

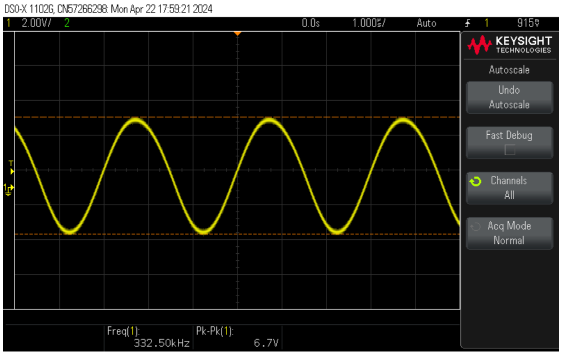
The depicted test results of the amplitude analysis can be seen in figure 6.18 and table 6.1.

Capacitance	Frequency	Amplitude	Frequency Variance
Low	$341.705kHz$	$7.6V_{pp}$	$\pm 1.5Hz$
Middle	$332.318kHz$	$6.7V_{pp}$	$\pm 1.5Hz$
High	$323.321kHz$	$6.0V_{pp}$	$\pm 1.5Hz$

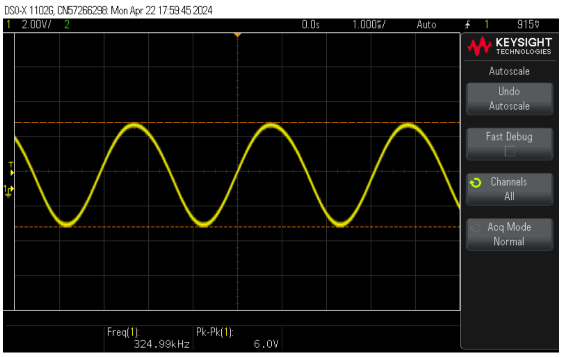
Table 6.1: Test data results of all tests.



(a) Test result for the amplitude test for low capacitance.



(b) Test result for the amplitude test for mid capacitance.



(c) Test result for the amplitude test for high capacitance.

Figure 6.18: Figures showing the test results of the amplitude test.

Note that the final circuit was changed during integration, which also changed the final output amplitude of this circuit. In the final integration the peak-to-peak amplitude is around $13V_{pp}$.

6.3.5 Summary

In summary, all of the requirements have been met. The frequency of the oscillator lies between 323kHz and 341kHz and only varies $\pm 1.5Hz$ or $3Hz$.

6.4 Pitch Module

The purpose of the pitch module is to create an oscillator to be used with the pitch antenna. The pitch module's purpose differs from the local module as the local module is supposed to be a fixed, but tuneable, oscillator, whereas the pitch module is a variable oscillator dependent on antenna capacitance, while still being tuneable. The pitch module will be largely similar to the local module described in section 6.3 starting page 67. The main difference will be an addition of the capacitance posed by the antenna parallel with the C1 capacitor shown in figure 6.9 on page 67.

6.4.1 Specification

The pitch module will yield similar specifications as the local module.

- The frequency must be within 50kHz of the signal produced by the local module
- The pitch module's frequency needs to be tuneable to ±25kHz of the original signal
- The pitch module must be variable by ±1.5kHz using the pitch antenna described in section 6.2.2 on page 58 as a capacitor

6.4.2 Design

As the design of the pitch module is similar to the local module, the exact same amplifier will be used, whereas the LC-tank will be changed to accommodate the antenna.

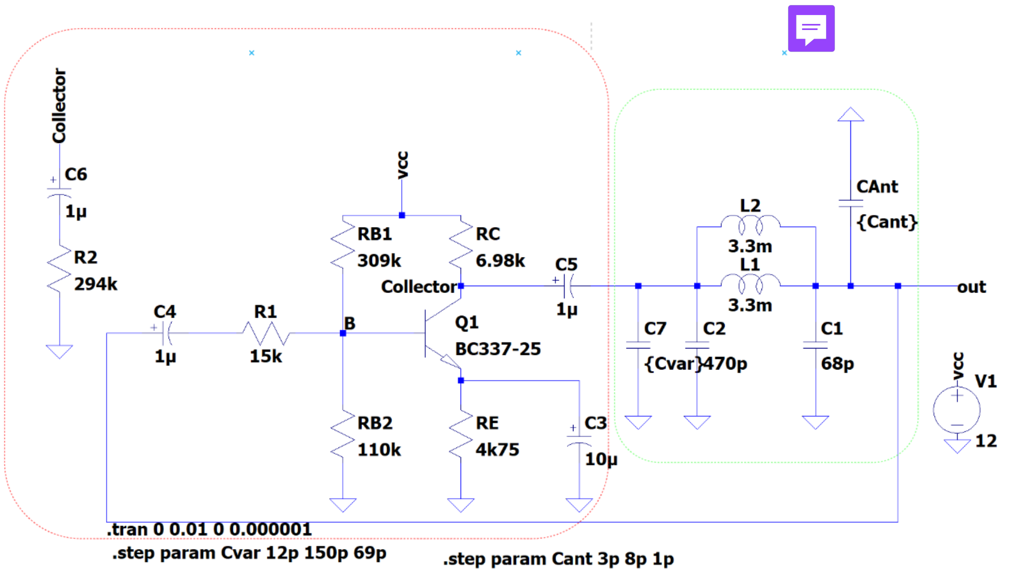


Figure 6.19: The circuit to be used for the pitch module. As mentioned, the amplifier (red) will be identical to the local module. Notice the added "C_{ant}" capacitor and the changed inductor values in the LC-tank (green). These are the only differences from the local module.

Choice of Frequency

As the pitch module has to operate near the local module's frequency, the pitch module will aim for the same range as the local module, as the amplifier part of the circuit is exactly the same. This means that the amplifier part should have the exact same impact on the circuit.

Design of LC-Tank

The LC-tank is largely the same as specified for the local oscillator in section 6.3.2 on page 68. The main difference is the addition of "C_{ant}", being the capacitance introduced by the antenna. The "C_{ant}" is added to the LC-tank, effectively changing the frequency, as it is the variable element in the pitch module, aside from the tuning capacitor. "C_{ant}" has a value of 0.644pF - 5.35pF in a clean environment and 0.666pF - 5.25pF in a noisy environment, apart from the static capacitance of approximately 3pF $\pm$0.5pF depending on actual surroundings. The test and results of capacitance for the pitch antenna can be read in section 6.2.4 page 63, while the raw data is available in appendix A.6 on pages 162, 163, 166, and 167. The varying distance between the antenna and the thereminist's hand causes the varying capacitance, with specific measurements available in appendix A.6 starting page 162. To mimic the frequency set by the local module, the following values and equations are used:

- $L = 1.65mH$, as this was a value for the inductor that was available.
- $C_1 < C_2$ as the same frequency is wanted as for the local oscillator, but C_1 needs to be a smaller value to ensure that the antenna has a higher influence on the output frequency.
- $f = 390kHz = 2.47 \cdot 10^6 \frac{rad}{s}$ when the antenna is not affected by the hand, and $f = 387kHz = 2.43 \cdot 10^6 \frac{rad}{s}$ when the hand is 1cm away from the antenna. This represents a change from 3pF to 8pF from the antenna.
- The equation used to calculate the tank can be seen in equation 6.4.

$$\omega = \frac{1}{\sqrt{L \cdot \left(\frac{(C_1+C_{ant})C_2}{C_1+C_{ant}+C_2}\right)}} \tag{6.4}$$

Solving equation 6.4 with respect to C_1 and C_2 with the 2 different frequencies means that the capacitance will be:

$$2.47 \cdot 10^6 \frac{rad}{s} = \frac{1}{\sqrt{L \cdot \left(\frac{(C_1+3pF)C_2}{C_1+3pF+C_2}\right)}} \tag{6.5}$$

$$2.43 \cdot 10^6 \frac{rad}{s} = \frac{1}{\sqrt{L \cdot \left(\frac{(C_1+8pF)C_2}{C_1+8pF+C_2}\right)}} \tag{6.6}$$

$$C_1 = 176pF \ \ \& \ \ C_2 = 231pF$$

This was calculated using Maple's "solve" function. Through simulation of the circuit, these values were found to not be the needed values. The final used values in the actual circuit were:

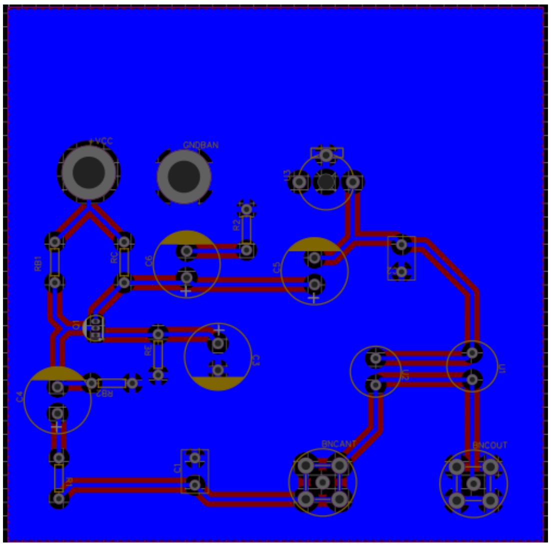
$$C_1 = 68pF \ \ \& \ \ C_2 = 470pF \tag{6.7}$$

Design of Amplifier

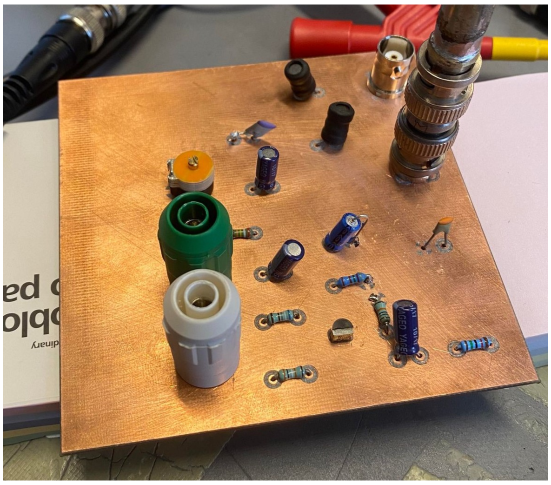
As the amplifier is identical to that of the local oscillator, the corresponding section can be read in section 6.3.2 on page 69.

6.4.3 Implementation

The circuit is implemented on a PCB. In implementation, banana plugs have been added for power, one BNC connector has been added for output, and another is used for connecting the antenna to the board. The additions can be seen in figure 6.20a with the actual PCB being shown in figure 6.20b:



(a) The final PCB layout of the pitch oscillator.



(b) The final PCB of the pitch oscillator in real life.

6.4.4 Test

Test Setup

The setup for testing the pitch module consists of:

- 1x Pitch PCB
- 1x Pitch antenna
- 1x HAMEG HM7042-2 lab bench power supply (Serial no. 30B0)
- 2x Test leads with banana plug
- 1x Test jig from antenna testing
- 1x Philips PM6668 high resolution counter 1GHz (Serial no. 08324) frequency counter
- 1x Ground connection from PCB to testee

Setting up the test should be done following figure 6.21. The pitch PCB should be placed in the test jig, and the test jig should be set up as specified in 6.2.4 page 60.

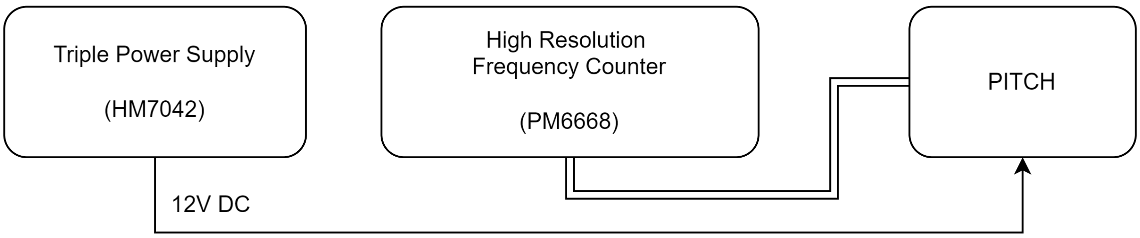


Figure 6.21: Test diagram of the pitch module test.

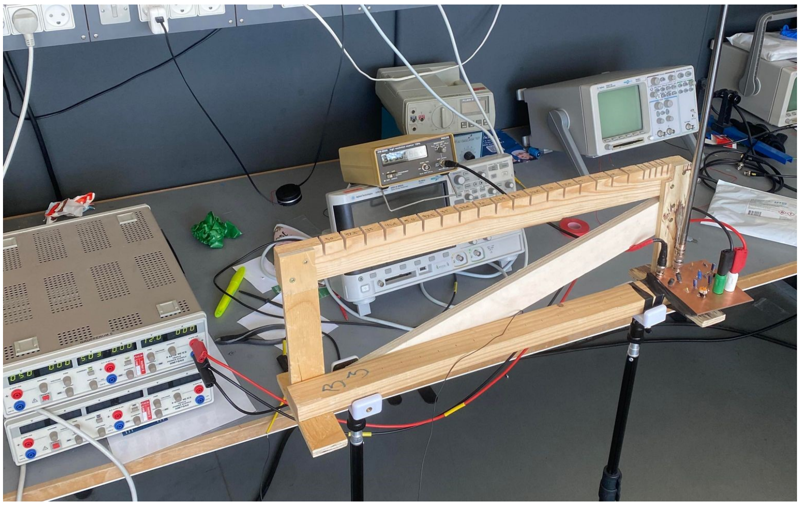


Figure 6.22: Test setup in real life.

Test A - Stability Testing
The pitch module's frequency/static capacitance of the antenna must be tested at both ends of the variable capacitors range as well as the middle. The antenna should have a minimum of 50cm to all auxiliary equipment and be performed in a noisy environment, to simulate future use environments of the theremin the best. The frequency measurements are an average observation over 60 seconds noted in table 6.2 and made with the frequency counter. The test should also be performed without the antenna connected, to establish stability of the oscillator.

Test B - Frequency Range
To meet the criteria set by the functional specification in 5.2.2 on page 53 the full frequency range of 30Hz - 3kHz should be observed by placing the hand of a testee 1cm from the antenna and sweeping to 50cm. The test must be performed 5 times and data logged similar to how C_{Mutual} was found for the antenna. The test should be performed at all 3 intervals of variable capacitance posed by the variable capacitor, to ensure similar frequency ranges available in all configurations. The test should be performed in a noisy environment using the frequency counter.

Test C - Pitch Drift
Testing pitch drift is meant to confirm or disprove the need for vibrato while playing the theremin. The test consists of observing the frequency for a minute at each interval of the test jig, to see if the frequency rises, as proposed by various forums. The resulting frequency must be noted at the beginning of each measurement, time zero, and every 10 seconds thereafter. The resulting frequencies are plotted into a graph and compared along the time axis, while also compared to results posed by test B. The test should be performed in a noisy environment using the frequency counter to find the exact frequency.

Actual Testing

Testing was conducted in the group room adjacent to the regular group room to make a more controlled environment while still being "noisy". During test A, Johan was the only person present in the room, observing the frequency counter. During tests B and

C, Christian acted as the tested, to make C_{Mutual} identical to other antenna tests, while Johan noted frequencies down. Johan was placed approximately 2 meters from the setup, making him irrelevant to the circuit. As with any other antenna tests, the test jig was used and setup according to specifications made in section 6.2.4 on page 60.

Test Results

Test A - Stability Testing

Testing the stability yielded an average deviance within ±1.3Hz of the frequency outputted by the oscillator. The system was left on its own, and observed per the test specification. In table 6.2 results can be seen, with the last three columns denoted with an "A" denoting tests with the antenna connected.

C_{var}	Low	Middle	High	Low A	Middle A	High A
f deviation [Hz]	-0.8	-1.3	0.08	-0.08	-0.98	0.12

Table 6.2: Average deviations in frequency for the pitch module in Hz. The "A" denotes the system with antenna connected. Raw data available in appendix A.49 page 190.

During the stability tests the amplitude of the system with no interference was also tested. This can be seen in table 6.3.

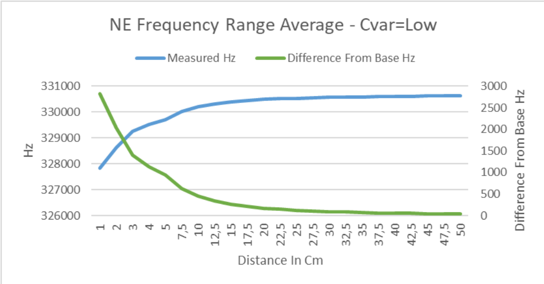
C_{var}	Low	Middle	High	Low A	Middle A	High A
AVG V_{pp}	11.5	11.16	10.6	11.62	11.3	10.86

Table 6.3: Average amplitudes in peak-to-peak voltage for the pitch module. The "A" denotes the system with antenna connected. Raw data available in appendix A.49 page 190.

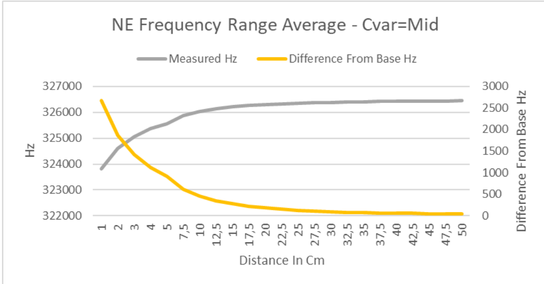
Note that the final circuit used in the integration was altered slightly, which resulted in a higher amplitude at around $12V_{pp}$.

Test B - Frequency Range

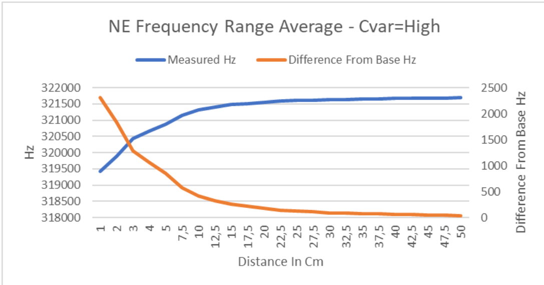
Testing the frequency range yielded a slightly smaller range than anticipated, with the largest average range being from 40.4Hz - 2821.6Hz with C_{var} being at its lowest, 12pF. The average frequency range of C_{var} at its middle was 42.8Hz - 2672Hz and with C_{var} at its highest, 180pF, the average range is 33.6Hz - 2316Hz. Raw data can be found in appendix A.8 starting page 191. While this test was meant to find the range, it also exhibited what frequencies the pitch module would oscillate at. In figure 6.23 the various frequency ranges can be seen, while also viewing the frequency at which the pitch module oscillates. As the module has not yielded a range of 30Hz-3kHz, the module does not fulfill the specification, however, as time is dwindling, no more modifications will be made.



(a) Frequency range with C_{var} set at its lowest.



(b) Frequency range with C_{var} set at its middle.



(c) Frequency range with C_{var} set at its highest.

Figure 6.23: Frequency ranges exhibited by the pitch module at various C_{var} settings.

Test C - Pitch Drift

A popular theory amongst thereminists is the existence of "pitch drift". Therefore the existence has been tested according to the test specification. In figure 6.24 the full range of the theremin can be seen, while a more interesting range can be seen in figure 6.25.

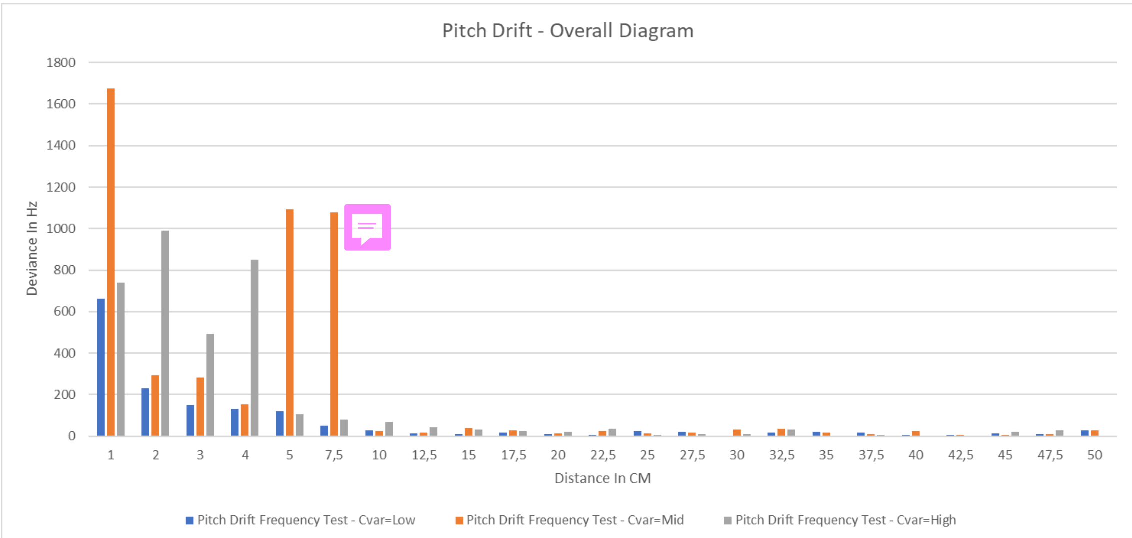


Figure 6.24: Graph of frequencies measured over a 60-second timelapse. In this graph, the full range can be seen, and it is clearly visible that measurement errors make the first 10cm void.

The graph shown in figure 6.25 is more relevant as few thereminists play within the first 10cm. Furthermore, at more than 10cm the largest deviance observed is 67Hz, but most of the deviances lie beneath 30Hz, and can be attributed to measuring errors, rather than actual pitch drift. Moreover, most deviances appeared at irregular rates, and any sign of pitch drift could only be observed within the first 5cm, where deviances in this range of the observed size at observed time intervals, are completely unrealistic to experience while playing the theremin. In short, it can be concluded that pitch drift does not exist at this iteration of the circuit. All the raw data can be accessed in appendix A.9 on page 194. The data must be considered with measurement inaccuracies as it is nearly physically impossible to keep the body completely still for a minute, in a "playing" position, even when using the test jig, especially as it has been noted that small deviations such as breathing could interfere with capacitance levels.

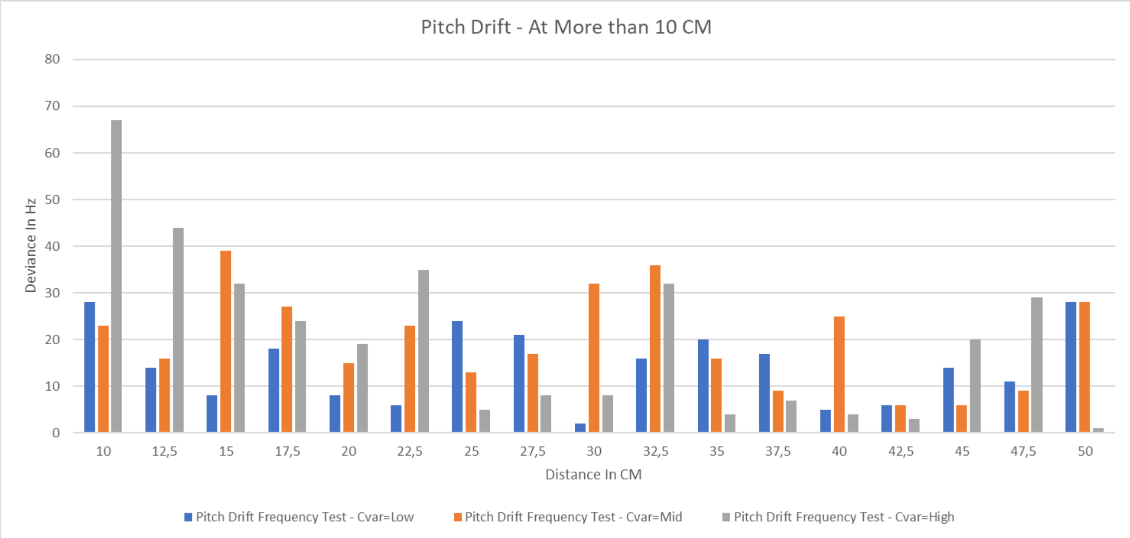


Figure 6.25: At this graph the range above 10cm away from the antenna can be seen. The largest deviation is 67Hz, exhibited with C_{var} at its highest.

6.4.5 Summary

As mentioned several times before, the pitch module is very similar to the local module, with the main difference found in the LC-tank circuit. In the LC-tank circuit, the C1 and C2 capacitors have been changed to accommodate the relatively small capacitance imposed by the antenna, C_{Mutual}, while also implementing a different variable capacitor, to make it match the new LC-tank circuit. Apart from modifying the local modules' LC-tank, the pitch module has proven overwhelmingly stable at all intervals of the variable capacitor. While being stable, the pitch module has also yielded a frequency range of 40Hz - 2.6kHz at all intervals posed by the variable capacitor, therefore not adhering to expectations. Furthermore, the pitch drift theory has been disproven for this exact circuit, as the frequency only varied 67Hz over 60 seconds, proving there is no need for the vibrato hand posture, other than artistic flamboyancy.

6.5 Mixer Module

The MIXER modules' purpose is to derive the frequency difference between the PITCH and LOCAL modules, resulting in the audible frequency, which needs to be amplified in the PRE-AMP module, see section 6.7. The mixer will comprise of 3 submodules each performing a vital task for the combined mixer.

6.5.1 Specification

The requirements for the MIXER module are:

- Have two inputs and one output for signals
- Operate with input frequencies ranging from 200kHz - 800kHz
- Output a sine-wave equal to the frequency difference between two input sine-waves
- The output should vary within ± 1Hz, when the two input frequencies are stable
- The output should have a peak-to-peak voltage of $70mV \pm 5mV$
- Contain no IC's

6.5.2 Design

From the specifications listed above, a design for the MIXER can be created. It can be broken into 4 functions, listed below. Figure 6.26 shows a block diagram of the module.

- **Attenuation:** The two signal amplitudes from LOCAL and PITCH have to be attenuated for optimal mixer performance
- **Mixing:** Two parallel BJTs will be used to mix the signal, to separate LOCAL and PITCH modules from each other and avoid interference
- **Amplification:** The double BJTs will also amplify the signal, sending it to the de-modulation
- **De-modulation:** This will be the diode, and filter, ensuring only the difference of the mixed signals is outputted

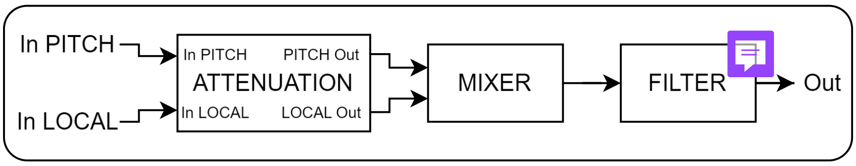


Figure 6.26: Block diagram of the mixer module.

6.5.3 Attenuation

The attenuation module is responsible for reducing the amplitude of the two input signals, to optimize the BJT-mixer. The optimal amplitudes were determined through testing during the development of the mixer sub-module. During the integration, it was discovered a buffer amplifier was also needed between the two oscillators and the mixer.

Specification

The requirements for this sub-module:

- Buffer both inputs
- Attenuate the LOCAL input from ~$13V_{pp}$ - $2.5V_{pp}$ $+0.25V_{pp}$
- Attenuate the PITCH input from ~$12V_{pp}$ - $1V_{pp}$ $+0.25V_{pp}$

Design

The need for this sub-module was discovered late in the process resulting in an implementation using an OPAMP, violating the requirement of not using IC´s in the system. With more time this module could have been designed and implemented with BJT's but this was not available. Figure 6.27 depicts the module schematic for both signals. The first buffer amplifiers are non-inverting to reduce backwards signal feedback from the mixer, and the attenuation is inverting.

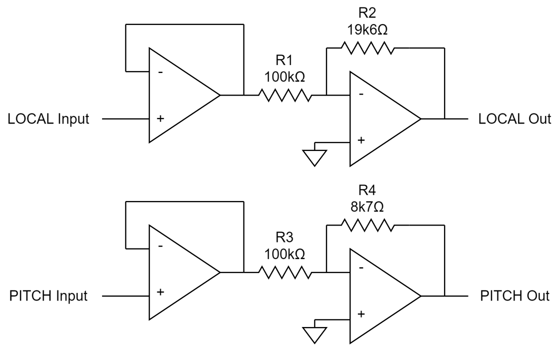


Figure 6.27: Diagram of buffering and descaling of signals.

The equations 6.8 and 6.9 is used to calculate the desired theoretical value of R2, while 6.10 and 6.11 is to calculate the theoretical value for R4. $R1 = R3 = 100k\Omega$ is a chosen value. The closest available values for R2 and R4 was chosen, see figure 6.27 for the specific values.

$$A_{v_{LOCAL}} = \frac{2.5V_{pp}}{13V_{pp}} = 0.192[\cdot] \tag{6.8}$$

$$|A_v| = \frac{R2}{R1} \rightarrow 0.192 = \frac{R2}{100k\Omega} = 19.2k[\Omega] \tag{6.9}$$

$$A_{v_{PITCH}} = \frac{1V_{pp}}{12V_{pp}} = 0.083[\cdot] \tag{6.10}$$

$$|A_v| = \frac{R4}{R3} \rightarrow 0.083 = \frac{R4}{100k\Omega} = 8.3k[\Omega] \tag{6.11}$$

As can be seen in figure 6.27 the values are set to higher values than the calculated ones as the signal is better to have a slightly higher, as opposed to a lower, amplitude than the desired $2.5V_{pp}$ and $1V_{pp}$.

Implementation

The TLE2074 quad OPAMP from Texas Instruments is chosen, [81]. The reason for this choice is mainly it was available and that it can be supplied with up to $\pm 19V$ DC. The OPAMP is supplied with $\pm 15V$ DC. The supply voltage is set to 15V DC as it needs to be supplied with a larger voltage than the input signal.

6.5.4 Mixer

The mixer block should perform one task, which is to mix the two input signals. Any nonlinear device can serve as a mixer as nonlinearity is required. The mixer has been through three iterations, two of which will be described here, and the final one, in its own subsection, see subsection 6.5.6 on page 90. This is done to get a better understanding of the process and time that has been spent getting this module to work.

Simple Collision

The first idea was to adopt and improve upon the method by Robert Moog, [5]. It was a simple collision in a node, and then mixing it over the diode connecting it to ground. It can be seen in figure 6.28:

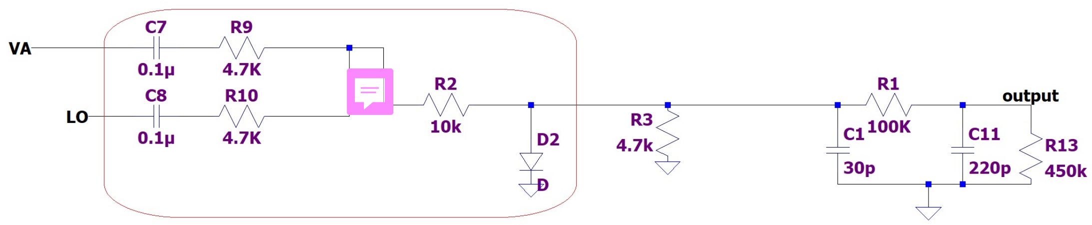


Figure 6.28: First iteration of the mixer module, with the red box showing the mixer.

This worked in every simulation. However, when implementing it on a breadboard it was clear that the two oscillators ended up affecting each other, giving unstable outputs. Therefore this was quickly scratched, for a mixer design that could separate the two input signals.

The Dual-Gate MOSFET

To separate the two signals, a Dual-Gate MOSFET was implemented, as done in "Solid State Radio Engineering", [44]. This is done for the primary reason that it allows the two signals to remain separate and not affect each other. Using the BF981 as the mixer allows for this, and lives up to the specification. The design of the mixer can be seen in figure 6.29.

C_{lo}, C_{va} and C_c are all DC-blockers. To remove potential DC from any of the two inputs and from the final mixed output, they are implemented, with a value of 1μF each. R_{lo} and R_{va} are set to 1kΩ. This is to have an input impedance and could have a wide variety of values, and only affect the current. R_{vcc} and R_e are chosen as these have been the recommended values as done in the book, [44].

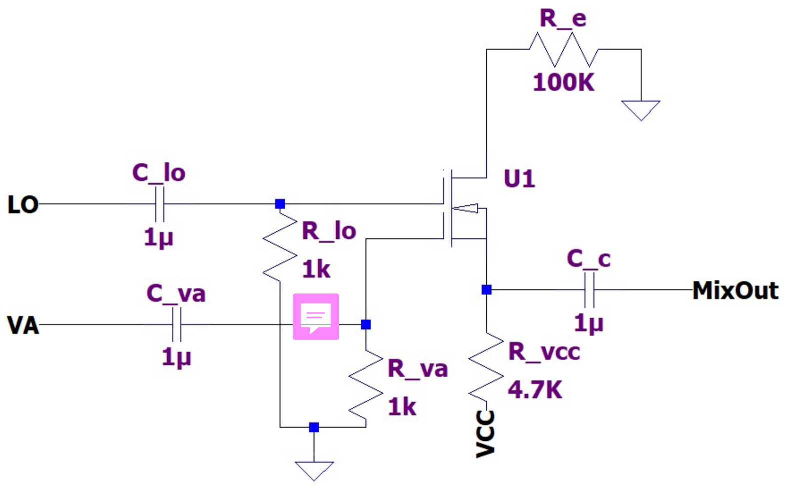


Figure 6.29: Final design of mixer, using the BF981.

A lot of attempts to better understand the Dual-Gate MOSFET have been made, including understanding why there is a large attenuation of the signal. On top of that, the gain is the same if V_{CC} is on or grounded. Attempts to bias both gates have proven to have no effect, along with several attempts in reality.

Simulations of the BF981 are possible in LTspice but do not reflect reality, as there is a positive gain in LTspice. Therefore everything with the Dual-Gate MOSFET has to be tested in reality. While working with high frequencies, the breadboard has proven difficult as well and has been the cause of much hardship and unpleasantries. This is because of the intrinsic capacitance, which has been measured to 22pF from row-to-row and 35pF row-to-rail.

Despite this, the Dual-Gate was accepted as it accomplished its tasks, mixing the two signals. But it could not be explained further and in detail. It was also revealed in integration, that the Dual-Gate MOSFET did not work, as the mixer gave an output of $5mV_{pp}$, compared to the usual $40mV_{pp}$. Therefore, a third mixer using the principles of transistor amplifiers was chosen instead.

Two Parallel BJT's as a Mixer

In effect, this means that two separate modules, MIXER and AMPLIFICATION modules, become redundant. As it is based upon all the knowledge gathered by building the transistor amplifier, in subsection 6.5.5 it will be designed in its own subsection, afterward in subsection 6.5.6. It will become a single module performing both tasks.

6.5.5 Transistor Amplifier

As the signal after the old mixer, the Dual gate MOSFET, had a heavy attenuation, it needed to be amplified, before being sent to the next module. This will be done by a transistor amplifier.

The design used is the one analyzed in section 4.4 starting on page 30.

Requirements for the Module

- Amplify frequencies, between 30Hz and 3kHz
- Have a maximum difference of 1dB, in the bandwidth between 30Hz and 3kHz

The final design can be seen in figure 6.30.

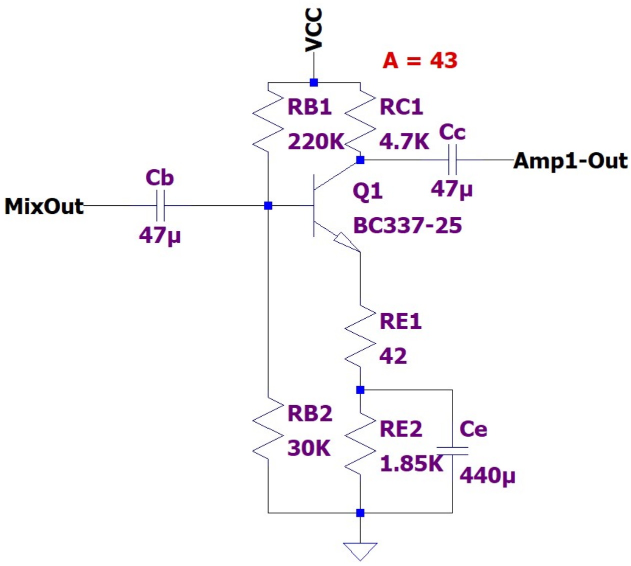


Figure 6.30: Final design of the transistor amplifier.

V_{CC} is set to 12V, and from here the design takes place. Power optimization has not been a focus of this project, and through testing $R_{B2} = 30K$ and $R_{B1} = 220k$ proved to work quite well. R_{B1} and R_{B2} should be rather large, and is therefore in kilo Ω range, as mega Ω proved to be too large. This means a V_b of:

$$V_b = \frac{R_{B2}}{R_{B2} + R_{B1}} \cdot V_{CC} = \frac{30k\Omega}{220k\Omega + 30k\Omega} \cdot 12V = 1.4[V] \quad (6.12)$$

The V_{CE} for the chosen transistor is 0.7V, [82], and an assumed V_t of $25mV - 26mV$, as it is a regular transistor. With this set the next values can be found.

$$I_c = \frac{V_b - V_{CE}}{R_{B1} + R_{B2}} = \frac{1.44V - 0.7V}{220k\Omega + 30k\Omega} = 391.12\mu[A] \quad (6.13)$$

$$re = \frac{V_t}{I_c} = \frac{26mV}{391.12\mu A} = 66.64[\Omega] \quad (6.14)$$

In order to find the amplification, both R_{C1} and R_{E1} have to be decided, along with the desired amplification. When designing the first prototype for the filter, a new one has later been designed, there was an attenuation in it, which meant that an output of 1.7V was desired.

$$40mV \cdot A_v = 1.7V \leftrightarrow= \frac{1.7V}{40mV} = 42.5[\cdot] \quad (6.15)$$

Therefore an amplification of 43 is chosen and R_{C1} is set to 4.7KΩ and from this R_{E1} can be found:

$$A_v = \frac{R_{C1}}{R_{E1} + re} \leftrightarrow 43 = \frac{4.7k\Omega}{R_{E1} + 66.64\Omega} \leftrightarrow R_{E1} = \frac{43 \cdot 66.64\Omega - 4.7k\Omega}{43} = 42.66[\Omega] \quad (6.16)$$

Turning this into dB gives:

$$A_{V_{dB}} = 20log_{10}(A_v) = 20log_{10}(42.66) = 32.73[dB] \tag{6.17}$$

It's important to remember, that despite the formula the amplification is inverted. With the midband section, finding F_L can begin.

F_L for the Amplifier at the Base

When doing the low-frequency response, one needs to find the β value. For the BC337-25, which is used, β is between 160 and 400, [82]. The average β value is taken as it's otherwise impossible to continue further.

$$\beta = \frac{160 + 400}{2} = 280[\cdot] \tag{6.18}$$

Remember from section 4.4 that:

$$R_{base} = \frac{1}{\frac{1}{R_{B1}} + \frac{1}{R_{B2}} + \frac{1}{\beta \cdot re}} = \frac{1}{\frac{1}{220k\Omega} + \frac{1}{30k\Omega} + \frac{1}{280 \cdot 66.64\Omega}} = 10.916k[\Omega] \tag{6.19}$$

R_{sig} is emulating the resistance before the BJT. As $F_{L_{base}}$ should be below 30Hz, making R_{sig} smaller than expected will ensure that $F_{L_{base}}$ is low. Setting R_{sig} to 100Ω and isolating for C_b yields:

$$F_{L_{base}} = \frac{1}{2\pi \cdot (R_{sig} + R_{base}) \cdot C_b} \leftrightarrow$$

$$C_b = \frac{1}{2\pi F_{L_{base}} \cdot (R_{sig} + R_{base})} = \frac{1}{2\pi \cdot 30Hz \cdot (100\Omega + 10.916K\Omega)} = 481.56n[F] \tag{6.20}$$

What this says is, that C_b should be $481.56nF$ or more. It has been set to $47\mu F$ as not to act like a highpass filter, as a lower value would create a highpass filter with the emitter resistors, with a cutoff frequency within the wanted frequency range. It also should not have any effect, as F_L should be as low as possible.

F_L for the Amplifier at the Collector

Following the same principle as above and as described in section 4.4 on page 30. In order to find ro, the early voltage effect has to be found. This can be done by looking in the datasheet, but unfortunately, the BC337-25 does not contain any of the values, nor the graphs to determine this. For similar BJTs, V_A is ~ between 100mV and 200mV. Therefore, to see the difference between 100mV and 200mV and to see if it has a significant effect, two different calculations are made, ro_1 and ro_2:

$$ro_1 = \frac{V_A}{I_c} = \frac{100mV}{391.12\mu A} = 255.68k[\Omega] \tag{6.21}$$

$$ro_2 = \frac{200mV}{391.12\mu A} = 511.35k[\Omega] \tag{6.22}$$

To see how these effects $R_{collector}$, component $R_{collector_1}$ and $R_{collector_2}$ are calculated:

$$R_{collector_1} = R_{C1}||ro = \frac{1}{\frac{1}{R_{C1}} + \frac{1}{ro_1}} = \frac{1}{\frac{1}{4.7K\Omega} + \frac{1}{255.68k\Omega}} = 4,614.91[\Omega] \tag{6.23}$$

$$R_{collector_2} = R_{C1}||ro = \frac{1}{\frac{1}{R_{C1}} + \frac{1}{ro_2}} = \frac{1}{\frac{1}{4.7K\Omega} + \frac{1}{511.35k\Omega}} = 4,660.24[\Omega] \tag{6.24}$$

The difference here is so small, that $R_{collector} \approx R_{collector_1} \approx R_{collector_2} \approx 4.7k\Omega$ for all future calculations, as a 4.7kΩ resistor exists. $ro_1 = ro$ for future calculations as well. The same method is used for setting R_{sig} smaller than expected, ensuring a low F_L, is done for R_{load}. R_{load} is the resistance after the BJT and $R_{load} = 100\Omega$.

$$C_c = \frac{1}{2\pi \cdot F_{L_{collector}} \cdot (R_{collector} + R_{load}}) = \frac{1}{2\pi \cdot 30Hz \cdot (4.7k\Omega + 100\Omega)} = 1.10\mu[F] \tag{6.25}$$

What this means is that the collector capacitor should be 1.10 μF or more. As mentioned for C_b, it has been set to 47μF instead, to place the F_L lower than 30Hz.

F_L for the Amplifier at the Emitter

Following the same method gives:

$$R_{emitter_{final}} = R_{E2}||R_{emitter} = R_{E2}||(R_{C1} + re + \frac{R_{B1}||R_{B2}||R_{sig}}{\beta} = 97.82[\Omega] \tag{6.26}$$

$$C_e = \frac{1}{2\pi R_{emitter_{final}} \cdot F_{L_{emitter}}} = \frac{1}{2\pi \cdot 30Hz \cdot 97.82\Omega} = 54.23\mu[F] \tag{6.27}$$

Therefore C_e should be 54.23μF or more, which is quite a bit larger compared to the other F_L found for C_c and C_b. To ensure that the F_L at C_e is low enough it has been set to 440μF. This seems very high, but through testing, it has proven to be the best value.

Chosen Component Values for the Capacitors

While choosing the different component values for the capacitors, C_b, and C_c were originally set to 1μF, but it was discovered in testing that they made for a highpass filter in the system, blocking a 30Hz signal. They were therefore instead set to 47μF to ensure a very low cutoff frequency, effectively making the highpass filter irrelevant. It was also discovered that C_e worked best at 440μF and that is why that value was chosen.

F_H for the Transistor

When looking at the F_H for the CEA, it's the internal stray capacitance that determines this, as explained in section 4.4 beginning on page 30. As the main focus has been placed on the F_L's due to the low frequencies, the F_H's have been de-prioritized, and will instead be investigated if they are problematic with the chosen existing values. The component values, as they depend on the transistor have not been found. The internal capacitance, C_{bc} and C_{be} is usually quite small, around a few picofarads. The BJT amplifier should have a dominant F_H at a minimum of 750kHz. Therefore to check what eventually could be a problem, the values C_{bc} and C_{be} are investigated. Both $F_{H_{out}}$ and $F_{H_{in}}$ = 750kHz, for the equations 6.31 and 6.35.

Remember from section 4.4 the formula for R_{out}, F_H, and the Miller equivalent.

$$R_{out} = R_{C1}||R_{load}||ro = 3k\Omega||100\Omega||255k\Omega = 96.73[\Omega] \tag{6.28}$$

$$F_H = \frac{1}{2\pi \cdot R \cdot C} \tag{6.29}$$

$$C_{miller_{out}} = C_f \left(1 - \frac{1}{A_v}\right) \tag{6.30}$$

Rewriting the formula to isolate for $C_{out_{miller}}$ gives that:

$$F_{H_{out}} = \frac{1}{2\pi R_{out} \cdot C_{out_{miller}}} \leftrightarrow C_{out_{miller}} = \frac{1}{2\pi R_{out} \cdot F_{H_{out}}} = 2.193n[F] \tag{6.31}$$

And we know from Millers theorem that $C_{out_{miller}}$ is:

$$C_{out_{miller}} = C_{bc}\left(1 - \frac{1}{A_v}\right) \leftrightarrow C_{bc} = -\frac{C_{out_{miller}}}{-1 + \frac{1}{A_v}} = 2.27n[F] \tag{6.32}$$

This means that C_{bc} would have to be 50-100 times larger than usual if it were to affect the desired midband, and this is unrealistic. Similarly as done above, it can be done for the input capacitor. Remember that:

$$R_{in} = R_{sig}||R_{B1}||R_{B2}||\beta(re||R_{E1}) =$$

$$100\Omega||220K\Omega||30K\Omega||(280 \cdot (66.47\Omega||42\Omega)) = 98.26[\Omega] \tag{6.33}$$

$$C_{in_{miller}} = C_f(1 - A_v) + C_{be} \tag{6.34}$$

Which means that $C_{in_{miller}}$ would have to be:

$$F_{H_{in}} = \frac{1}{2\pi \cdot R_{in} \cdot C_{in_{miller}}} \leftrightarrow C_{in_{miller}} = \frac{1}{2\pi R_{in} \cdot F_{H_{in}}} = 2.159n[F] \tag{6.35}$$

Where $C_{in_{miller}}$ can be written as:

$$C_{in_{miller}} = C_{bc}(1 - A_v) + C_{be} = 2.159n[F] \tag{6.36}$$

C_{bc} and C_{be} would have to be well above the normal picofarad range if it should affect the signal at 750kHz. It has therefore been chosen to not go further into the analysis of F_H as it's within the specification and should be tested instead. However, if $C_{bc} = 4pF$ and $C_{be} = 8pF$, which could be typical values, the F_H's would then be:

$$F_{H_{in}} = \frac{1}{2\pi \cdot R_{in} \cdot C_{in_{miller}}} = \frac{1}{2\pi \cdot 98.26\Omega \cdot 12pF} = 134M[Hz] \tag{6.37}$$

$$F_{H_{out}} = \frac{1}{2\pi \cdot R_{out} \cdot C_{out_{miller}}} = \frac{1}{2\pi \cdot 96.73\Omega \cdot 3.85pF} = 426M[Hz] \tag{6.38}$$

Which means a dominant F_H of 134MHz. Increasing the capacitor values will drop the F_H. However, the internal capacitance would have to be significantly larger than realistic and has therefore not been further examined.

Testing of Frequency Response of the Transistor Amplifier

To test this submodule, a frequency response has been made to ensure that the transistor amplifies as desired. The calculated amplification in dB was found to be 32.73dB, in equation 6.17 on page 86.

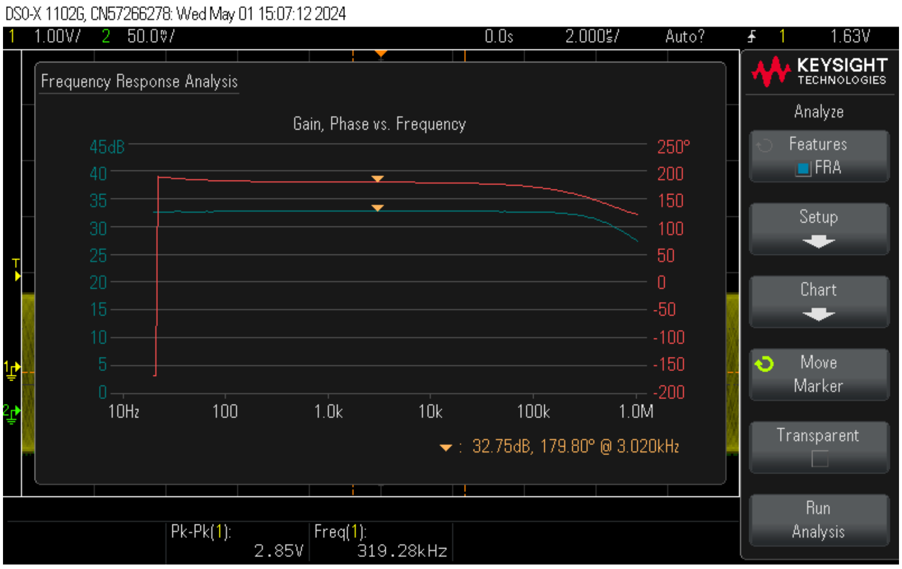


Figure 6.31: Frequency response of the CEA at 3kHz.

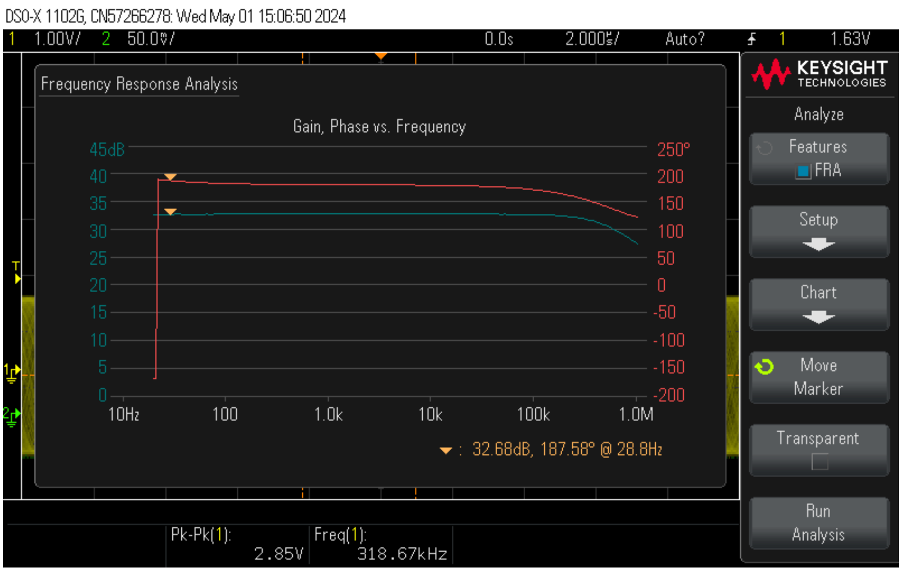


Figure 6.32: Frequency response of the CEA at 30Hz.

As can be seen in figures 6.31 and 6.32 there is only a 0.07dB difference between the amplification at 30Hz and 3kHz. There also looks to be no attenuation which is what is desirable. The amplification is exactly as calculated and is exactly what was desired. It can also be seen that attenuation starts at ~900kHz, but this has been ignored to look further into, as our designed BJT in practice only needs to be flat from 30Hz - 3kHz.

From the test, it can be concluded, that the transistor amplifier stays within the specification for this module, as it amplifies between 30Hz and 3kHz, with a difference of only 0.07dB.

6.5.6 Parallel BJTs As a Mixer

The mixer, using two parallel BJTs as both mixer and amplifier will rely heavily on all the knowledge and information gathered in subsection 6.5.5. Most of the component values are the same. However, it is unknown how well the knowledge and theory translate from a single BJT to two in parallel and there will not be made extensive efforts to figure it out, before testing, due to time constraints.

Expansion and Changes Made to the Transistor Amplifier

- Determine the optimal attenuation for both input signals
- A_v, needs to be adjusted, to change the amplification
- V_{BE}, needs to be changed, to move the bias

Furthermore, through simulations and experimenting, it has been discovered that:

- Having the collectors separated gave a more stable, higher, and better output when looking into the FFT
- Having the two emitters connected reduced unwanted harmonic frequencies

Chosen Setup

The final schematic of the BJT-mixer that has been designed can be seen in figure 6.33:

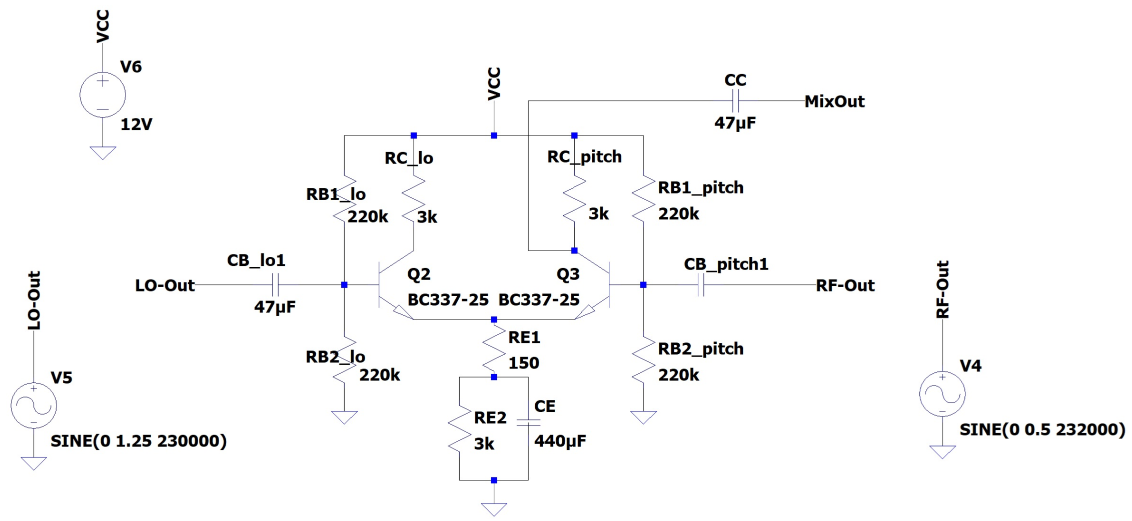


Figure 6.33: Schematic of BJT mixer, RF is simulating the pitch module.

Attenuation of Input Signals

As the input strength of the signals from PITCH and LOCAL modules is ~$12V_{pp}$ and $12V_{pp}$ respectively. It has been discovered that the best FFT, for the BJT-mixer, occurs when the inputs have a strength of $1V_{pp}$ on PITCH and $2.5V_{pp}$ on LOCAL. The design and implementation of this attenuation are described in the previous subsection 6.5.3 on page 81.

V_{BE} for the Input

A new V_{BE} is needed. For simplicity and to ensure there is no clipping, V_{BE} will be placed in the middle. Having them as equally large values will ensure this. $R_{B1_{LO}} = R_{B1_{pitch}} = 220k\Omega$ and with a $R_{B2_{LO}} = R_{B2_{pitch}} = 220k\Omega$.

$$\frac{220k\Omega}{220k\Omega + 220k\Omega} \cdot 12V = 6[V] \tag{6.39}$$

Calculating a New A_v

As the signal is no longer mixed when entering the amplifier as before, designed in subsection 6.5.5, mixing and amplification will happen simultaneously. The input strength of the difference, which we will call V_{f_Δ}, is unknown and hard to calculate as it is a mixed signal. So whilst the fully mixed signal has an amplitude of e.g. $300mV_{pp}$, the mixed signal, which is what will pass through the filter may only be e.g. $50mV_{pp}$. Therefore, calculating the exact amplification desired is problematic. Given a rough estimate looking at the scope, V_{f_Δ} is however a sixth of the mixed signal peak-to-peak. However finding the mixed signal, WITHOUT the amplification has not been possible.

Setting $R_{E1} = 500\Omega$ would give a theoretical amplification of:

$$A_v = \frac{R_{B1_{pitch}}}{R_{E1} + re} = \frac{3k\Omega}{500\Omega + 15.42\Omega} = 5.8[\cdot] \tag{6.40}$$

Testing showed that the output coming out of the mixer and filter was 17mV_{pp}. This would also mean that the signal before amplification is theorized to be:

$$V_{f_\Delta} = \frac{17mV_{pp}}{5.8} = 2.9m[V_{pp}] \tag{6.41}$$

Which is quite small, and probably not the reality. As $\frac{70}{17} = 4.1$, the amplification configuration should be times 4.1 larger to get an output of 70mV_{pp}. Making R_{E1} a fourth of the size, it would give an amplification of:

$$A_v = \frac{3k\Omega}{125\Omega + 15.42\Omega} = 21.10[\cdot] \tag{6.42}$$

From the components available $R_{E1} = 150\Omega$ was chosen, giving an amplification of:

$$A_v = \frac{R_{B1_{pitch}}}{R_{E1} + re} = \frac{3k\Omega}{150\Omega + 15.42\Omega} = 18.13[\cdot] \tag{6.43}$$

Which is found acceptable, and is what will be used for the testing of the module. However, when the module was tested, only an output of $24mV_{pp}$ was measured, which is an increase of $\frac{24}{17} = 1.41$, which is quite different compared to the expected 4.1 increase. Further testing and diving deeper into the theory could be done, but due to time constraints, it has been chosen not to. But it is obvious there is something that happens, affecting the amplification that cannot be understood from the current foundation of knowledge.

The circuit was simulated in LTspice, see figure 6.33, and an FFT of the output can be seen in figure 6.34. The FFT shows the desired signal V_{f_Δ}, the base signals, and the summed signal, $f_{PITCH+LOCAL}$. The FFT reveals a great number of harmonics which is not desirable. Due to time constraints minimizing these was not possible.

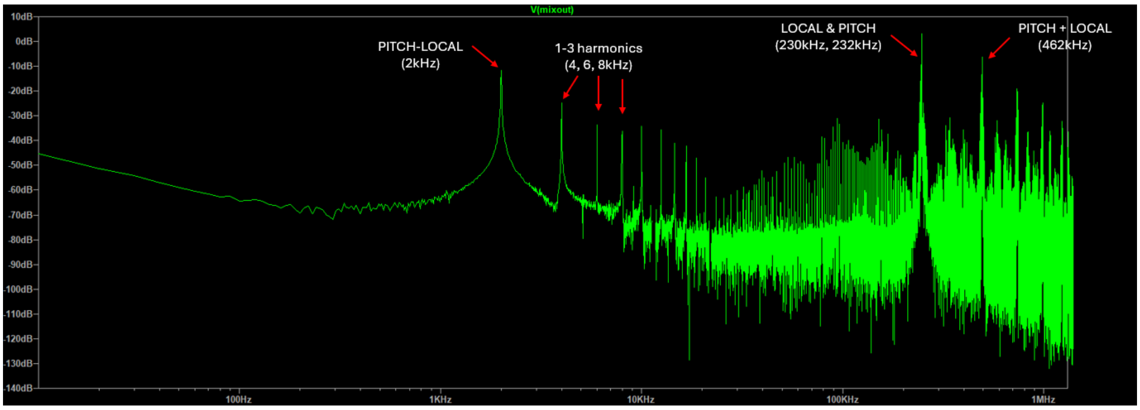


Figure 6.34: FFT of simulated mixer output.

A THD analysis could be possible, but it was not done due to time constraints. In conclusion, it can be seen that the BJT-mixer performs the essential task of mixing the two input signals, which is essentially what is desired. Unfortunately, there are a lot of harmonic frequencies, which will affect the theremin, especially at the low frequencies.

6.5.7 De-modulation

The de-modulation module should obtain the desired difference, f_Δ, from the mixer. The demodulator is comprised by a single diode and a 5th-order filter. The final design of the de-modulation can be seen in figure 6.35.

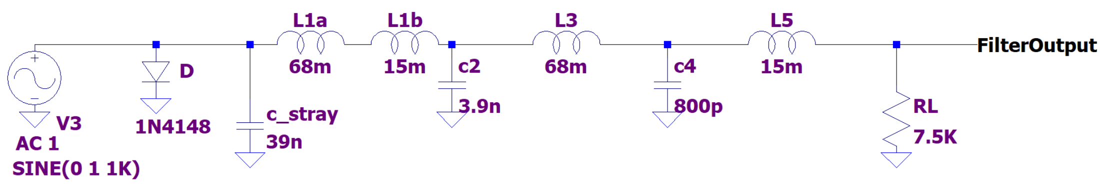


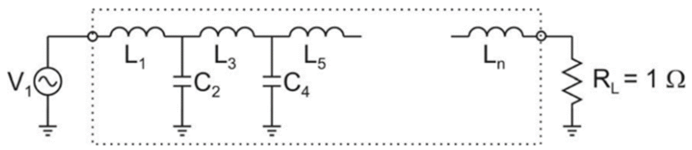
Figure 6.35: Final design of de-modulator.

Diode

As the diode takes ~$0.7V$ on its own, instead of passing it through the diode, connecting the diode directly to ground will instead ensure ~$0.7V$ is not lost in the diode. Therefore it's the negative half that will be used to de-modulate the signal when passing it through the 5th-order filter.

5th Order Filter

To get a clean and crisp signal between the desired 30Hz to 3kHz, a 5th-order filter has been designed. A 5th-order filter has been chosen to get a very steep roll-off and ensure the other products are filtered out. The filter has been designed as a 5th-order Butterworth filter, in a ladder circuit. To save time building the filter, the filter will be dimensioned after a normalized filter, and then scaled as described in "Analog Filters" by Kendall Su, [83]. A picture of the filter components and their placement can be seen in figure 6.36.



Order	L1	C2	L3	C4	L5	C6	L7
2	1.4142	0.7071					
3	1.5000	1.3333	0.5000				
4	1.5307	1.5772	1.0824	0.3827			
5	1.5451	1.6944	1.3820	0.8944	0.3090		
6	1.5529	1.7593	1.5529	1.2016	0.7579	0.2588	
7	1.5576	1.7988	1.6588	1.3972	1.0550	0.6560	0.2225

Figure 6.36: Dimension values for scaling filter, depending on the order of the filter, [83].

In order to scale each component to its proper value the formulas below can be used to find the components of the desired filter. Cutoff frequency has been set to 25kHz, as the most relevant frequencies to filter out are from 200kHz and above, and to have them attenuated as much as possible.

$$K_f = \frac{\omega_{cutoff}}{\omega_{norm}} \rightarrow K_f = \frac{2\pi \cdot 25kHz}{1\frac{rad}{s}} = 157.08 \cdot 10^3[\cdot] \tag{6.44}$$

Where $\omega_{cutoff} = 2\pi \cdot desiredCutoffFrequency$.

$$K_z = \frac{R_{load}}{R_{norm}}; K_z = \frac{7500\Omega}{1\Omega} = 7500[\cdot] \tag{6.45}$$

Where R_{load} is a value to freely choose. From this, the different component values for the filter can be found. The scaled values to dimension once filter can be found in figure 6.36 and are:

$$\begin{aligned} l1 &= 1.5451[H] \\ c2 &= 1.6944[F] \\ l3 &= 1.3820[H] \\ c4 &= 0.8944[F] \\ l5 &= 0.3090[H] \end{aligned}$$

This means the component values will be:

$$L_1 = \frac{K_z}{K_f} \cdot l_1 = 68.85m[H] \tag{6.46}$$

$$C_2 = \frac{1}{K_f \cdot K_z} \cdot C_c = 1.54n[F] \tag{6.47}$$

$$L_3 = \frac{K_z}{K_f} \cdot l_3 = 61.59m[H] \tag{6.48}$$

$$C_4 = \frac{1}{K_f \cdot K_z} \cdot c_4 = 813.42p[F] \tag{6.49}$$

$$L_5 = \frac{K_z}{K_f} \cdot l_5 = 13.77m[H] \tag{6.50}$$

From these component values, a filter can be realized and built. Due to the components available at, the values are instead as can be seen in figure 6.37. Different values were wanted, but as they were not available it was built with what was available and possible. Furthermore, during testing of the filter, stray capacitance could be observed and another capacitor was added to the filter. A filter build with the available components can be seen in figure 6.37, and has been simulated in LTspice. The filter topology can be seen in figure 6.37 and the bodeplot from the filter in figure 6.38.

L_{1a} and L_{1b} are two inductors, to ensure that $L_1 > L_3$. It has been comprised of these components, as it was available.

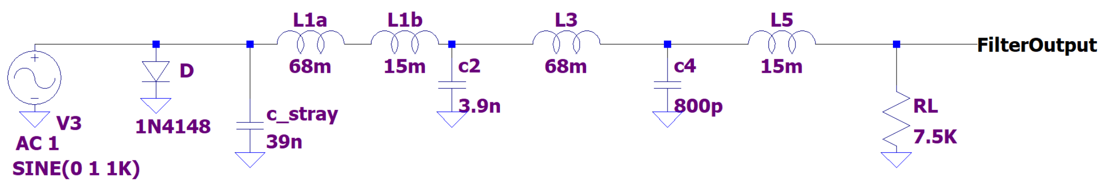


Figure 6.37: The 5th order filter build in LTspice.

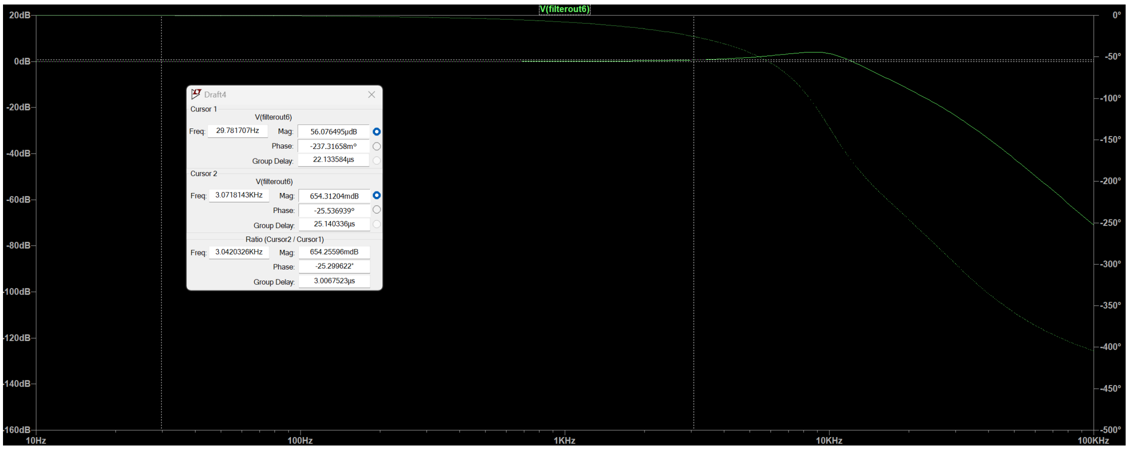


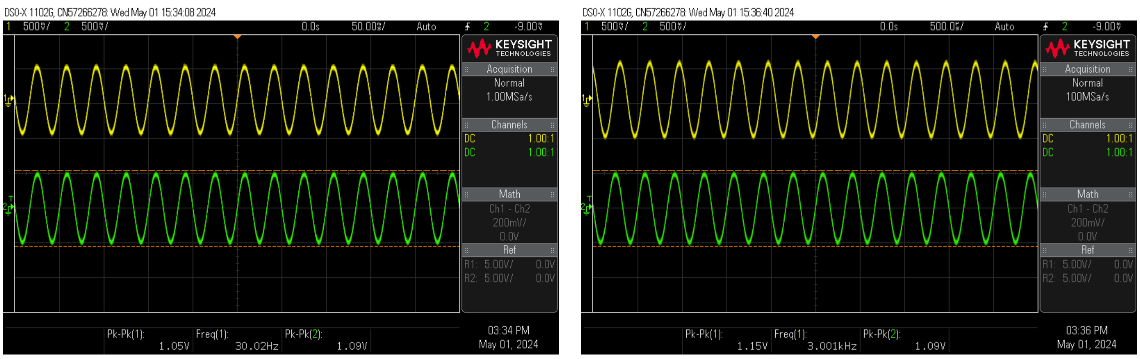
Figure 6.38: AC-sweep for the filter, from 10Hz - 500kHz, zoomed in.

Testing the Filter on a PCB

To test the filter in real life a real frequency response on a KeySight oscilloscope is made. The frequency response can be seen in figure 6.39.

Figure 6.39: Frequency response of the filter, on an oscilloscope.

Here there is a 0.7dB difference, which is not entirely optimal for the filter, but has been accepted. This is probably due to the inductor values, being different from those that were wanted. The scope also says there is a -10dB attenuation which is curious, however, as can be seen in figure 6.40, there is no attenuation when testing it at $1V_{pp}$, at the different frequencies. The filter at 30Hz and 3kHz, can also be seen in figure 6.40:



(a) The filter with a 30Hz input.

(b) The filter with a 3kHz input.

Figure 6.40: The filter being tested on an oscilloscope, with $1V_{pp}$.

Where the difference between the two signals' peak-to-peak is:

$$\frac{1.15V_{pp} - 1.05V_{pp}}{1.05V_{pp}} = 0.095 = 9.5\% \tag{6.51}$$

While it is not as accurate as desired, it has been chosen as acceptable, as better components have not been available. This problem could probably be fixed if the right components were available.

6.5.8 Implementation

As mentioned earlier there have been a lot of difficulties in implementing all the different MIXER sub-modules. The final design that has been implemented can be seen in figure 6.41. This has then been implemented on a PCB, figure 6.42a and 6.42b show the PCB layout. In implementation, banana plugs have been added for power, with BNC connectors for both input and output. Between each sub-module a BNC connector has been added for easier testing, and jumpers have been added before and after each test port. The jumpers allow for easy isolation between each sub-module and allow for individual module tests. Figure 6.43 shows the PCB and the jumpers.

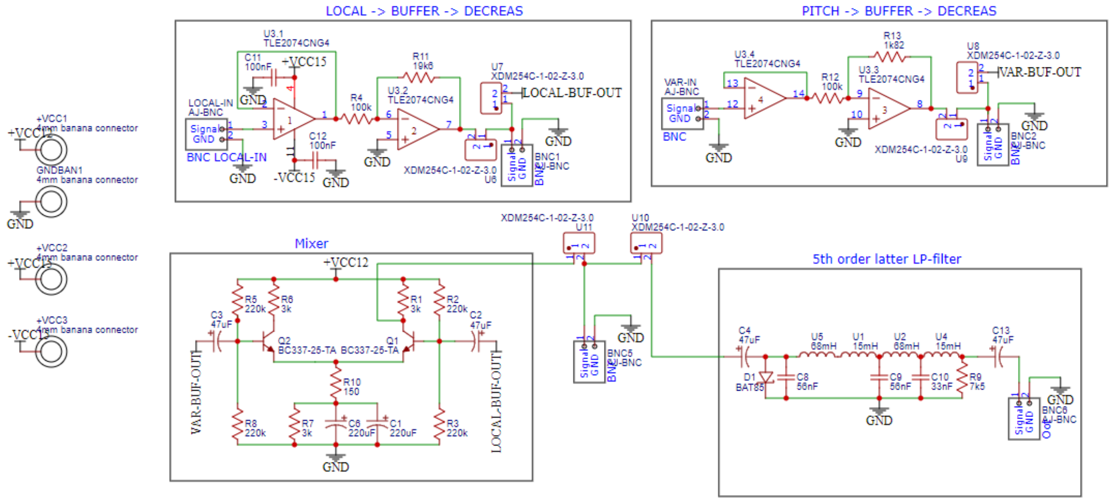
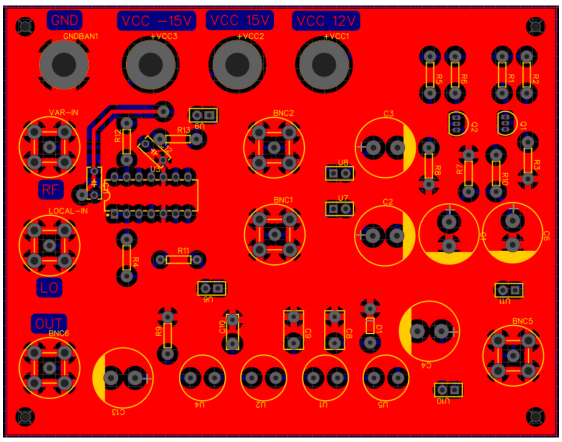
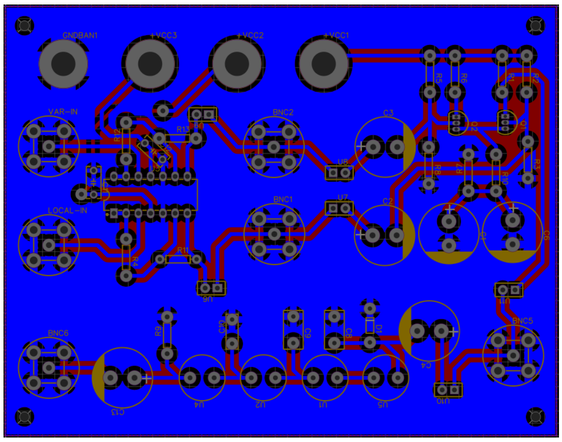


Figure 6.41: Schematic of final mixer module.



(a) Top layer of PCB layout.



(b) Bottom layer of PCB layout.

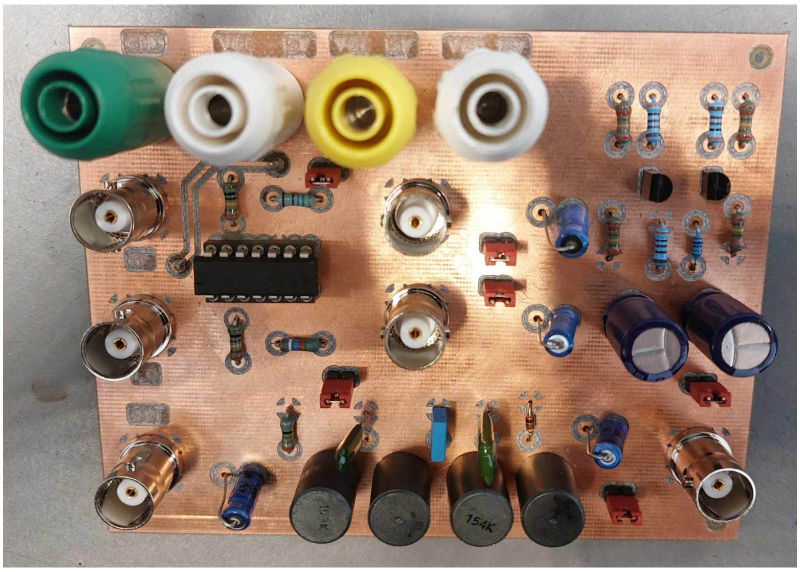


Figure 6.43: Final PCB with components mounted. Note the labels cut into the PCB and the red jumper connectors. The jumpers can be removed to isolate each sub-module.

6.5.9 Test

This section describes the testing of the mixer module. 4 test will be conducted; **A: Attenuation Module**, **B: Filter Module**, **C: Stability Test**, and **C: End-to-end Test**.

Test A: Attenuation Module

The tests' purpose is to verify the attenuation module is operating as desired.

Test Materials

- 1x Mixer module PCB
- 1x Oscilloscope, KeySight DSOX1102G (Serial no: CN5726678)
- 1x Arbitrary Waveform Generator, Aligent 33120A (Serial no: MY 46012392)
- 1x Triple Power Supply, HAMEG HM7042 (Serial no: 48/00 3052)
- 4x BNC-Coax cables
- 4x Test leads with banana plugs

Test Setup

Figure 6.44 depicts a block diagram of the test setup, and figure 6.45b depicts the test setup in real life.

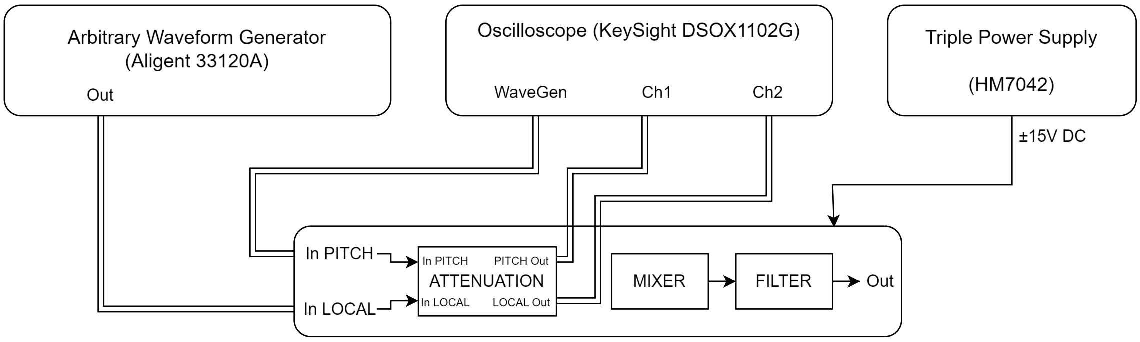
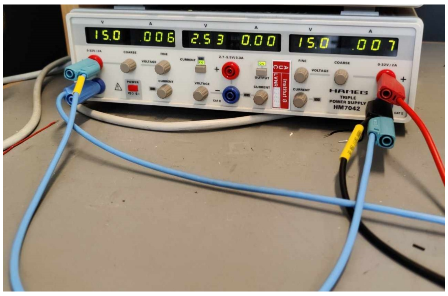
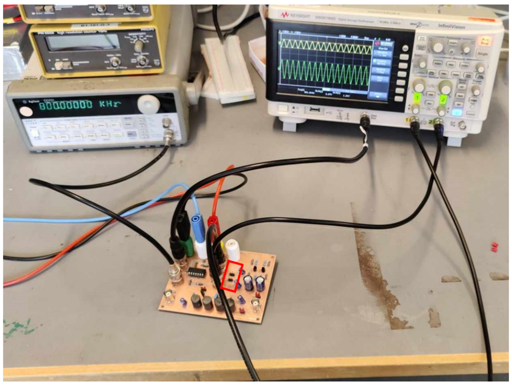


Figure 6.44: Block diagram of attenuation sub-module test setup.



(a) PSU configuration for the attenuation module test.



(b) Test setup of the attenuation module. Notice the red box, marking out the two missing jumpers to isolate the attenuation module.

Figure 6.45: Test setup of attenuation module test.

1. Remove the two jumpers before the mixer sub-module, see red marking in figure 6.45b.
2. Connect the oscilloscope WaveGen to the PITCH input at $12V_{pp}$ and the arbitrary WaveGen to the LOCAL input at $13V_{pp}$.
3. Connect the two BNC connectors after the attenuation module to the two channels on the oscilloscope.
4. Connect the power supply to; +15V, -15V and GND, see figure 6.45a.
5. Set both WaveGens to the same frequency, at 200kHz and note down the output frequency and amplitude of both signals.
6. Repeat the previous step at 500kHz and 800kHz.

Test Results

Test results from the attenuation test can be seen in table 6.4 and table 6.5 and pictures from the oscilloscope of both output signals in figure 6.46.

LOCAL ATTENUATION

Input f	Input ampl.	Output f	Output ampl.	Deviation	Final ampl.
200kHz	$13V_{pp}$	200kHz	$2.73V_{pp}$	$0.23V_{pp}$	0.2100
500kHz	$13V_{pp}$	500kHz	$2.77V_{pp}$	$0.27V_{pp}$	0.2130
800kHz	$13V_{pp}$	800kHz	$2.97V_{pp}$	$0.47V_{pp}$	0.2285

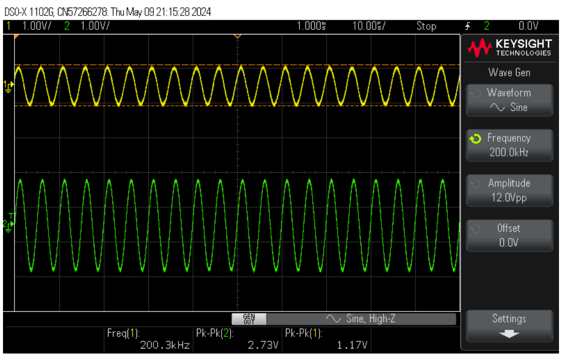
Table 6.4: Test data from the LOCAL attenuation.

PITCH ATTENUATION

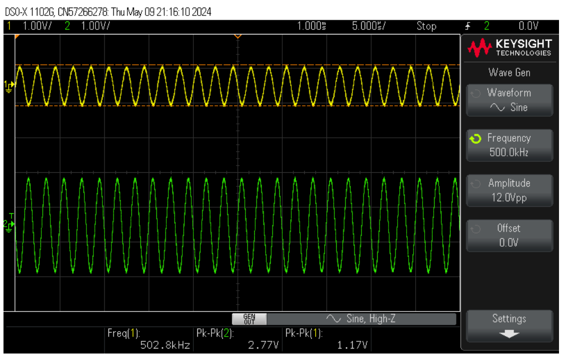
Input f	Input ampl.	Output f	Output ampl.	Deviation	Final ampl.
200kHz	$12V_{pp}$	200kHz	$1.17V_{pp}$	$0.17\ V_{pp}$	0.0975
500kHz	$12V_{pp}$	500kHz	$1.17V_{pp}$	$0.17\ V_{pp}$	0.0975
800kHz	$12V_{pp}$	800kHz	$1.21V_{pp}$	$0.21\ V_{pp}$	0.1008

Table 6.5: Test data from the PITCH attenuation.

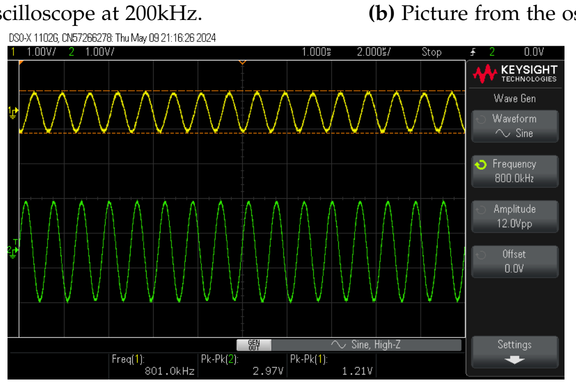
Table 6.4 shows an attenuation but not as closely as desired. The largest deviation from the expected $2.5V_{pp}$ is $0.47V_{pp}$, which is more than desired, but at 200kHz, the amplification is within the specification. Similar to the test data in table 6.5, the largest deviation from the expected $1V_{pp}$ is $0.21V_{pp}$, which meets the specification. The frequency may look to be unstable, but this is due to the oscilloscope's WaveGen and measuring errors. This can also be seen in figure 6.46.



(a) Picture from the oscilloscope at 200kHz.



(b) Picture from the oscilloscope at 500kHz.



(c) Picture from the oscilloscope at 800kHz.

Figure 6.46: Pictures from the oscilloscope from test A. Do note, that the oscilloscope has a measuring error which is why the frequency is not exact on the figures.

While the attenuation module has a large deviation from their desired amplification, this is due to the resistors' values and it has been prioritized to focus on more vital parts. Therefore no changes have been made for the Attenuation module. The Attenuation module fulfills the specification: a stable frequency, at 200kHz for LOCAL, and all frequencies for PITCH.

Test B: Filter Module

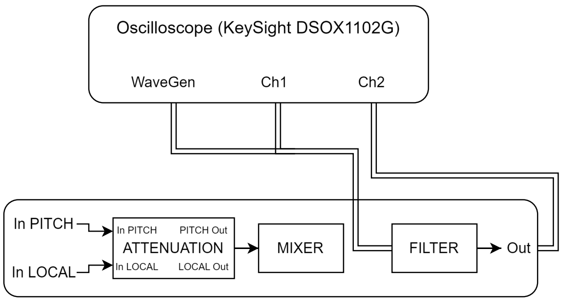
The test purpose is to verify the frequency response of the filter module is as desired.

Test Materials

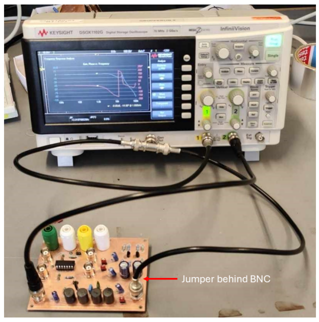
- 1x MIXER module
- 1x Oscilloscope, KeySight DSOX1102G (Serial no: CN5726678)
- 3x BNC-Coax cable
- 1x BNC T-connector

Test Setup

Figure 6.47a depicts a block diagram of the test setup, and figure 6.47b depicts the test setup.



(a) Block-diagram of ffilter module test.



(b) Test setup of the filter module in real life.

Figure 6.47: Test setup, both block-diagram and real setup.

1. Remove the jumper after the mixer sub-module, see red marking in figure 6.47b.
2. Connect the BNC T-connector to the WaveGen.
3. Connect a BNC-Coax cable from the T-connector to channel 1 on the oscilloscope.
4. Connect a BNC-Coax cable between the T-connector and the BNC connector to the right on the PCB, this is the filter input port.
5. Connect the last BNC-Coax cable between the oscilloscope channel 2 and the output port on the PCB.
6. Perform a frequency response analysis with the oscilloscope from 20Hz to 100kHz with a signal amplitude of $1V_{pp}$.

Test Results

The frequency response of the filter can be seen in figure 6.48:

(a) Frequency response of the filter at 30Hz.

(b) Frequency response of the filter at 1kHz.

(c) Frequency response of the filter at 3kHz.

Figure 6.48: Pictures from the oscilloscope from test B.

The filter has a differences 1.06dB (-0.32dB, +0.74dB) between 30Hz and 3kHz, which is not expected. This leads to a difference in the output amplitude over the played spectrum. This will give amplification difference of:

$$10^{\frac{1.06}{20}} = 1.129 \tag{6.52}$$

Which is equal to a difference of 12.9% when playing over the entire spectrum. Why it changes from the tested amplification done in subsection 6.5.7, which was 9.5%, is unknown. But having a filter with the desired component values would probably fix it. No more time will be put into design.

C: Stability Test

This is to test the stability, and the internal requirement of the output varying within $\pm$1Hz at the final output.

Test Materials

- 1x MIXER module
- 1x Keysight DSOX1102G (Serial no. CN57266367) Oscilloscope (built-in signal generator)
- 1x Arbitrary WaveGen, Aligent 33120A (Serial no: MY 46012392)

- 3x High Resolution Frequency Counter, Phillips PM6668 (Serial no: NO SM 5299, NO SM 5916, NO SM 5909)
- 6x BNC-Coax cables
- 3x BNC, T-connector
- 2x HAMEG HM7042-2 lab bench power supply (Serial no. 48/00 3025, 46/00 2988)
- 6x Test leads with banana plugs; +12V, -15V, +15V and GROUND

Test Setup

Figure 6.49 depicts a block diagram of the test setup, and figure 6.50 depicts the test setup in real life.

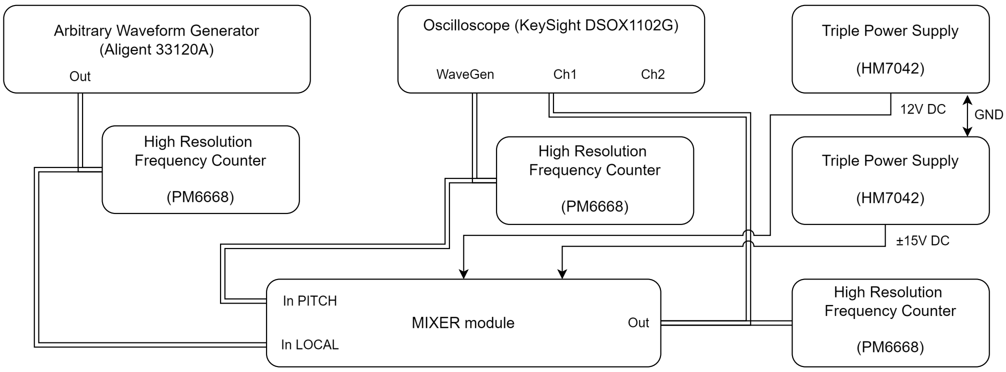
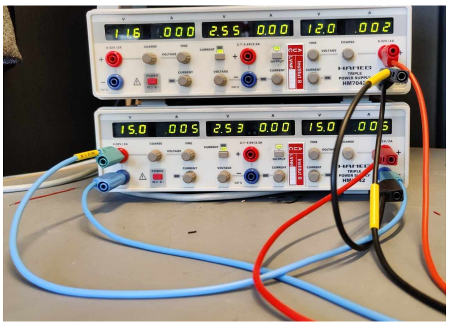
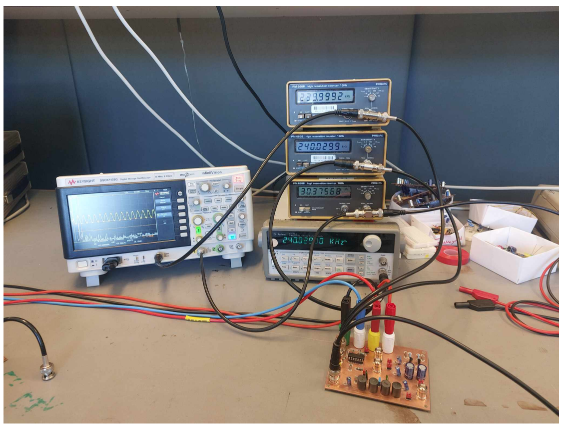


Figure 6.49: Block diagram of MIXER module stability test setup.



(a) PSU configuration for the stability module test.



(b) Test setup of the MIXER module stability test.

Figure 6.50: Test setup of MIXER module stability test.

1. Connect a BNC T-connector to the three frequency counters.
2. Connect a BNC-Coax cable between one frequency counter and the oscilloscope WaveGen followed by a BNC-Coax cable from the T-connector to the PITCH input on the MIXER module.
3. Connect a BNC-Coax cable between the second frequency counter and the Arbitrary WaveGen followed by a BNC-Coax cable from the T-connector to the LOCAL input on the MIXER module.

4. Connect a BNC-Coax cable between the third frequency counter and output of the mixer, followed by a BNC-Coax cable between Channel 1 on the oscilloscope to the output on the MIXER module.
5. Connect the power supply to; +12V, +15V, -15V and GND, see figure 6.50a.
6. Set both WaveGens to their specified frequency and amplitude in table 6.7, except the last two, and note down the output frequency and amplitude of both signals.
7. Repeat the previous step for each row in the table mentioned, taking 5 samples.
8. Make an FFT on the scope, zoom in to see the difference in frequency and the surrounding ones.

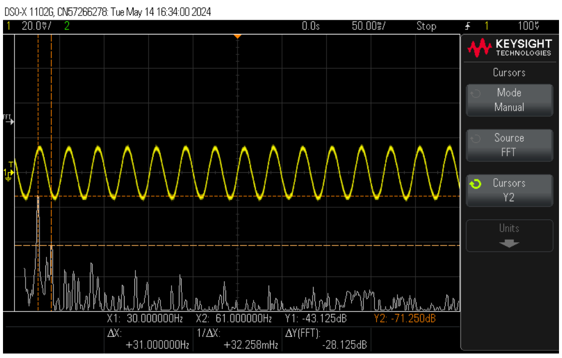
Test Results

The results can be seen in figure 6.6 and pictures from the scope can be seen in figure 6.51.

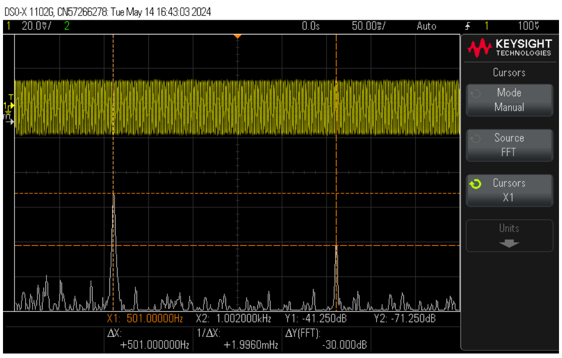
LOCAL f	PITCH f	Desired f	Mean f	Deviation f
240,000Hz	240,030Hz	30Hz	30.458Hz	0.458Hz
240,000Hz	240,500Hz	500Hz	500.498Hz	0.498Hz
240,000Hz	241,000Hz	1000Hz	1000.387Hz	0.387Hz
240,000Hz	241,500Hz	1500Hz	1500.411Hz	0.411Hz
240,000Hz	242,000Hz	2000Hz	2000.402Hz	0.402Hz
240,000Hz	242,500Hz	2500Hz	2499.394Hz	0.605Hz
240,000Hz	243,000Hz	3000Hz	3000.003Hz	0.0032Hz

Table 6.6: Test result only containing the mean from the test, using the frequency counter.

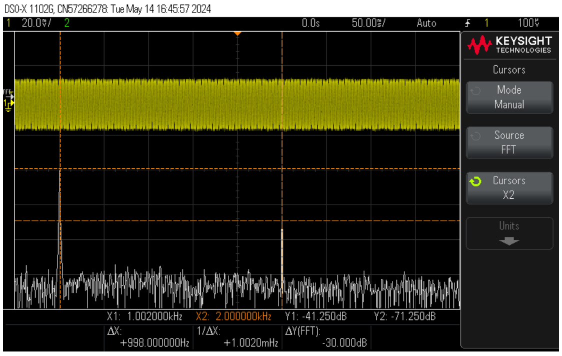
As can be seen in figure 6.6, the results are stable, and the 5 measurements taken can be seen in appendix, section A.11, were all within a difference of 0.2Hz of each other.



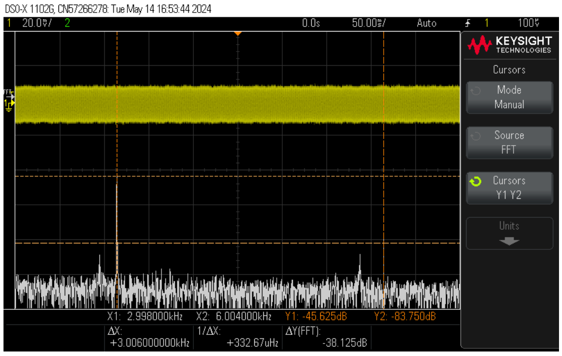
(a) Pictures from the scope with a 30Hz difference.



(b) Pictures from the scope with a 500Hz difference.



(c) Pictures from the scope with a 1000Hz difference, at 3kHz on the FFT.



(d) Pictures from the scope with a 3000Hz difference, at 3kHz on the FFT.

Figure 6.51: Pictures from the oscilloscope for the stability test.

D: End-to-end Test

The purpose of the test is to verify the MIXER module as a whole is operating as desired.

Test Materials

- 1x MIXER module
- 1x Keysight DSOX1102G (Serial no. CN57266367) Oscilloscope (built-in WaveGen)
- 1x Arbitrary waveform Generator, Aligent 33120A (Serial no: MY 46012392)
- 2x High Resolution Frequency Counter, Phillips PM6668 (Serial no: NO SM 5299, NO SM 5916)
- 5x BNC-Coax cables
- 2x BNC, T-connector
- 2x HAMEG HM7042-2 lab bench power supply (Serial no. 48/00 3025, 46/00 2988)
- 6x Test lead with banana plugs; +12V, -15V, +15V and GROUND

Test Setup

Figure 6.52 depicts a block diagram of the test setup, and figure 6.53 depicts the test setup.

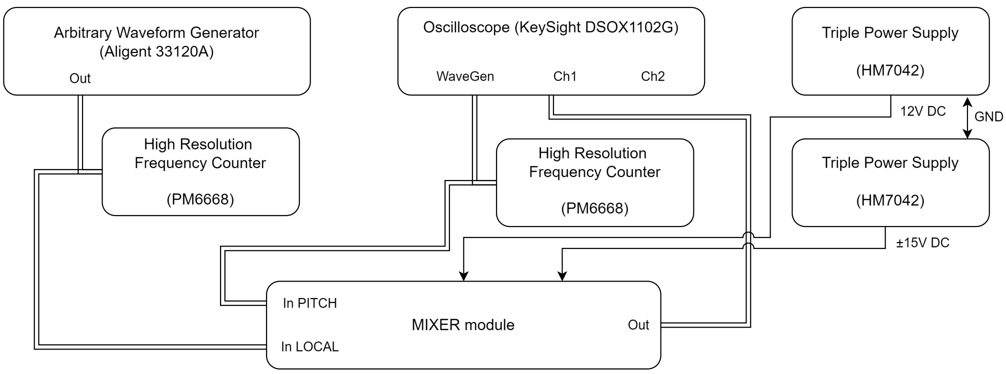
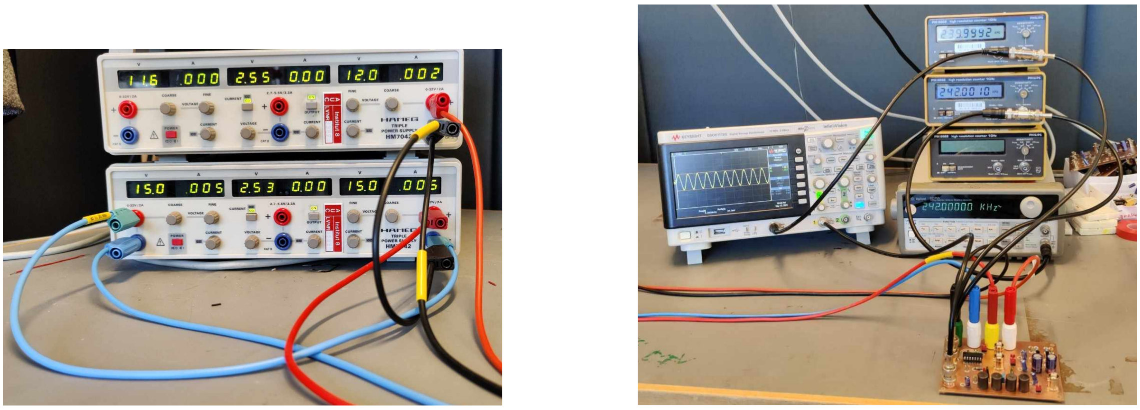


Figure 6.52: Block diagram of the MIXER module end-to-end test setup.



(a) PSU configuration for the end-to-end module test.

(b) Test setup of the MIXER module end-to-end test.

Figure 6.53: Test setup of the MIXER module end-to-end test.

1. Connect a BNC T-connector to the two frequency counters.
2. Connect a BNC-Coax cable between one frequency counter and the oscilloscope WaveGen followed by a BNC-Coax cable from the T-connector to the PITCH input on the MIXER module.
3. Connect a BNC-Coax cable between the second frequency counter and the Arbitrary waveform Generator followed by a BNC-Coax cable from the T-connector to the LOCAL input on the MIXER module.
4. Connect a BNC-Coax cable between the output of the mixer and channel 1 on the oscilloscope.
5. Connect the power supply to; +12V, +15V, -15V and GND, see figure 6.53a.
6. Set both WaveGens to their specified frequency and amplitude in table 6.7, and note down the output frequency and amplitude of both signals.
7. Repeat the previous step for each row in table 6.7.

A series of tests will be conducted, see table 6.7 for the parameters. The input signals are sinusoidal signals with a specified frequency and amplitude.

Aligent f	Aligent V_{pp}	WaveGen f	WaveGen V_{pp}	Δf
240,000Hz	$13V_{pp}$	240,000Hz	$12V_{pp}$	0Hz
240,030Hz	$13V_{pp}$	240,000Hz	$12V_{pp}$	30Hz
240,500Hz	$13V_{pp}$	240,000Hz	$12V_{pp}$	500Hz
241,000Hz	$13V_{pp}$	240,000Hz	$12V_{pp}$	1000Hz
241,500Hz	$13V_{pp}$	240,000Hz	$12V_{pp}$	1500Hz
242,000Hz	$13V_{pp}$	240,000Hz	$12V_{pp}$	2000Hz
242,500Hz	$13V_{pp}$	240,000Hz	$12V_{pp}$	2500Hz
243,000Hz	$13V_{pp}$	240,000Hz	$12V_{pp}$	3000Hz
800,030Hz	$13V_{pp}$	800,000Hz	$12V_{pp}$	30Hz
803,000Hz	$13V_{pp}$	800,000Hz	$12V_{pp}$	3000Hz

Table 6.7: Testing parameters.

Test Results

A summary of the test results can be seen in table 6.8 and table 6.9. Some of the test results can be seen in figure 6.54, with both the output signal and an FFT of the signal. The full set of oscilloscope images can be seen in appendix A.11.1, starting on page 200.

Input Δf [HZ]	0	30	500	1k	1.5k	2k	2.5k	3k
f_{out} [Hz]	0	30	500	1k	1.5k	2k	2.5k	3k
Output [mV_{pp}]	0	92	80	74	70	66	60	58

Table 6.8: Frequency and amplitude of test results, for LOCAL at 240kHz.

The results in table 6.9, were to confirm that the module also worked at high frequencies. Therefore not many measuring points were taken, and will not be analyzed in depth, but this will instead use the result from table 6.8.

Input Δf [Hz]	0	30	500	1k	1.5k	2k	2.5k	3k
f_{out} [Hz]	0	30	N/A	N/A	N/A	N/A	N/A	3k
Output [mV_{pp}]	0	117	N/A	N/A	N/A	N/A	N/A	79

Table 6.9: Frequency and amplitude of the test results, for inputs at 800kHz.

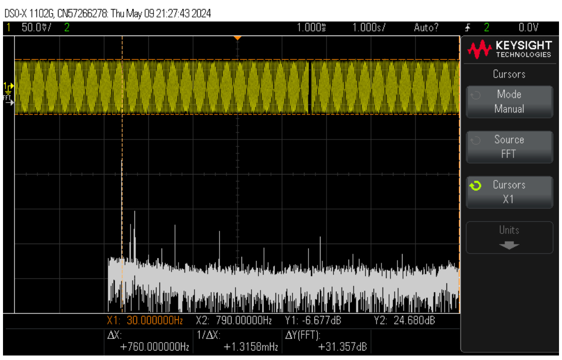
The desired output should have been $70mV_{pp}$, which means the deviation is:

$$\frac{92mV_{pp} - 70mV_{pp}}{70mV_{pp}} = 0.3142 \rightarrow 31.42\% \tag{6.53}$$

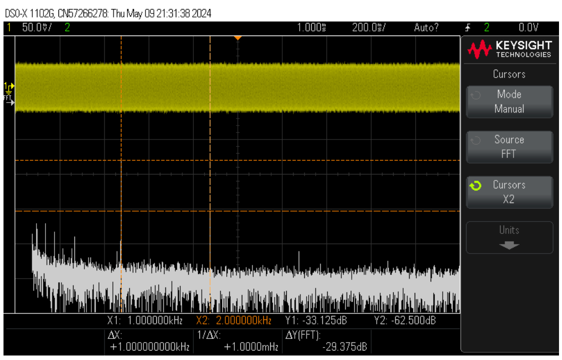
$$\frac{58mV_{pp} - 70mV_{pp}}{70mV_{pp}} = -0.1714 \rightarrow -17.14\% \tag{6.54}$$

This is quite a large deviation, from the desired and otherwise expected stable output. The pictures from the scope can be seen in figure 6.54. The signal is also stronger at 800kHz, which is not desired as it means it is not linear, but has a similar decrease as when LOCAL = 240kHz.

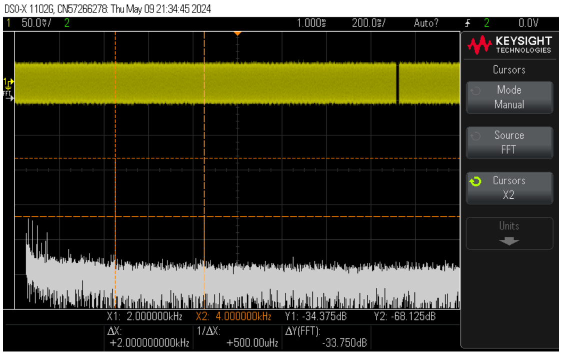
Furthermore, as can be seen in figure 6.54a, the 30Hz, difference is quite visible, but the harmonic frequencies are so as well. This becomes all the more clear in figure 6.54b, where the next harmonic frequency at 2kHz, is half the dB of the 1kHz difference. This continues throughout figure 6.54c and figure 6.54d and unfortunately shows a heavy harmonic distortion. This is not something that can be solved by applying a filter but is instead a problem that occurs in the BJT-mixer.



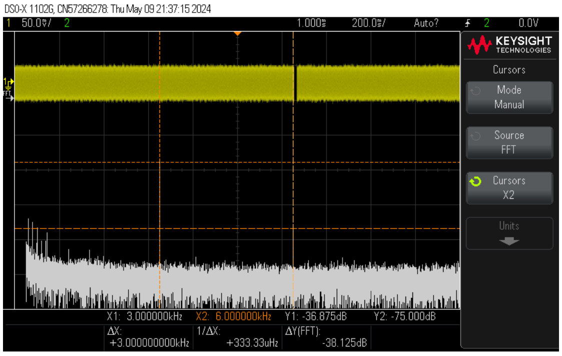
(a) Picture of the oscilloscope with 30Hz difference.



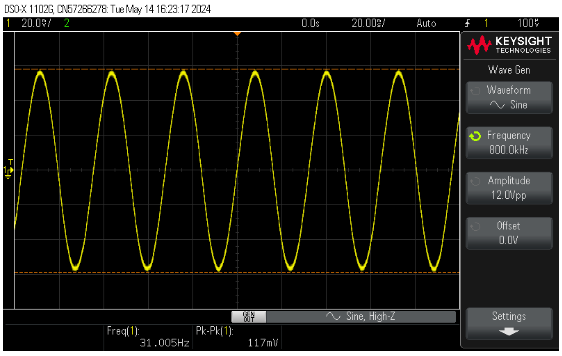
(b) Picture of the oscilloscope with a 1kHz difference.



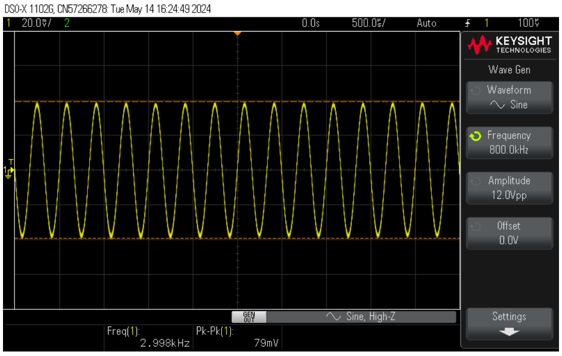
(c) Picture of the oscilloscope with a 2kHz difference.



(d) Picture of the oscilloscope with a 3kHz difference.



(e) Picture of the oscilloscope with a 30Hz difference.



(f) Picture of the oscilloscope with a 3kHz difference.

Figure 6.54: Picture of the oscilloscope of both the signal and the FFT, done by the oscilloscope. The oscilloscope has been zoomed to get an appropriate FFT. Pictures 6.54a - 6.54dwith LOCAL = 240kHz, while in pictures 6.54e and 6.54f with LOCAL = 800kHz.

6.5.10 Summary

While the mixer does work, it is not optimal and far from desired. This is probably because of the many iterations and rushed designs for the mixer module, most notably the parallel BJT-mixer. There are quite an amount of THD, as can be seen in figure 6.54. But, as it accomplishes that task of mixing the two signals, is stable within ±1Hz, with a somewhat close output V_{pp} as desired, and has therefore been implemented and kept as is.

6.6 Volume Module

Just like the pitch module, the volume module is oscillator-based. The volume module is responsible for adjusting the volume of the theremin. Unfortunately, due to time constraints, this module will not be made. Nevertheless, the volume module will still be described as if it would be designed.

6.6.1 Specification

The volume module has to adhere to various sub-requirements as stated in HLS 1 and 2 on 52.

- The volume range should be adjustable by moving a hand between 2cm and 50cm from the antenna.
- The volume has to be adjustable separately from adjusting the pitch.
- The volume module has to oscillate at a lower frequency than the other oscillators.
- The volume antenna described in figure 6.3 must be used.

6.6.2 Design

Just as the local and pitch modules, the volume module will utilize a Colpitts oscillator. It should oscillate at a lower frequency than the other oscillators, to minimize the risk of interference. The module should output a variable frequency dependent on hand placement, and input it into a voltage controlled amplifier, VCA, processor so that a VCA can be used for volume control. The design will not be handled more in depth, as this module will not be developed.

6.6.3 Implementation

The module cannot be implemented, as it will not be developed.

6.6.4 Test

Testing will not be conducted as the module is not developed.

6.6.5 Summary

Due to time constraints, the volume module will not be developed. The basic design of the volume module is similar to that of the local and pitch modules, with the main difference being a change of frequency and addition of a VCA processor.

6.7 Amplification Module

The amplification module aims to amplify the signal coming out of the MIXER module, as it is very low. This section describes the design of a PRE-AMP, so that the output signal can drive a Hi-Fi amplifier. This section utilizes the knowledge described in section 4.4 on page 30.

6.7.1 Specification

- Must be supplied by 12V DC
- Cutoff frequency for the low frequency must be 30Hz or less
- Input signal amplitude of $70mV_{pp}$
- Must output $\geq 900mV_{pp}$
- Output must be tuneable

6.7.2 Design

Amplification

Under the electrical specification, 5.3.1, it states that the output should be $\geq 900mV_{pp}$. The output specification of the MIXER Module states that the output is $70mV_{pp}$. Therefore the input for the PRE-AMP should be $70mV_{pp}$. This means that the input signal should be amplified with a magnitude of around 13. The amplification of the transistor, where the mid-band will be, is controlled by the ratio of R_{C1} and R_{E1} plus the dynamic resistance, where re is the dynamic resistance. The dynamic resistance can be calculated with equation 4.26, from page 32. The amplification can therefore be chosen to be, $R_C = 3k\Omega$ and $R_E = 150\Omega$. By plugging this into equation 4.28 on page 32, the amplification can be found:

$$A_v = \frac{R_{C1}}{R_{E1} + re} = \frac{3k\Omega}{150\Omega + 70.27\Omega} = 13.6[\cdot] \tag{6.55}$$

To tune the output, R_C will be a potentiometer. This will ensure that the output can be configurable according to the thereminist's desire.

Biasing

To bias the transistor, the voltage divider topology has been chosen. The voltage divider is the most commonly used topology for discrete-circuit transistor amplifiers. The biasing resistors have been chosen to have a base resistor, R_B, of approximately $26k\Omega$. The ratio of the resistors has therefore been selected to be, $R_{B1} = 220k\Omega$ and $R_{B2} = 30k\Omega$.

Cutoff Frequencies

To ensure that the transistor amplifies all of the desired frequencies, the cutoff frequencies must be set. Since HLS 1.1 states that the theremin should play within the 30Hz - 3kHz range, then the low-frequency response must be quite precise, while the high-frequency response is less of a concern, and can therefore be slightly looser. To find the lower cutoff frequency of the capacitors connected, those being the ones at the base, collector, and emitter, the equation 4.30 seen in section 4.4.3 on page 33, must be used. This equation will be used to find all the cutoff frequencies of the capacitors.

$$f_{cutoff} = \frac{1}{2\pi RC} \tag{6.56}$$

The cutoff frequency of the capacitor on the base is found by equation 4.32:

$$F_{L_{base}} = \frac{1}{2\pi(R_{sig} + R_{base}) \cdot C_b} = \frac{1}{2\pi(10\Omega + 11.27k\Omega) \cdot 47\mu F} = 0.30[Hz] \tag{6.57}$$

The cutoff frequency of the capacitor on the collector is found by equation 4.35:

$$F_{L_{collector}} = \frac{1}{2\pi(R_{collector} + R_{load}) \cdot C_c} = \frac{1}{2\pi(4.67k\Omega + 10M\Omega) \cdot 47\mu F} = 338.63\mu[Hz] \tag{6.58}$$

The cutoff frequency of the capacitor on the emitter is found by equation 4.37:

$$F_{L_{emitter}} = \frac{1}{2\pi \cdot R_{emitter_{final}} \cdot C_e} = \frac{1}{2\pi \cdot 195.92\Omega \cdot 440\mu F} = 1.85[Hz] \tag{6.59}$$

As stated in section 4.4.3, for the low-frequency cutoff, the largest pole will be the most dominant pole. This means that in this case, the dominant pole for F_L is the capacitor on the emitter, and can therefore be assumed that the cutoff frequency is approximately 1.85Hz.

For the high-frequency cutoff, the capacitors must also be found. The capacitors needed to be found are the Miller capacitors, which are described in section 4.4.1. The method of calculating the Miller's capacitors, have been described in section 4.4.4. To start with, the cutoff frequency of the capacitor going in is found by equation 4.40

$$F_{H_{in}} = \frac{1}{2\pi \cdot R_{in} \cdot C_{in_{Miller}}} = \frac{1}{2\pi \cdot 9.99\Omega \cdot 12pF} = 1.33G[Hz] \tag{6.60}$$

Then the cutoff frequency of the capacitor going out is found with equation 4.43

$$F_{H_{out}} = \frac{1}{2\pi R_{out} \cdot C_{out_{Miller}}} = \frac{1}{2\pi \cdot 4.67k\Omega \cdot 8pF} = 4.26M[Hz] \tag{6.61}$$

As stated in section 4.4.4, the lowest F_H is the most dominant. This means that the dominant F_H is the capacitor going out. It can therefore be assumed that the cutoff frequency is approximately 4.26MHz.

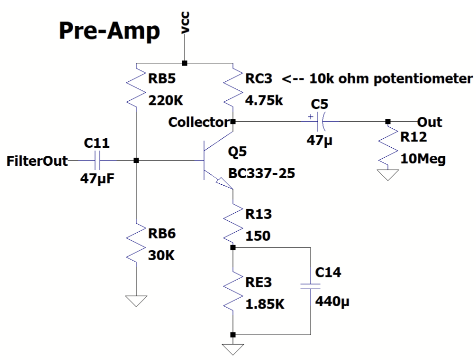


Figure 6.55: Final amplifier circuit.

The R_{13} and C_{14} on figure 6.55 has been added to have less distortion in the signal.

Total Harmonic Distortion

When analyzing the system, the FFT in figure 6.56, shows the fundamental frequency and that it has 1 meaningful harmonic distortion, with the subsequent harmonic distortions having such a low voltage amplitude that they can be ignored. By using equation 4.18, the THD of the system is therefore calculated to be 7.1% in equation 6.62.

$$THD = \frac{\sqrt{(29.72mV)^2 + (1.9mV)^2}}{414.8mV} \cdot 100 = 7.1\% \tag{6.62}$$

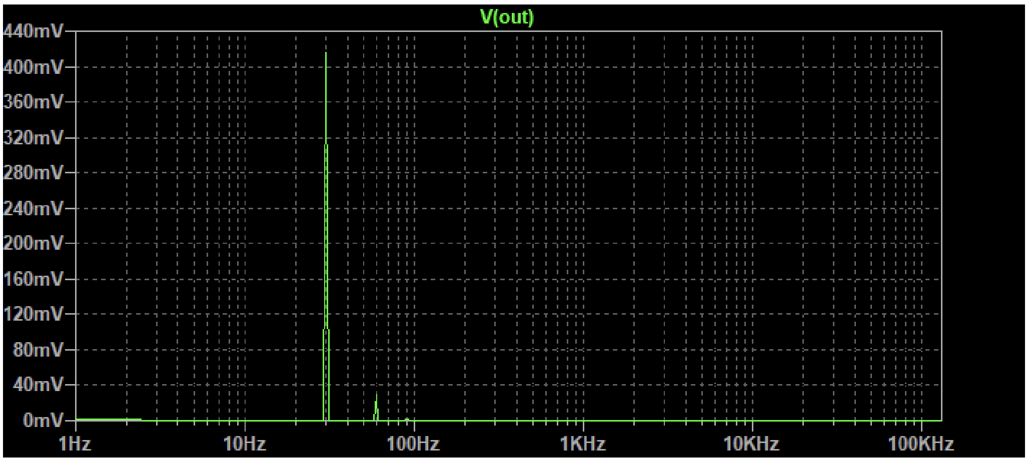


Figure 6.56: Linear representation of the FFT. The 30Hz signal is the fundamental frequency, anything after it are harmonic distortions.

To ensure the calculation is correct, *.four <frequency> [N Harmonics] [N Periods] <Data Trace>* will be used. The directive will then look as follows: *.four 30 7 -1 V(out)*. A thing to note here is that when the n periods are given as -1, the analysis will be performed over the entire simulation data range, [38].

```
Warning: Multiple definitions of model "2scr375p" Type: BJT
Warning: Multiple definitions of model "bc857b" Type: BJT
Warning: Multiple definitions of model "bc847c" Type: BJT
Warning: Multiple definitions of model "bc847b" Type: BJT
Error on line 9 : v2 n001 0 sine(0 0.035 30) ac ac1
                    Unknown parameter "ac1"
Direct Newton iteration for .op point succeeded.
N-Period=30.00
Fourier components of V(out)
DC component:-0.00574355

Harmonic          Frequency          Fourier          Normalized
 Number             [Hz]            Component          Component
    1             3.000e+1          5.884e-1           1.000e+0
    2             6.000e+1          4.203e-2           7.144e-2
    3             9.000e+1          2.695e-3           4.580e-3
    4             1.200e+2          2.747e-4           4.668e-4
    5             1.500e+2          3.583e-5           6.090e-5
    6             1.800e+2          2.329e-4           3.959e-4
    7             2.100e+2          1.133e-4           1.925e-4
Partial Harmonic Distortion: 7.158489%
Total Harmonic Distortion:   7.173915%
```

Figure 6.57: THD calculated by LTspice.

6.7.3 Implementation

The final design, which can be seen in figure 6.58, has been implemented on a PCB, which can be seen in figures 6.59a and 6.59b. As seen in figure 6.60, banana plug connectors have been implemented to supply the circuit, with the white banana plug connector being the V_{cc} 12V DC, and the green banana plug connector being ground. The input and output of the module is connected with BNC-Coax cables, to easier test the module individually. The potentiometer has also been added with some wires connecting it to the PCB.

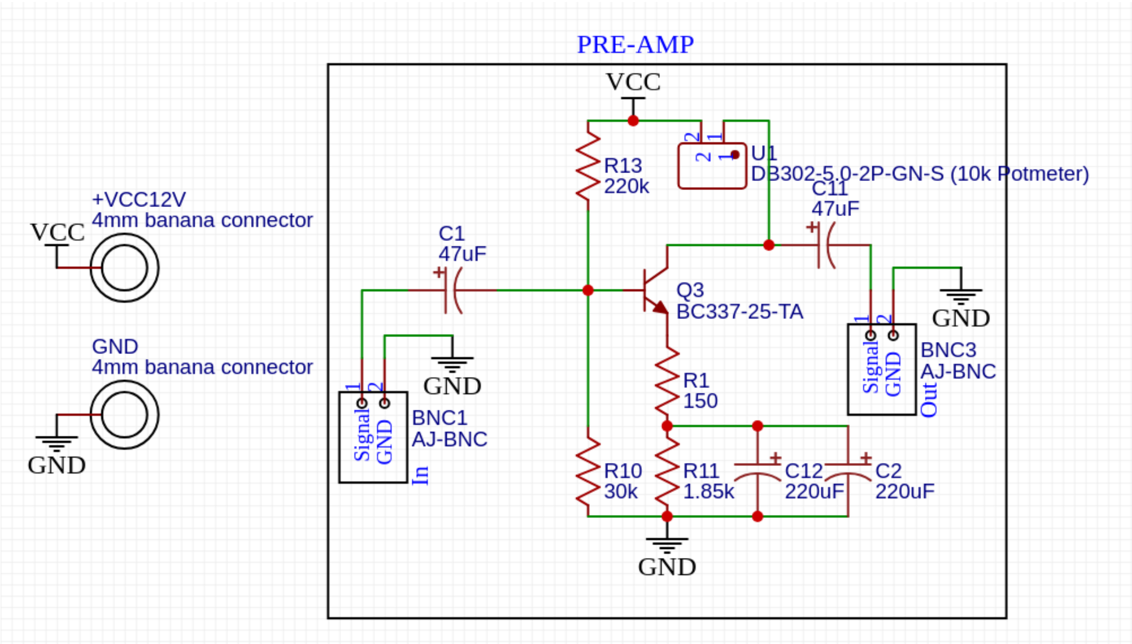
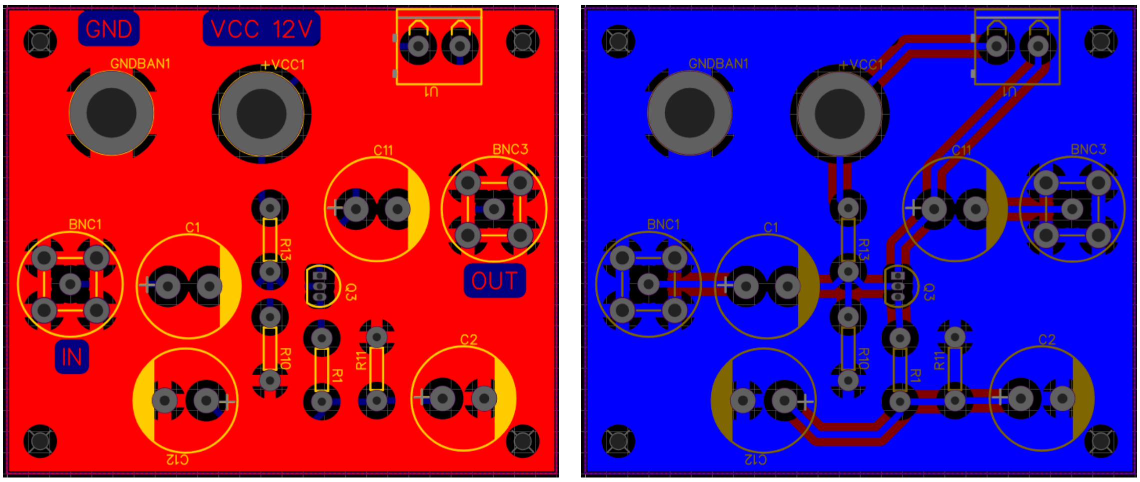


Figure 6.58: Schematic of the amplification module.



(a) Top layer of PCB layout.

(b) Bottom layer of PCB layout.

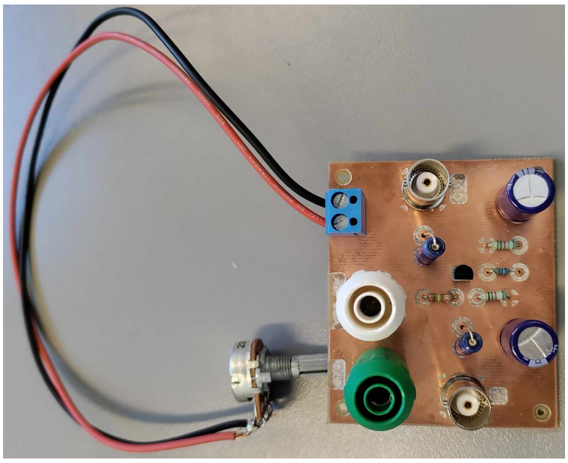


Figure 6.60: Final PCB of the amplification module with components mounted.

6.7.4 Test

The purpose of the test is to see if the incoming signal is amplified as desired, without changing the frequency. Furthermore, the PRE-AMP will also be tested to see the frequency response and the THD.

Test Setup

To test the PRE-AMP, the following things are required:

- 1x Keysight DSOX1102G (Serial no. CN57266278) Oscilloscope (built-in WaveGen)
- 1x HAMEG HM7042-2 lab bench power supply (Serial no. 48/00 3025)
- 2x Test leads with banana plugs
- 3x BNC-Coax cables
- 1x BNC T-Connector
- 1x NI PCI-4461

The banana plugs should be connected to the power supply, one to supply 12V DC and one for ground. Connect two of the BNC-Coax cables to the BNC-Coax T-Connector. The BNC T-Connector should be connected to the WaveGen of the oscilloscope, while the two other cables should be connected to the input of the module and channel 1. The last BNC-Coax cable should be connected to the output and channel 2.

Actual Testing

The test setup for the amplification and frequency response are similar and can be seen in figure 6.61. To test the amplification of the PRE-AMP, the measure functions of the oscilloscope were used. The frequency and the peak-to-peak voltage were utilized for both the input and output. By changing the frequency on the WaveGen within the desired range as specified in the functional specification 5.2.1, the amplification could be tested.

To test the frequency response of the PRE-AMP, a couple of things must be set up to do so. To start, the "analyze" function must be utilized. Then select the "frequency response analysis" under the "features" tab. Then under the "setup" tab, the sweep must be taken between 20Hz - 100kHz and the amplitude must be $70mV_{pp}$. Under the "sources" tab, the input should be channel 1 and output channel 2. Then the setup is done and the frequency response analysis is ready to run.

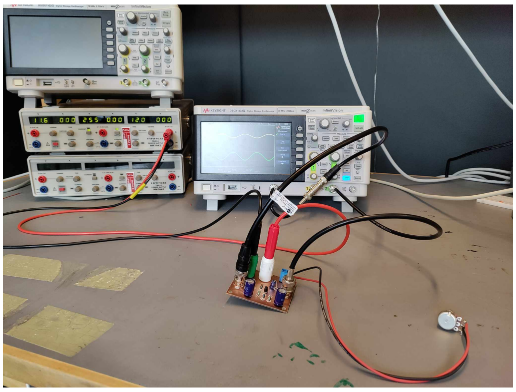


Figure 6.61: Test setup of amplification and frequency response.

To test the THD of the PRE-AMP, a NI-PCI-4461 can be utilized. The NI-PCI-4461 is a high-accuracy data acquisition module that is used for sound and vibration applications. As can be seen in figure 6.62b, the output channel of the NI-PCI-4461 labeled A 0-0 is split up by a BNC T-Connector, where one of the BNC-Coax cables goes to the input of the amplification module, while the other is fed back into the input channel of the NI-PCI-4461 labeled A 1-0. The other input channel of the NI-PCI-4461 labeled A 1-1 is connected to the output of the PRE-AMP. To test the THD the sine sweep program must be utilized here. Under the "source settings" a sweep must be taken between 20Hz - 4kHz, the input signal must be $70mV_{pp}$, and under the "THD settings" the THD units must be in percent instead of dB. Once this has been done, the analysis is ready to run.

(a) Test setup of the THD test. **(b)** Pinout of the NI-PCI-4461.

Figure 6.62: Test setup of NI-PCI-4461.

6.7.5 Test Results

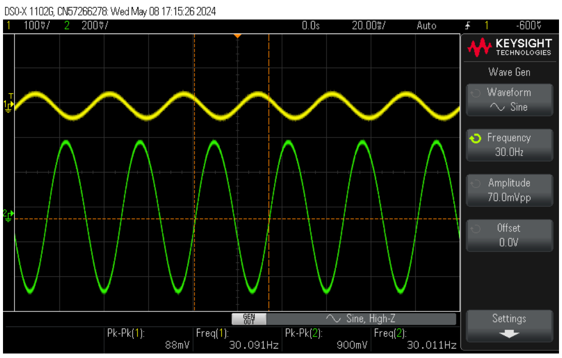
Amplification Test

The results can be seen in table 6.10, pictures of the results can be seen in the sub-figures of figure 6.63. The amplification test shows that an output amplitude of $\geq 900mV_{pp}$ is achievable within the desired frequency range, without altering the output frequency. Figure 6.63d shows that the output can also be tuneable by the potentiometer.

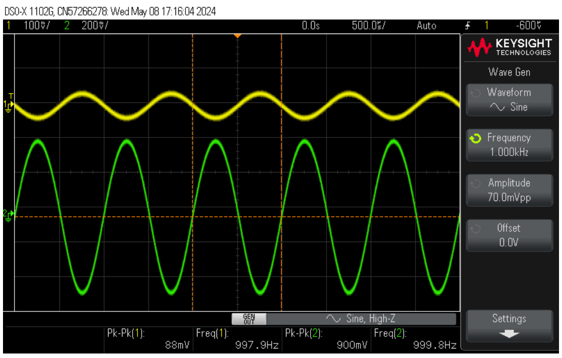
AMPLIFICATION RESULTS

Input f	Input ampl.	Output f	Output ampl.	Deviation
30Hz	$70mV_{pp}$	30Hz	$900mV_{pp}$	$0mV_{pp}$
1kHz	$70mV_{pp}$	1kHz	$900mV_{pp}$	$0mV_{pp}$
3kHz	$70mV_{pp}$	3kHz	$900mV_{pp}$	$0mV_{pp}$

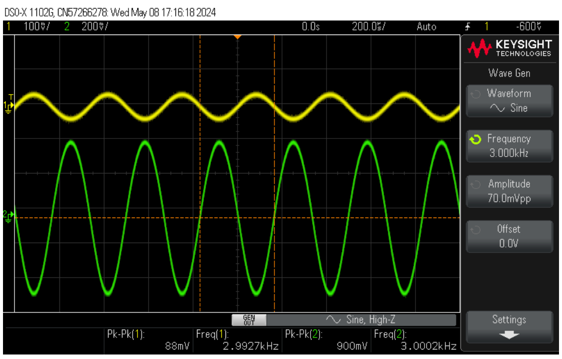
Table 6.10: Test results from the amplification test. Results is from the sub-figures 6.63a - 6.63c.



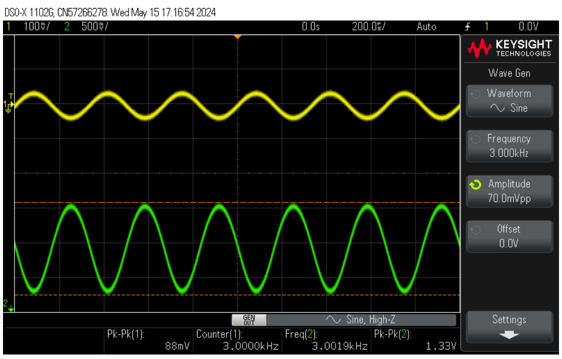
(a) Amplification tested at 30Hz.



(b) Amplification tested at 1kHz.



(c) Amplification tested at 3kHz.

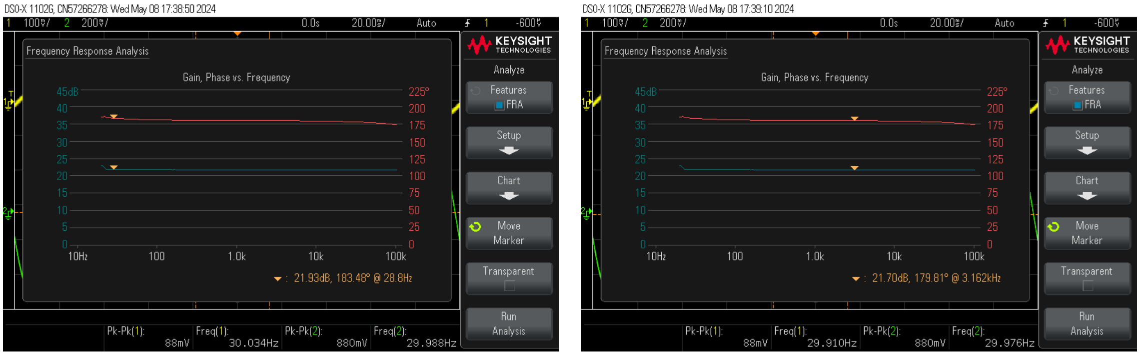


(d) Amplification test with a new potentiometer value.

Figure 6.63: Test of amplification. The yellow is the input, and the green is the output.

Frequency Response Test

As can be seen in figure 6.64a, the frequency response does unfortunately not go below 20Hz. However, the frequency response does show a bump near 30Hz, which indicates that the cutoff frequency is there. The frequency response for the 3kHz signal, as seen in figure 6.64b, shows that the mid-band doesn't change, which means that the amplification stays the same within the desired range.



(a) Frequency response near 30Hz.

(b) Frequency response near 3kHz.

Figure 6.64: Frequency response of the PRE-AMP.

THD Test

The test, which can be seen in figure 6.65, shows a THD of approximately 6.75% within the desired range. Since a desired THD is typically somewhere in between 0.5% and 1%, then this is a very undesirable THD.

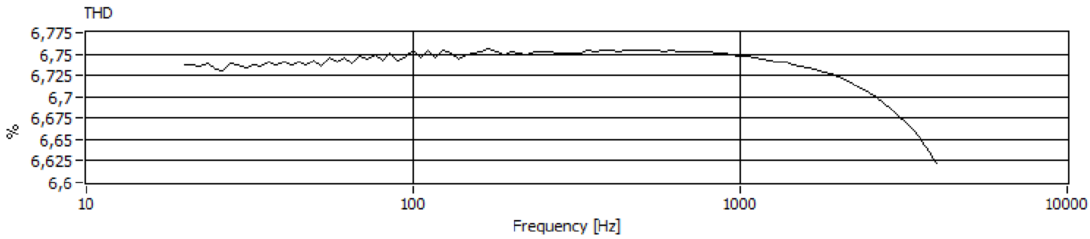


Figure 6.65: THD plotted across the input frequency.

As discussed in section 4.3.2 under class AB, biasing a BJT with the voltage divider topology can cause problems when trying to match the I-V curves of the BJT. A few possible solutions to try and reduce the THD, would be to reduce the gain of the PRE-AMP or use the topology with diodes, as seen in figure 4.12b. This would hopefully help with the PRE-AMP being driven within the linear range. Unfortunately, this won't be done because of time constraints on the project.

6.7.6 Summary

The PRE-AMP is constructed with a BJT, and biased with the voltage divider topology. The LTspice simulations showed a THD of 7.1%, while the measured THD was 6.75%. This THD is undesirable, but because of time constraints, further attempts to improve the THD will not be made. For future work, optimizing the biasing with the diode biasing topology, introducing a feedback signal, or implementing a filter could be attempted.

The constructed PRE-AMP was able to amplify the incoming signal to $\geq m900V_{pp}$, without altering the output frequency. The frequency response analysis showed that the amplification was consistent within the desired mid-band and indicated that the cutoff frequency near 30Hz was beginning to attenuate.

7 | Integration

This chapter will focus on implementing each module in steps to minimize integration problems. The integration will be in steps corresponding to the order in which it's presented. Each section will describe the integration of the modules.

7.1 Integration of Mixer - PRE-AMP

This step consists of integrating the MIXER and PRE-AMP modules. Figure 7.1 shows the modules that are part of this integration step. The integration consist of connecting the two modules with a BNC-Coax cable and power.

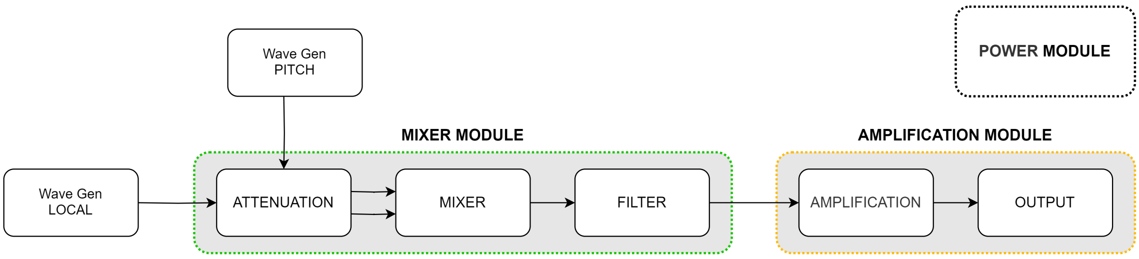


Figure 7.1: An overview showing what modules are part of the first integration step.

7.1.1 Implementation

As each of the modules has been tested on its own, integration consists of connecting the output from MIXER to the input of the PRE-AMP module. The test will determine if the integrated modules still behaves as desired and as tested in their own separate module tests. If not, adjustments will be made and addressed accordingly.

7.1.2 Test

Test Materials:

- 1x MIXER module
- 1x PRE-AMP module
- 1x KeySight DSOX1102G Oscilloscope (Serial no: CN5726678)
- 1x Arbitrary wWaveGen, Aligent 33120A (Serial no: MY 46012392)
- 2x High-Resolution Frequency Counter, Phillips PM6668 (Serial no: NO SM 5299, NO sm 5916)
- 2x Triple Power Supply, HAMEG HM7042 (Serial no. 48/00 3025, 46/00 2988)

- 6x BNC-Coax cable
- 2x BNC T-Connectors
- 8x Test lead with banana plugs; +12V, -15V, +15V and GROUND

Test Setup

A block diagram of the test can be seen in figure 7.2 and the test performed in real life in figure 7.3.

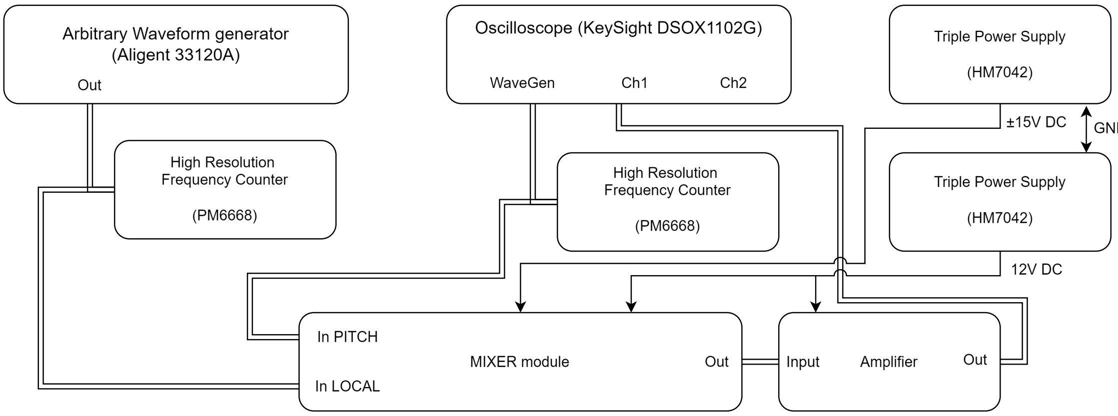
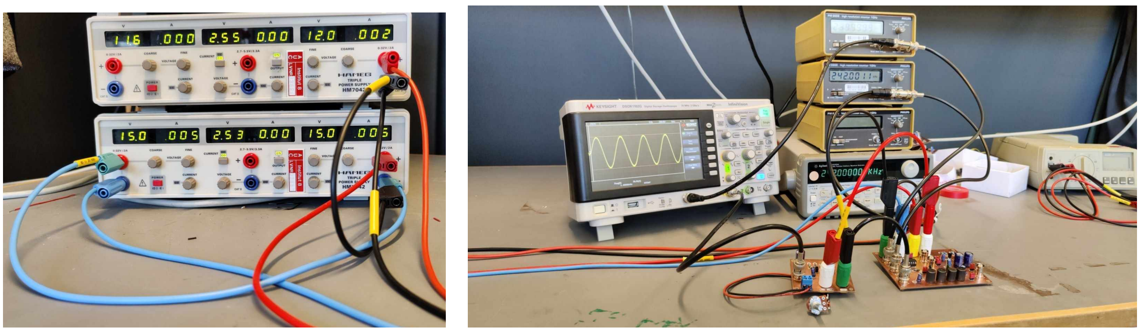


Figure 7.2: Block diagram of the test setup for integration for the MIXER and PRE-AMP. Single line denotes test lines, double lines denote BNC-Coax cables.



(a) PSU configuration for the test.

(b) Test setup of the integration test in real life.

Figure 7.3: Test setup of the integration test.

1. Connect a BNC T-Connector to the two frequency counters.
2. Connect a BNC-Coax cable between one frequency counter and the oscilloscope WaveGen followed by a BNC-Coax cable from the T-Connector to the PITCH input on the MIXER module.
3. Connect a BNC-Coax cable between the second frequency counter and the Arbitrary WaveGen followed by a BNC-Coax cable from the T-Connector to the LOCAL input on the MIXER module.
4. Connect the output from MIXER to the input of PRE-AMP, with a BNC-Coax cable
5. Connect a BNC-Coax cable between the PRE-AMP output and channel 1 on the oscilloscope.

6. Supply both modules, with 12V, MIXER module with additional ± 15V and a shared ground, from a lab bench power supply, see figure 7.3a.
7. Set both WaveGens to their specified frequency and amplitude in table 7.1, and note down the output frequency and amplitude of the signal.
8. Repeat the previous step for each row in table 7.1.

Aligent f [Hz]	Aligent [V_{pp}]	WaveGen f [Hz]	WaveGen [V_{pp}]	Δf [Hz]
240,000	13	240,000	12	0
240,030	13	240,000	12	30
240,500	13	240,000	12	500
241,000	13	240,000	12	1000
241,500	13	240,000	12	1500
242,000	13	240,000	12	2000
242,500	13	240,000	12	2500
243,000	13	240,000	12	3000

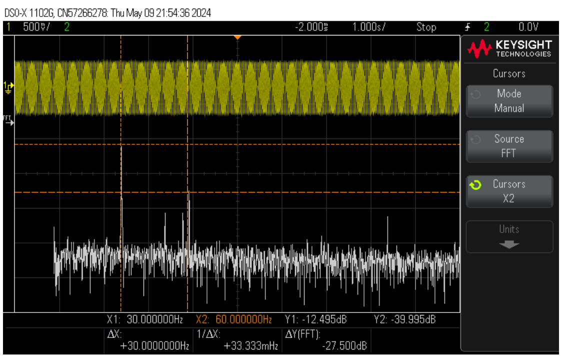
Table 7.1: Testing parameters.

7.1.3 Test Results

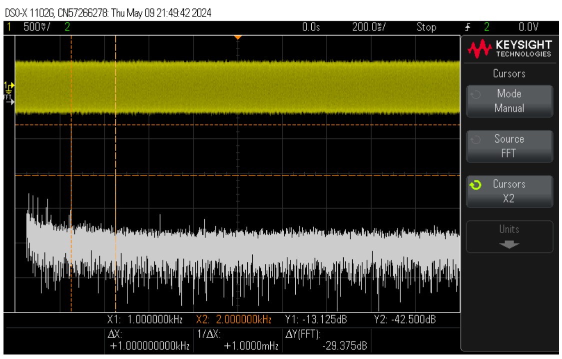
Table 7.2, shows the results from the test, whilst figure 7.4, shows a selection of the output frequency and the FFT. f_Δ is the input difference between the two input frequencies, V_{out} is the amplitude measured whilst f_{out} is the measured output frequency. The full set of oscilloscope images can be seen in appendix A.12.1, starting on page 202.

f_Δ [Hz]	0	30	500	1000	1500	2000	2500	3000
V_{out} [V_{pp}]	0	0.82	0.84	0.8	0.76	0.7	0.62	0.58
f_{out} [Hz]	0	30	500	1000	1500	2000	2500	3000

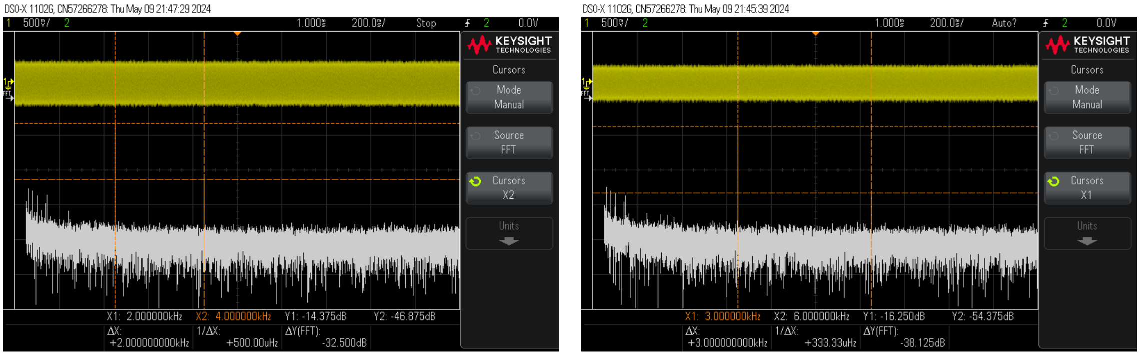
Table 7.2: Table showing results from the integration test of MIXER - PRE-AMP.



(a) Picture of the oscilloscpe with 30Hz difference.



(b) Picture of the oscilloscope with a 1kHz difference.



(c) Picture of the oscilloscope with a 2kHz difference.

(d) Picture of the oscilloscope with a 3kHz difference.

Figure 7.4: Pictures of the oscilloscope of both the signal and the FFT, done by the oscilloscope.

As seen in table 7.2 and figure 7.4, the signal from the MIXER module is amplified as expected but with harmonic distortion, which is not desired. The output amplitude varies as the frequency changes, this is expected, but not desired. The change is related to the change in output amplitude from the MIXER Module which is then carried through the PRE-AMP Module.

7.1.4 Summary

This part of the integration was successful as no modification was needed to integrate the two modules together.

7.2 Final Integration

This step consists of integrating the PITCH, LOCAL, MIXER, and PRE-AMP modules. Figure 7.5 shows the modules that are part of this integration step. The integration consists of connecting the modules with BNC-Coax cables and power.

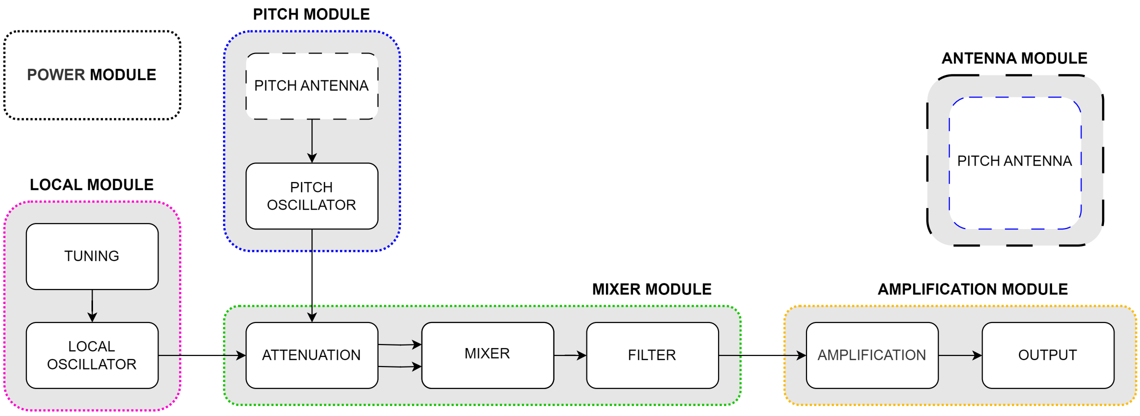


Figure 7.5: A figure showing the modules used in the final integration step of this project.

7.2.1 Implementation

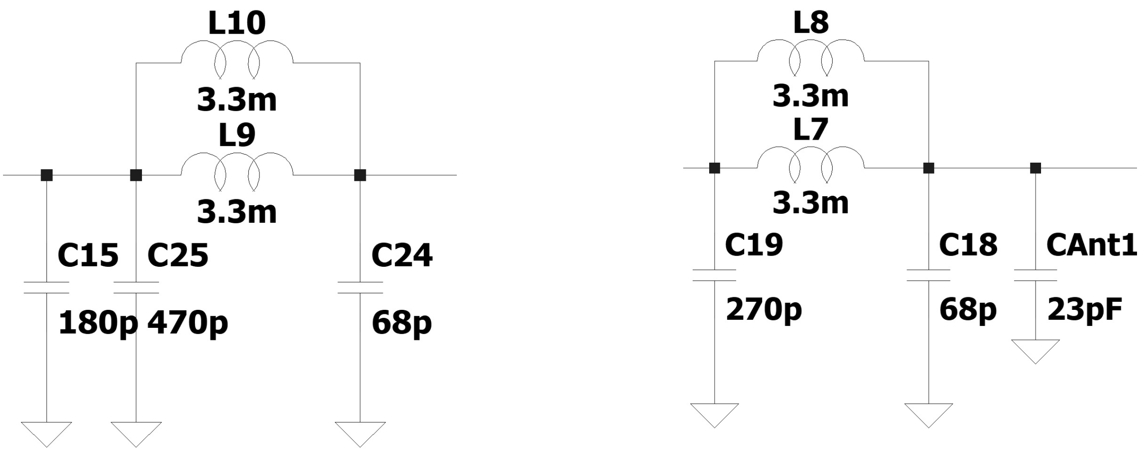
As each of the modules has been tested on its own, integration consists of connecting the output from LOCAL and PITCH to the inputs of the MIXER and MIXER output to PRE-AMP input. The test will determine if the integrated modules still behave as desired and as tested in their separate module tests. If not, adjustments will be made and described in the following sub-section.

Problems Arisen During This Integration Step

During this integration two problems occurred; **impedance matching** and **spontaneous synchronization**. These were resolved and described in the following sub-sections. During this integration the need for input buffering in the MIXER module was discovered, the design and implementation of this can be seen in section 6.5.3 starting page 81.

Impedance Matching

The PITCH oscillator was designed to be more sensitive to small capacitance changes compared to the LOCAL oscillator. This meant that the LOCAL oscillator was found to be more "robust" to the capacitance of the coax cable, and the input impedance of the MIXER module. This resulted in a frequency much lower for the PITCH module compared to the LOCAL module. This meant that the circuits were changed to make sure that the frequencies matched. The final circuits can be seen in figure 7.6:



(a) Updated tank circuit of the LOCAL module. **(b)** Updated tank circuit of the PITCH module.

Figure 7.6: Updated tank circuits of the LOCAL and PITCH modules.

Spontaneous Synchronisation

As mentioned in section 2.3.4, spontaneous synchronization is something that may occur when 2 entities "oscillate" at frequencies close to each other. When spontaneous synchronization happens the frequencies line up to be the same. This is something that can be observed in everything from humans clapping in rhythm to fireflies flashing, but also in electrical circuits, [84]. Curiously this was observed to mainly happen through the radiating frequencies coming out of the circuits and was observed to begin synchronizing when a frequency difference between the oscillators was around 500Hz. To counteract this, a Faraday Cage was built around the LOCAL oscillator, as can be seen in figure 7.7. Another measure that is taken, is placing the 2 oscillators as far away from each other as physically possible, while making sure that the cables stay the same length, to make sure that the coax cables have the same impact on the already tuned circuit.

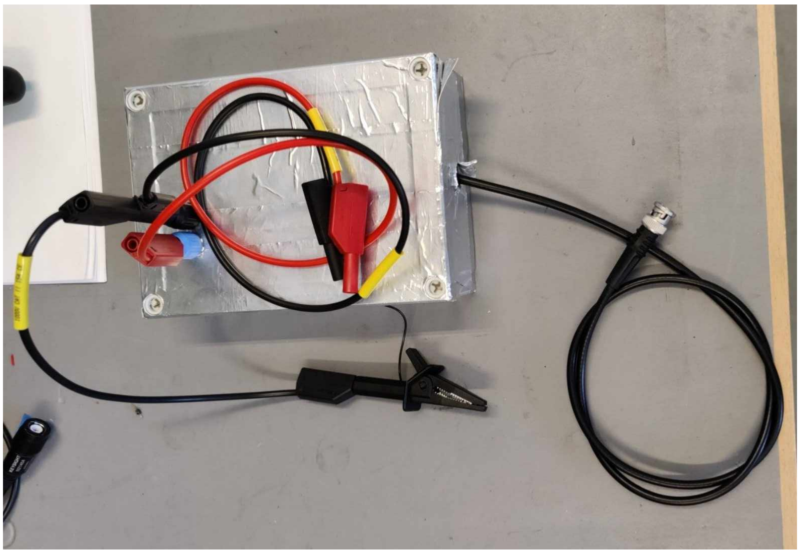


Figure 7.7: A picture showing the built Faraday Cage with the LOCAL module mounted inside, that was used to combat synchronization.

It is noteworthy that spontaneous synchronization still occurs even with the Faraday Cage. This happens as the cage is not 100% EMC resilient. However the signal entering is very weak, and therefore it was observed that the synchronization only happened with an ~$20Hz$ frequency difference between the oscillators, which is out of the desired frequency range so it does not impact the system, but rather helps it meet the requirements of zero beat frequency.

7.2.2 Test

The integration test carried out in this integration is equivalent to the acceptance test. The test is therefore only described and analyzed in the acceptance test chapter, see section 8.1 starting on page 123.

7.2.3 Summary

This part of the integration was successful, though a couple of issues had to be resolved. The test is described and carried out in the acceptance test, chapter 8.

8 Acceptance Test

To evaluate the complete circuit, an acceptance test has to be conducted. The purpose of the acceptance test is to ensure, that the final system fulfills the acceptance criteria. As a reminder, the high-level specification states that:

As a thereminist I want:

1. *A theremin where I can play a broad range of tunes and adjust the volume of them simultaneously with ease*
2. *A theremin where I can play the entire range without over- or under-exaggerating my movements to change the pitch and volume*
3. *A theremin where I can tune it to allow different players and other conditions to become irrelevant*
4. *A theremin with a simple interface, allowing me to control the tuning, power, ground, and output from the theremin safely*
5. *A theremin where I can replace or change broken parts to increase the life span of my theremin*

These requirements have already been introduced as more test-friendly specifications, which can be found in section 5.2 on page 53.

8.1 General Test Setup

As most of the theremins acceptance criteria are based upon a final product and interaction with a final product, there can be an almost universal test setup for all acceptance tests. The test setup consists of the following:

- 1x PITCH module
- 1x Test jig from antenna testing
- 1x LOCAL module
- 1x Faraday Cage
- 1x MIXER module
- 2x HAMEG HM7042-2 lab bench power supply (Serial no. MY40012392, Serial no. MY40012395)
- 1x Keysight DSOX1102G oscilloscope, serial number: CN57266298
- 1x Philips PM6668 high resolution counter 1GHz (Serial no. 08324) frequency counter
- 1x Ground connection to testee
- 13x Test leads with banana plugs
- 6x BNC-Coax cables
- 2x BNC T-connectors

- 1x Speaker with an internal active amplifier

The test must be conducted on a test bench. The pitch oscillator should be placed in the test jig, enabling accurate distance measurements. The local oscillator must be placed within a Faraday Cage to mitigate possible synchronization of the oscillators. Both oscillators must be connected to the MIXER. The last frequency counter should be connected to the output of the MIXER, to enable accurate readings of the outputted frequency. Furthermore, the MIXER output should be connected to the oscilloscope, so that FFT's and other frequency analyses can be performed. In figure 8.1 an illustration of the test setup can be seen:

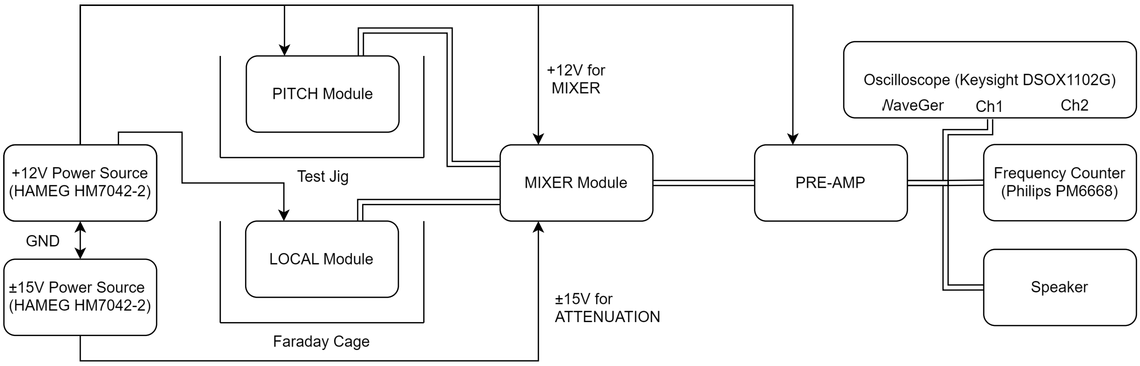


Figure 8.1: General diagram showing how the acceptance test should be set up. Notice that the PITCH module is placed in the test jig and the LOCAL module in a Faraday Cage. The double lines represent BNC-Coax cables.

Figure 8.2 shows the overhead view of how the table that the tests were conducted on was set up:

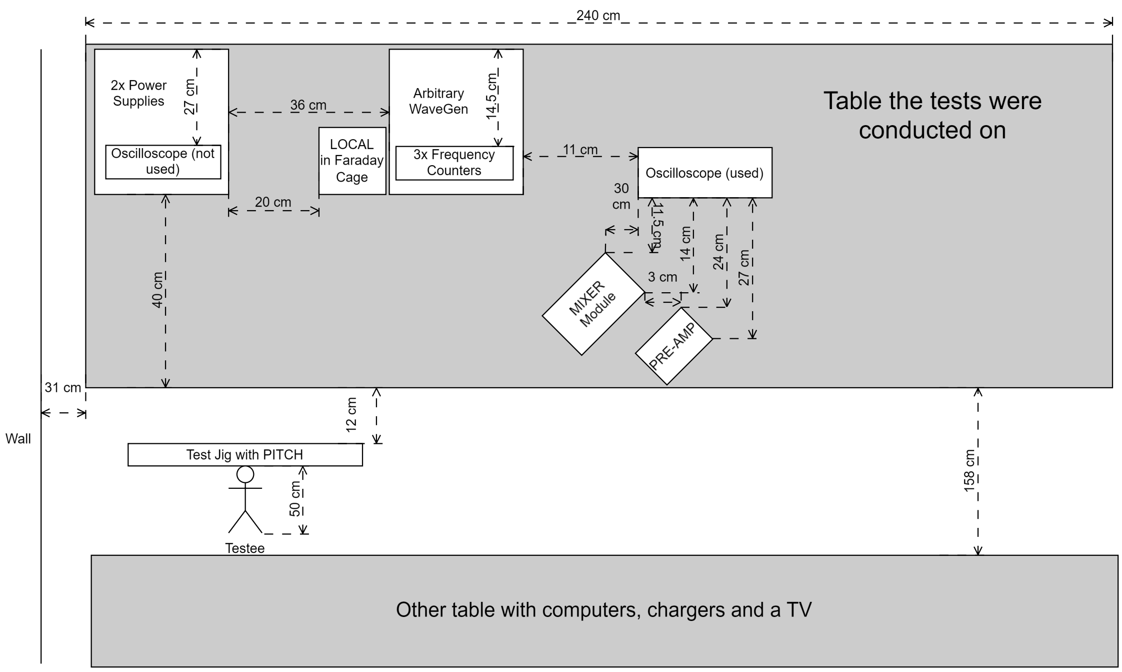


Figure 8.2: An overhead view of how the table was set up for the acceptance test. Note that the 2 power supplies and unused oscilloscope are stacked on top of one another, and the same is true for the WaveGen and 3 frequency counters.

8.1.1 Test Results

The results of the tests can be seen in figure 8.3, figure 8.4, table 8.1, and table 8.2.

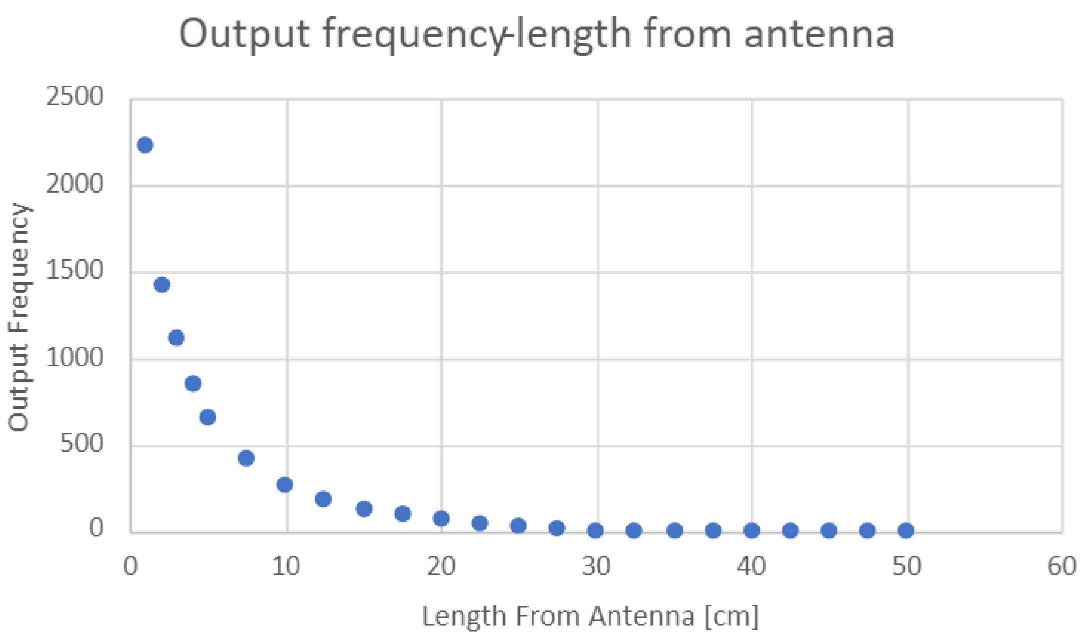


Figure 8.3: A graph showing the average output frequency of the system, when the hand is different lengths from the antenna.

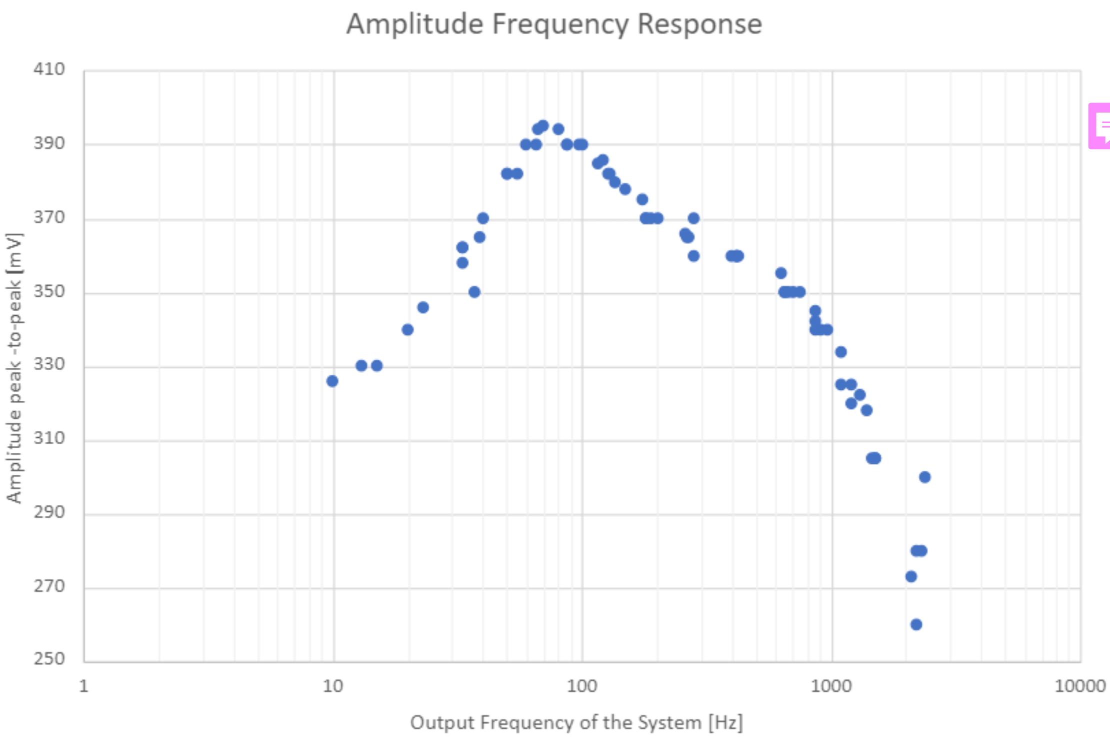


Figure 8.4: A graph showing the amplitude frequency response of the full integration.

Figure 8.4 shows that the maximum output peak-to-peak voltage never surpassed $400mV_{pp}$.

Range Test

d [cm]	1	2	3	4	5	7.5	10	12.5	15	17.5	20	22.5
f [Hz]	2240	1430	1114	848	660	417	271	185	133	96	67.8	45.4
d [cm]	25	27.5	30	32.5	35	37.5	40	42.5	45	47.5	50	
f [Hz]	30.6	11.6	4.6	0	0	0	0	0	0	0	0	

Table 8.1: A table showing the averages of the test results of the range test performed on the entire system. Where d denotes the distance between the PITCH antenna and the testees hand.

The complete set of results of the range test can be seen in appendix A.13 on page 204.

Stability Test

Seconds	f at 50cm	f at 25cm	f at 10cm
0	$57.22Hz$	$461.5Hz$	$505.0Hz$
10	$57.5Hz$	$461.1Hz$	$505.8Hz$
20	$57.9Hz$	$461.4Hz$	$505.9Hz$
30	$58.1Hz$	$461.5Hz$	$506.0Hz$
40	$58.7Hz$	$461.7Hz$	$506.4Hz$
50	$58.8Hz$	$461.9Hz$	$507.0Hz$
60	$58.9Hz$	$462.2Hz$	$507.2Hz$

Table 8.2: A table showing the results of the stability test. The results are shown as the frequency at a given distance after a given time in seconds.

Therefore the acceptance test can be made as follows, with "AC" meaning accept criteria:

8.2 Pitch and Volume

"A theremin where I can play a broad range of tunes and adjust the volume of them simultaneously with ease"

AC1: I want the opportunity to play from 30Hz to 3kHz as this is the range a piano roughly plays within.
Results: This is technically possible, but the hand has to be EXTREMELY close in order to play 3kHz. 30Hz can be easily played, as the Faraday Cage around LOCAL means that spontaneous synchronization does not occur until the frequency drops below 10Hz.

AC2: I want the distance between my hand and the pitch antenna to determine the pitch.
Results: This is met, as the hand affects the capacitance, changing the frequency of the PITCH module.

AC3: I want to easily and simultaneously adjust the volume of the pitch while playing.
Results: This is not met, as the VOLUME module wasn't developed, and adjusting the volume is a potentiometer.

AC4: The theremin should be playable without any physical contact.
Results: This is not met, as the volume is adjusted by a potentiometer.

8.3 Movement to Play the Theremin

"A theremin where I can play the entire range without over- or under-exaggerating my movements to change the pitch and volume"

AC1: When my hand is $\geq$50cm away from the pitch antenna, there should be a frequency between 0Hz and 15Hz, zero beat frequency, generated by the theremin.
Results: This is met as the oscillator synchronizes, resulting in no difference between frequencies.

AC2: When my hand is 5cm $\pm$2.5cm away from the pitch antenna, the highest specified frequency, 3kHz, should be outputted.
Results: This is not met as the hand has to be EXTREMELY close. A distance of ~2mm play 3kHz.

AC3: Adjust the entire volume range of the pitch by vertically moving my hand between 2cm and 50cm above the volume antenna.
Results: This is not met as this module was not developed.

AC4: When I'm in a neutral playing position, the placement of my hands should be slightly wider than my body's width, in line with my elbows and arms down/slightly out the side of my body.
Results: This is met, when using the test jig, for the pitch.

8.4 Control and Tuning

"A theremin where I can tune it to allow different players and other conditions to become irrelevant"

AC1: I want a way to tune the theremin pitch circuit so 50cm $\pm$2.5cm is where zero beat frequency is.
Results: Tuning of the theremin is possible, so zero beat frequency can be found.

AC2: I want a way to tune the theremin volume so that when my hand is 5cm $\pm$2.5cm away from the VOLUME antenna it will result in no output voltage, and when my hand is $\geq 50cm$$\pm$2.5cm away from the VOLUME antenna the output voltage will not increase further.
Results: This is not met, as the VOLUME module was never developed.

8.5 Interface With the Theremin

"A theremin with a simple interface, allowing me to control the tuning, power, ground, and output from the theremin safely"

AC1: There should be an interface which allows me to tune the theremin.
Results: Both LOCAL and PITCH are tuneable, but VOLUME was never developed.

AC2: The output should be a single phono connector where I can choose to attach an active loudspeaker or directly digitally record my music.
Results: This is met and the theremin can be connected to an active loudspeaker.

AC3: A simple yet effective way to ground myself to the theremin.
Results: This is met, as the current setup involves a simple wire with one end wrapped around the players' finger and the other connected to ground.

8.6 Structure and Composition of the Theremin

"A theremin where I can replace or change broken parts to increase the life span of my theremin"

AC1: The theremin should be built as subsystems to increase the overview of the theremin and subsystems should be easy to replace. There should therefore be a clear interface between them.
Results: This is met as the interface between all modules are BNC-Coax cables.

AC2: Each internal component should be leaded to enable replacement with basic soldering skills.
Results: This is met as the theremin are made of leaded components on PCBs.

8.7 Electrical Specification

AC1: The theremin should be supplied by a single 12V DC barrel jack adapter.
Results: This is not met, due to the OPAMP using a ±15V power supply.

AC2: The theremin should not contain any pre-brought circuits or IC's.
Results: This is not met as the OPAMP was introduced, but could be replaced with transistors with more time available.

AC3: The phono connector should output $\geq 900mV_{pp}$.
Results: This is not met as the output of the entire system was measured between 300-400mV, which is far below the 900mV needed to meet this criteria.

8.8 Physical Specification

AC1: The interface between the modules should be BNC-Connectors.
Results: This is met.

AC2: The theremin should be approximately the same size as the Moog Etherwave (450x160x85mm without antennas, [79]).
Results: The finished modules could easily be placed in a box with the same dimensions as the Moog Etherwave, 450x160x85mm.

8.9 Hardware Specification

AC1: At steady state, the output should not vary more than ±10Hz.
Results: As the output varied only 2.5Hz with a stationary copper plate, this criteria is met.

AC2: At steady state the final peak-to-peak of the signal should not vary more than ±5%.
Results: At steady state the peak-to-peak value of the output does not vary, so this criteria is met.

8.10 Summary of Acceptance Test

The table below is a summary of the accept-criteria that the project is based upon.

Criteria	Not fulfilled	Untested	Works in theory	Fulfilled
ACCEPT CRITERIA 8.2: Pitch and Volume				
AC1:				X
AC2:				X
AC3:	X			
AC4:	X			
ACCEPT CRITERIA 8.3 Movement to Play the Theremin				
AC1:				X
AC2:	X			
AC3:	X			
AC4:				X
ACCEPT CRITERIA 8.4 Control and Tuning				
AC1:				X
AC2:	X			
ACCEPT CRITERIA 8.5 Interface With the Theremin				
AC1:				X
AC2:				X
AC3:				X
ACCEPT CRITERIA 8.6 Structure and Composition of the Theremin				
AC1:				X
AC2:				X
ACCEPT CRITERIA 8.7 Electrical Specification				
AC1:	X			
AC2:	X			
AC3:	X			
ACCEPT CRITERIA 8.8 Physical Specification				
AC1:				X
AC2:				X
ACCEPT CRITERIA 8.9 Hardware Specification				
AC1:				X
AC2:				X

Table 8.3: Summary of accept criteria and other specifications.

9 Discussion

9.1 Late End of Analog Electronics (Course)

While this is more of a study-related subject it nevertheless has had quite the impact on this project. The course "Analog Electronics" should have ended much sooner than it did, as much of the curriculum would have benefitted the project greatly. More often than not, challenges appeared during the development and understanding of the subjects, leading to frustration and a grinding halt of the current iteration, in some cases for a few weeks. It has led to understanding and building a lot of things from scratch, through forum posts, unorthodox methods, and a practical approach over a theoretical one. Most of the time building and designing the modules was done using unorthodox methods, only to get the needed information from the course a month later. By this time, it was too late to redesign almost every part, resulting in "amateur designs". All for the exact problems to be addressed in future coursework. This misprioritization in the study schedule has led to quite a lot of thrashed designs and misunderstood functions, leading to even more thrashed designs and wasted hours. The rant could continue, but the point should have been made already: Prioritize "Analog Electronics" over other courses in the schedule.

9.2 Adhering the Study Order

As with any other semester, the given study order must be followed. This has led to section 4.5, which really isn't relevant to this project. Nevertheless, the section stands, solely to tick off a box in the study order. In general, it is obvious based on the study order and most of the "Analog Electronics" course, that this semester is dedicated to building a Hi-Fi amplifier, and not much else. This has also led to some issues in finding useful information, as barely any of the electronics used in a theremin is covered in the study order, leading to vast amounts of time spent researching and understanding various circuit designs besides understanding the courses.

9.3 Oscillator Design

The design process of the oscillator was a difficult one. In the beginning, a very low understanding of what made oscillators oscillate hindered the design process a lot. Firstly, the oscillator from EM theremin was designed and made to work. However, the group had no idea how and why the oscillator worked, so the circuit was scratched. Next, the group attempted and successfully built a local Collpitts oscillator. However when trying to convert this into the pitch oscillator other problems arose. Firstly, the group went into the design process with the idea that the antenna could be one of the capacitors and not a capacitor in parallel. This resulted in a peculiar outcome, where the oscillation would start, stop, and start again periodically in simulations. This was found to be due to the inductor value being much larger than the capacitors. The exact reason why this happened was never found, as the group just changed the design philosophy and circuit to what can be seen in the final design.

Another issue that occurred was the sensitivity of the systems. As the capacitors used have very low capacitances, the fact that the BNC-Coax cables that were available to the group, has a capacitance between 30pF - 100pF, was a big issue. In hindsight, a buffer should have been added to the system before the BNC-Connector, but in the end, this was used as an advantage, as it was used to lower the frequency of the LOCAL oscillator to make tuning easier and possible.

9.4 Mixer Design

The mixer was originally suspected to be a relatively easy and simple module as all the research done showed that it should have been simple, easy, and unproblematic to build and with very few components, see section 4.2. This did however turn out not to be true. Formulas and knowledge of how and why they worked have not been able to be procured, and a very practical approach of simulations and testing has instead been chosen to not be at a standstill. Most notable is probably the time that has been spent trying to understand the Dual-Gate MOSFET, and working with it which has been extremely difficult. A lot of people use it, and it has not been possible to obtain information as to why, and getting a deeper theoretical knowledge was impossible to achieve. It eventually proved impossible to implement because it gave a far too low output amplitude when connected to the filter. In a last-minute effort, two parallel BJTs were instead used to create both a mixer and an amplifier. It has been based on knowledge acquired for the BJT and does not translate 1:1, for reasons that definitely exist but we don't know about. But there has not been the time to do the research in-depth for it, as could have been desired, before having to realize and test it, to finish the final product.

In an extension of that, the BJT amplifier was designed relatively early on in the process, about a month before the course "Analog Electronics" began covering this part. This meant that the group could either completely re-design and understand BJT from a different angle or choose to stay with the design made, despite its flaws and that it does not align with all of the course material. But as the calculation that was made worked and was easy to understand, it was chosen to keep this, to not re-do another module with a different design.

9.5 Amplifier Design

As discussed in section 6.7, the THD is rather high for the amplifier. Unfortunately, because of time constraints, further attempts to improve the THD could not be implemented. Better biasing with either the voltage divider or diodes to try and match the I-V curve would probably improve the THD. Trying to bias the BJT proved to be more difficult than first expected, and quite a lot of time was spent on trying to bias the BJT. This is because there is no universal formula that can be used for biasing all BJTs, as the method is much more based on an engineering method than a theoretical one.

As previously mentioned, the course "Analog Electronics" introduced the relevant material very late in the design process. This meant that a large amount of time had to be spent on researching the relevant material instead of spending that time trying to design and implement it. If the relevant material had been introduced much earlier in the semester, then more time could have been spent developing most of the modules.

9.6 Lack of Data

A component that has proven much more complex than first imagined, is the antenna. At first, it was assumed that some information existed regarding the length of the antenna, size, and shape, and their influences on a theremin. Or at least that some exact data used en masse would be present. Disheartened it was quickly discovered that little to no actual data exists regarding antenna capabilities and actual well-described scientific information even less. The main source for data regarding theremins has been the forum "Theremin World" and scientific data regarding antennas provided by "dewster" and to some extent "ILYA". While the latter has not been used directly in this project, his test setup for finding capacitative effects of theremin antennas has given some insight into what to consider in such a test, [52, 57, 58]. Furthermore, "ILYA" has proposed some data and some graphs, but nothing that was suitable for this projects approach to understanding the antenna. Therefore, the only real data available to the group was that made by "dewster". While his data has given a better understanding of the antenna, his data does not compare too well with that found during testing. While this has been attributed to differences in measurements/test setups, it would still be beneficial to fully understand the differences.

Another lackluster data observation is that barely any truly scientific papers are made regarding theremins. While there exist overwhelmingly many guides, forums, depictions, and opinions about the workings of a theremin, very few of them have the same approach, and even fewer reach the same conclusions, leaving the theremin as an electronic curiosity rather than a scientific subject.

9.7 "My Theremin Works"

A hurdle that kept coming forth, was that even though many theremins are based upon the same principles and use the same methods, often even the same type of oscillator and mixer, quite a lot of other users experience tremendous trouble even accomplishing the basic functionality of a theremin. This conundrum leads to forum threads without end about how to "improve" and change a theremin, based upon narrow designs. Spice it up with ever-perseverant forum members who have firm beliefs in what is right and wrong, and most information becomes biased on some level. With the addition of most DIY guides being either too specific about insignificant parts or not specific enough, while never utilizing the exact same design, theremins continue to elude the public.

It should be clear that theremins are very much still a niche subject and with the unconscious gatekeeping that exists throughout the internet, they will remain that way. Even though most guides and forums set out to enable the average Joe the ability to build a theremin, very few take the time to describe and explain why certain design choices are made, and even fewer make proof of their theories and statements. While a working theremin isn't uncommon, it's rare to have it explained and understood.

9.8 Time Management

The project started off very well, as technical analysis started ahead of schedule and the problem analysis was made with a minimum of manhours as well. Five weeks into the project, progress began halting, as many concepts that still needed understanding simply had not been covered yet. Furthermore, modules such as the mixer and antenna began showing their true colors, as they were not anticipated to consume as much time, as they have. The mixer module especially has been an ongoing development throughout the semester, as it has occupied 1.5 group members for 11 out of the 15 weeks.

Apart from the misjudgment of time needed for certain modules, the courses stretched far into the semester as well. While being spread all over the semester, courses were also highly concentrated at the beginning of the semester, with most weeks being occupied by 60-70% courses for the first 5 weeks of the semester.

9.9 Summary

As can be read from the above, the biggest hurdle throughout the project has been the timing of the "Analog Electronics" course. Furthermore, the lack of useful information regarding theremins hasn't eased development in any way. Pairing it with a minimum of pre-existing knowledge regarding analog electronics made for a tumultuous semester. This is also exhibited clearly as all circuits made could benefit from being developed anew and improved upon.

10 | Future Work

As this project is made within a time constraint, some subjects have been left for future work. Fortunately, there can be made some clear distinguishment of what the next steps are:

10.1 Antenna Relations

Even though a big effort has been made to understand why and how the antennas perceive the world, there is still a long way to go. To make it more manageable, it has been broken down into the following subsections:

10.1.1 Size Relations

Despite the best efforts to find time for testing the capacitance of different antenna configurations, there has only been time available to test the regular pitch and volume antenna. In the future, it would be interesting to conduct similar experiments for other antenna sizes, comparing length, diameter, and shape. With such a dataset, finite element analysis would, hopefully, become redundant. Furthermore, a complete size relation datasheet could possibly help in making approximation formulas even better. Apart from helping in approximation, testing size relations could also yield a better understanding of what affects the capacitance yielded by unorthodox antenna sizes.

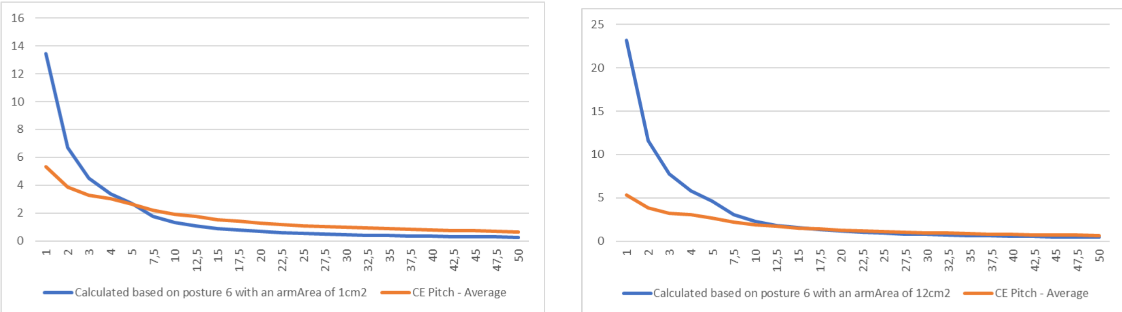
Another size relation to consider is how different body compositions of players would affect the theremin, as testing showed a clear difference of up to 1.2pF between Christian and Johan's capacitances. However, that might be more of a biological study rather than an electronic one.

10.1.2 Approximation Formula

Approximating possible capacitance relations would be of great benefit for any future work, and could possibly help explain size, environment, and testee relations. The current best approximating formula is equation 4.50 presented in section 4.6.4 on page 49. The formula takes base in "dewster"'s data and equation 4.45, however, a new suggestion would be that instead of adding the "dewster constant", the armArea is added to the total area instead, but making armArea a function dependent on the distance between the hand and antenna. The formula would therefore be equation 10.1:

$$C = \frac{\varepsilon \cdot (A + arm_{Area}(d))}{d} \tag{10.1}$$

This hypothesis is based upon figure 10.1 on page 135, which shows that manipulating armArea sufficiently could "always" enable the approximation to be equal to the measured capacitance. To achieve correct results within the first 5cm, armArea has to be made negative, thereby minimizing the area of the hand. It is therefore concluded that an approximation formula could be made using a logarithmic function describing armArea as a product of distance.



(a) In this graph, the "armArea" is set to $1cm^2$, making the approximation almost exact at a distance of 5cm.

(b) In this graph, the "armArea" is set to $12cm^2$, making the approximation almost exact at a distance of 15cm.

Figure 10.1: Examples of the approximation being almost exact at different armAreas, showcasing that if the armArea variable is changing in relation to the distance, an exact approximation is possible.

10.1.3 Environment and Testee Relations

As mentioned in section 10.1.1 the testee's composition has proven to be a factor in how the theremin plays. Furthermore, the environment has an incredibly large impact on the circuit. The oscillators were tested in the adjacent group room, 2.5 meters from the - identical - test bench used for the acceptance test. Nevertheless, the oscillating frequency changed by approximately 100kHz, simply by moving the setup and performing the same tests in a different - but almost identical room. This leaves quite a conundrum, as the frequency returns to the previously tested frequency, if the setup is moved back into the adjacent room. If time had allowed it, examining stray capacitances and other worldly interferences could possibly have given an understanding of how the environment interacts with the circuits.

A suggestion for future work would be to acquire a completely bare room, wherein iterative testing could be made, introducing different elements to the room, such as furniture, lamps, test equipment, PCs, people, etc..

10.2 Volume Module

As the volume module has been neglected completely in this project, everything regarding it has to be made in the future, to enable future users to adjust the volume without touching the theremin. To produce the volume module, it has to go through the same iterations as the local and pitch modules. This means the development of a new board/oscillator, made for a different frequency, integrating a voltage-controlled amplifier and a host of other things, as described in section 6.6 on page 108.

10.3 Power Module

Making the system complete and user-friendly would mean designing a complete power module, so that users would only have to plug the theremin into a wall socket, rather than applying test leads with banana plugs to each board. The power module should function as a power distribution unit, allocating the correct voltage and current to specific boards. The power module should furthermore include a net adapter operating from 110-240V AC.

10.4 Enclosure

An enclosure would be necessary in a final product, as users should not be able to touch the internal circuits. An enclosure would also make the theremin more userfriendly, as knobs could be made for tuning oscillators, adjusting the circuit, and having designated input/output plugs. Furthermore, the enclosure would make assembly of antennas and stands easier, as designated mounting points could be made. Apart from the practical aspects, an enclosure would also present a more aesthetically pleasing theremin.

10.5 Improving Circuitry

An obvious fault with this project was already introduced in the discussion; the lack of knowledge imposed by the lack of prioritization of the "Analog Electronics" course. As mentioned in the discussion, development could have been several times more effective, if the knowledge had been presented earlier. This has unfortunately led to subpar circuits, though they might work, their function could be improved:

10.5.1 Mixer

As discussed, the output of the mixer submodule is not as desired. The next step would be to improve the mixer itself, most notably reducing the harmonics from amplification and intermodulation distortion of the BJT-mixer. The use of an OPAMP for attenuation and buffering needs to be redesigned with BJT's to fulfill the requirement of not using IC's.

10.5.2 Oscillators

As the oscillators are a central part of the circuit, improving these is very desirable. The group found mainly 3 things that could be improved. Firstly raising the sensitivity of the pitch circuit, so the antenna can play the 30Hz - 3kHz range from 50cm - 2.5cm away from the antenna. Secondly adding a buffer before the output of both oscillators, to make sure that the following module/BNC-Coax cables do not have an impact on the frequency oscillation. Lastly, the amplifier can be redesigned, with the correct math and understanding of what impact the different resistors have on the amplification so that the output amplitude is known and can be calculated to match exactly what is desired.

10.5.3 Amplification Module

In isolation, the specified output amplitude of the PRE-AMP was met, and the THD was desired to be low, below the 1%. Unfortunately, the desired THD was not realized. Therefore for future work, the THD must be much lower than it currently is. This must be tested in isolation as the THD inevitably is worse with the rest of the modules integrated. As discussed earlier, potential methods of reducing THD could be to optimize the biasing. So either optimize the biasing with the voltage divider or try and bias with diodes, or switching amplifier type. Finally, another solution could be to have a filter or equalizer to either remove or attenuate unwanted frequencies or move the frequency response to enhance or reduce the signal.

10.6 Power Amplifier

As a final product was envisioned to be useable with a speaker, a power amplifier should be added to the circuit. This would enable the theremin to be plugged into any speaker within a later specified range, eliminating the need for an active speaker, such as the one currently in use. Apart from making the theremin more user friendly, a power amplifier would also make it more universal, enabling it to be played using a wider range of setups.

11 | Conclusion

This project aimed to make a theremin from scratch with a minimum of IC's, and has partially succeeded. Using the problem analysis, the following problem statement has paved the way for deep technical analysis and system design:

"How can a theremin, composed of a minimum of pre-produced IC circuits, be developed?"

To execute this statement, the technical analysis examined the composition of each subsystem, concluding that each element was possible to create from scratch without using IC's. This was still possible throughout system design, but not during integration, as an OPAMP became necessary during integration to ensure the signal strength from the oscillators was correct. This last addition could have been replicated without the use of an IC if time had not run out.

Nevertheless, the problem statement just required a minimum of IC's, making a single IC acceptable. Determining whether or not a theremin has actually been build is much harder to conclude. There is no doubt regarding the development of a functioning pitch oscillator and mixer capable of creating a sound similar to a theremin. However, as the physical range for playing the pitch antenna is far from the desired, combined with the lack of a volume antenna/module, one might argue that this design/product isn't a theremin. In spite of that, if the product is isolated to a mixed output between two oscillators, where one oscillator is dependent on capacitative changes between a hand and an antenna, a theremin has been made.

Looking broader than the problem statement for this project, it has proven that even "well-documented" devices such as the theremin have a lot of informational gaps. Considering that several circuits and theories utilized in the theremin are way off the study order, it becomes an even harder concept to grasp. At the beginning of the project, several group members had ideas about how the theremin would lack enough theory to fulfill the study order. During the system design phase, this thought was discarded, as the following weeks consisted of nothing but analog electronic systems. Another curiosity that was not anticipated to devour as much time as it did, was the antenna sections, as more thorough data was expected to be found, rather than having to test it ourselves. A whole study could be made regarding the antennas, therefore the testing and analysis have been constrained to the bare minimum, for having an idea of how the antenna functions in this relation.

So, to revisit the problem statement: has it been made clear how a theremin can be developed with a minimum of pre-produced IC circuits? Yes, most definitely. Has the group succeeded in developing a functioning theremin with a minimum of pre-produced IC circuits? Partially, as the modules that have been developed do work, just not optimally. And with the missing volume module, it hardly lives up to Leon Theremins' vision of a completely touchless instrument. Nonetheless, the group remains confident that with further research, development, and refinement, the current product could evolve into a fully-fledged theremin.

Bibliography

[1] Robert Moog. “ETHERWAVE THEREMIN”. In: (). URL: https://api.moogmusic.com/sites/default/files/2022-04/Etherwave-Theremin_Manual_2022.pdf.

[2] Albert Glinsky. “Theremin: Ether Music and Espionage 2000”. In: (). URL: https://monoskop.org/images/8/87/Glinsky_Albert_Theremin_Ether_Music_and_Espionage_2000.pdf.

[3] *RCATheremin.com*. URL: https://rcatheremin.com/.

[4] *How a Theremin Works | HowStuffWorks*. URL: https://electronics.howstuffworks.com/gadgets/audio-music/theremin.htm.

[5] Robert Moog. “Build the EM Theremin This classic electronic instrument gives good vibrations and excitations”. In: (). URL: https://www.cs.nmsu.edu/~rth/EMTheremin.pdf.

[6] *How to Play a Theremin | HowStuffWorks*. URL: https://electronics.howstuffworks.com/how-to-tech/how-to-play-theremin.htm.

[7] *How to Play the Theremin: 15 Steps (with Pictures) - wikiHow*. URL: https://www.wikihow.com/Play-the-Theremin.

[8] *Theremin World - Topic: Theremax Construction Project*. URL: http://www.thereminworld.com/forums/T/26395?post=177513.

[9] *Theremin World - Topic: First build, some basic questions about concepts, metal case, earthing*. URL: http://www.thereminworld.com/Forums/T/31605/first-build-some-basic-questions-about-concepts-metal-case-earthing.

[10] *Art's Theremin Page: The Minimum Theremin*. URL: https://www.theremin.us/101/101.html.

[11] Pedro Brito, David Gomez, and Patrick Mccabe. “Theremin”. In: (). URL: https://web.mit.edu/6.101/www/s2016/projects/jpmccabe_Project_Design_Presentation.pdf.

[12] *Theremin World - Topic: Volume antenna on minimum Theremin*. URL: http://www.thereminworld.com/Forums/T/26316/volume-antenna-on-minimum-theremin.

[13] Kenneth D Skeldon et al. “Theremin oscillators and oscillations”. In: *Citation: American Journal of Physics* 66 (1998), p. 1120. DOI: 10.1119/1.19004. URL: http://dx.doi.org/10.1119/1.19004http://scitation.aip.org/content/aapt/journal/ajp/66/11?ver=pdfcov.

[14] *Theremin World - Topic: On Theremin Antennas*, Real Antennas, and RF Emissions*. URL: http://www.thereminworld.com/Forums/T/32384/on-theremin-antennas-real-antennas-and-rf-emissions.

[15] *Theremin World - Topic: Let's Design and Build a (simple) Analog Theremin!* URL: http://www.thereminworld.com/Forums/T/30562/lets-design-and-build-a-simple-analog-theremin.

[16] *electromagnetism - How does a Theremin "antenna" work? - Electrical Engineering Stack Exchange*. URL: https://electronics.stackexchange.com/questions/11573/how-does-a-theremin-antenna-work.

[17] *Theremin World - Topic: I want to know everything about the antenna*. URL: http://www.thereminworld.com/Forums/T/26301/i-want-to-know-everything-about-the-antenna?Page=1.

[18] *Theremin Construction Advice*. URL: http://aetherwellen-musik.de/Theremin-Bau-Hinweise-Construction-Advice.

[19] *Theremin World - Topic: Burns B3 Deluxe Power Supply - advice please.* URL: http://www.thereminworld.com/Forums/T/27681/burns-b3-deluxe-power-supply---advice-please?Page=1.

[20] *Theremin World - Topic: 5 Watt Tube Amp for Theremin*. URL: http://www.thereminworld.com/Forums/T/27710/5-watt-tube-amp-for-theremin.

[21] *Aetherwellen Musik: General functionality of the Rockmore and Rosen Theremin*. URL: http://aetherwellen-musik.de/Theremin-Funktionsweise-Functionality.

[22] *Theremin World - Topic: Theremin Power Supply*. URL: http://www.thereminworld.com/Forums/T/28915/theremin-power-supply.

[23] *Open Theremin*. URL: https://www.gaudi.ch/OpenTheremin/index.php?option=com_content&view=article&id=99&Itemid=94.

[24] *Modular Setup*. URL: https://www.gaudi.ch/OpenTheremin/index.php/opentheremin-v4/modular-setup.

[25] *Build an open source theremin | Opensource.com*. URL: https://opensource.com/article/21/3/open-source-theremin.

[26] Aaron Danner. *Oscillators*. Mar. 2023. URL: https://www.youtube.com/playlist?list=PLXb3r5ny8_1W6sIWl6CWFOy-F31sAt9j_.

[27] Qasim Chaudhari. *The Heterodyne Principle and the Superheterodyne Receiver*. URL: https://wirelesspi.com/the-heterodyne-principle-and-the-superheterodyne-receiver/.

[28] *Pourquoi la superhétérodynie est-elle meilleure que la conversion directe?* URL: https://qastack.fr/electronics/432355/why-is-superheterodyning-better-than-direct-conversion.

[29] *Superheterodyne AM Receiver - Working with Block Diagram and Schematics*. URL: https://circuitdigest.com/article/superheterodyne-am-receiver.

[30] *60.17 – Theremin*. URL: https://web.physics.ucsb.edu/~lecturedemonstrations/Composer/Pages/60.17.html.

[31] *Understanding the Mixers Role in an RF-receiver | DigiKey*. URL: https://www.digikey.com/en/articles/understanding-the-mixers-role-in-an-rf-receiver-design.

[32] Analog Devices Inc. *ADL5350 LF to 4 GHz High Linearity Y-Mixer Data Sheet (Rev. 0)*. Tech. rep. 2008. URL: https://www.analog.com/media/en/technical-documentation/evaluation-documentation/ADL5350.pdf.

[33] *A Simple-To-Build Superhet Receiver | Electronic Design*. URL: https://www.electronicdesign.com/technologies/industrial/boards/article/21799731/a-simple-to-build-superhet-receiver.

[34] Stacy Johnson. "Active Mixer Design PathWave Advanced Design System (ADS) Taken from Keysight EEsof EDA Technical Note: Low Power Mixer Design Example Using Advanced Design System". In: (). URL: www.keysight.com.

[35] *Wayback Machine*. URL: https://web.archive.org/web/20090127021505/http://www.tech-systems-labs.com/books/hartley.pdf.

[36] *A Complete Guide to Design and Build a Hi-Fi LM3886 Amplifier - Circuit Basics*. URL: https://www.circuitbasics.com/design-hi-fi-audio-amplifier-lm3886/#Calculating-the-Component-Values.

[37] James M Fiore. "Semiconductor Devices: Semiconductor Devices: Theory and Application / 2E Theory and Application / 2E". In: (Feb. 2024).

[38] *FOUR_dot_command*. URL: https://ltwiki.org/files/LTspiceHelp.chm/html/FOUR_dot_command.htm.

[39] *Understanding THD in HiFi Audio — Nottingham HiFi*. URL: https://nottinghamhifi.co.uk/blogs/blog/understanding-thd-in-hifi-audio.

[40] *How to Reduce Distortion in Audio Amplifier Designs*. URL: https://www.linkedin.com/advice/0/what-best-ways-reduce-distortion-audio-amplifier-yaoze.

[41] *bjt - What happens when Vce is more than the value in the datasheet? - Electrical Engineering Stack Exchange*. URL: https://electronics.stackexchange.com/questions/635676/what-happens-when-vce-is-more-than-the-value-in-the-datasheet.

[42] *Electronics II-Topic 3:Frequency Response of BJT Amplifiers - YouTube*. URL: https://www.youtube.com/playlist?list=PLZvLSclgk4yIOWqeVk2i1f9diaRivg8mh.

[43] Adel Sedra & Kenneth C. Smith. *Microelectronic Circuits, International 8th edition*.

[44] Herbert L. Krauss, Charles W. Bostian, and Fredrick H. Raab. *Solid State Radio Engineering*. 1st ed. Vol. 1. Wiley, 1980, pp. 1–266.

[45] *Theremin World - Topic: Antenna length and sound frequency of a theremin.* URL: http://www.thereminworld.com/Forums/T/31781/antenna-length-and-sound-frequency-of-a-theremin?Page=0http://www.thereminworld.com/forums/T/31781?post=212057#212057.

[46] *Theremin World - Topic: Etherwave antenna dimensions*. URL: http://www.thereminworld.com/Forums/T/29258/etherwave-antenna-dimensions.

[47] *Theremin World - Topic: Theremin Linearity and Antenna Length...* URL: http://www.thereminworld.com/Forums/T/26480/theremin-linearity-and-antenna-length.

[48] *Theremin World - Topic: Let's Design and Build a (simple) Analog Theremin!* URL: http://www.thereminworld.com/Forums/T/30562/lets-design-and-build-a-simple-analog-theremin.

[49] *Theremin World - Topic: Odd question: Pitch antenna design ...* URL: http://www.thereminworld.com/Forums/T/28624/odd-question-pitch-antenna-design.

[50] *Theremin World - Topic: On Theremin Antennas*, Real Antennas, and RF Emissions*. URL: http://www.thereminworld.com/Forums/T/32384/on-theremin-antennas-real-antennas-and-rf-emissions.

[51] *Theremin World - Topic: Tuned Coil Theremin Antenna Design*. URL: http://www.thereminworld.com/Forums/T/31909/tuned-coil-theremin-antenna-design.

[52] *Theremin World - Topic: Measuring Antenna Capacitance*. URL: http://www.thereminworld.com/Forums/T/31505/measuring-antenna-capacitance?Page=3.

[53] *Theremin World - Topic: The Spring Antenna and "Perfect Linearity"*. URL: http://www.thereminworld.com/Forums/T/33001/the-spring-antenna-and-perfect-linearity?Page=1.

[54] *Theremin World - Topic: Plates, Shielding, Spread Spectrum, etc.* URL: http://www.thereminworld.com/Forums/T/29524/plates-shielding-spread-spectrum-etc.

[55] *Theremin World - Topic: What is the lowest life form that can create a sound?* URL: http://www.thereminworld.com/Forums/T/29202/what-is-the-lowest-life-form-that-can-create-a-sound.

[56] *Theremin World - Topic: Antenna question*. URL: http://www.thereminworld.com/Forums/T/33280/antenna-question.

[57] *Theremin World - Topic: Linearity Meter*. URL: http://www.thereminworld.com/Forums/T/31423/linearity-meter?Page=0.

[58] *Theremin World - Topic: Measuring Antenna Capacitance*. URL: http://www.thereminworld.com/Forums/T/31505/measuring-antenna-capacitance?Page=0.

[59] *Theremin World - Topic: Theremin's linearity between grounding on body and on Earth?* URL: http://www.thereminworld.com/Forums/T/33886/theremins-linearity-between-grounding-on-body-and-on-earth.

[60] *Theremin World - Topic: Let's Design and Build a (mostly) Digital Theremin!* URL: http://www.thereminworld.com/forums/T/28554?post=209592#209592.

[61] Michael T Brandt. "Fundamentals of Electrostatic Discharge Part Five-Device Sensitivity and Testing". In: (2010). URL: https://www.esda.org/assets/Documents/7dd436d0a3/FundamentalsPart5.pdf.

[62] *Mariagerfjord Lokalradio – FM 93,7 MHz*. URL: http://www.mflokalradio.dk/.

[63] *Denne liste opdateres ikke længere*. URL: https://www.dkradio.dk/lokalrad.htm.

[64] *Accurate Fletcher-Munson data | Page 2 | Audio Science Review (ASR) Forum*. URL: https://www.audiosciencereview.com/forum/index.php?threads/accurate-fletcher-munson-data.16495/page-2.

[65] Harvey Fletcher and W. A. Munson. "Loudness, Its definition, measurement and calculation ". In: *The Bell System Technical Journal* (Sept. 1933). URL: https://ia902909.us.archive.org/26/items/bstj12-4-377/bstj12-4-377.pdf.

[66] *What is an antenna? - NASA*. URL: https://www.nasa.gov/general/what-is-an-antenna/.

[67] *A simple guide to antenna selection based on frequency range,* URL: https://www.ahsystems.com/articles/antenna-selection.php.

[68] *Frequency and Wavelength Calculations*. URL: https://www.ahsystems.com/EMC-formulas-equations/frequency-wavelength-calculator.php.

[69] *6 LPWAN Antenna Placement Tips for Optimal Range – BehrTech*. URL: https://behrtech.com/blog/lpwan-antenna-placement/.

[70] *1/8 wave - Page 1*. URL: https://www.eevblog.com/forum/rf-microwave/18-wave/.

[71] Steven Ellingson. "Electromagnetics". In: (Aug. 2018). DOI: 10.21061/ELECTROMAGNETICS-VOL-1. URL: https://www.circuitbread.com/textbooks/electromagnetics-i/electrostatics/capacitance-of-a-coaxial-structure.

[72] *Capacitance of a Coaxial Structure | Electromagnetics I*. URL: https://www.circuitbread.com/textbooks/electromagnetics-i/electrostatics/capacitance-of-a-coaxial-structure.

[73] *5.3: Coaxial Cylindrical Capacitor - Physics LibreTexts*. URL: https://phys.libretexts.org/Bookshelves/Electricity_and_Magnetism/Electricity_and_Magnetism_(Tatum)/05%3A_Capacitors/5.03%3A_Coaxial_Cylindrical_Capacitor.

[74] *Capacitor*. URL: http://labman.phys.utk.edu/phys222core/modules/m2/capacitors.html.

[75] *5.3: Coaxial Cylindrical Capacitor - Physics LibreTexts*. URL: https://phys.libretexts.org/Bookshelves/Electricity_and_Magnetism/Electricity_and_Magnetism_(Tatum)/05%3A_Capacitors/5.03%3A_Coaxial_Cylindrical_Capacitor.

[76] David J Griffiths. "INTRODUCTION TO ELECTRODYNAMICS". In: (). URL: https://hansandcassady.org/David%20J.%20Griffiths-Introduction%20to%20Electrodynamics-Addison-Wesley%20(2012).pdf.

[77] "High-Speed Electronics in Practice". In: ().

[78] Kenneth D Skeldon et al. "Theremin oscillators and oscillations". In: *Citation: American Journal of Physics* 66 (1998), p. 1120. DOI: 10.1119/1.19004. URL: http://dx.doi.org/10.1119/1.19004http://scitation.aip.org/content/aapt/journal/ajp/66/11?ver=pdfcovhttps://isidore.co/misc/Physics%20papers%20and%20books/Zotero/storage/3837CDJ6/Skeldon%20et%20al.%20-%201998%20-%20Physics%20of%20the%20Theremin.pdf.

[79] Charlotte Sterland. *Moog Etherwave Theremin review | MusicRadar*. 2022. URL: https://www.musicradar.com/reviews/moog-etherwave-theremin.

[80] HAMEG. *HAMEG HM7042-2*. URL: https://docs.rs-online.com/1c4d/0900766b8003055e.pdf.

[81] Texas instrumernts. *TLE2074Datasheet*. URL: https://www.ti.com/lit/ds/symlink/tle2074.pdf?ts=1715418424529&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FTLE2074.

[82] *BC337-25 pdf, BC337-25 Description, BC337-25 Datasheet, BC337-25 view ::: ALLDATASHEET :::* URL: https://pdf1.alldatasheet.com/datasheet-pdf/view/2888/MOTOROLA/BC337-25.html.

[83] *Analog Filters - [PDF Document]*. URL: https://documents.pub/document/analog-filters.html?page=6.

[84] *(1) The Surprising Secret of Synchronization - YouTube*. URL: https://www.youtube.com/watch?v=t-_VPRCtiUg&ab_channel=Veritasium.

Glossary

audion A detector of radio signals developed by American inventor Lee De Forest. It is essentially a three-element vacuum tube, which is distinct from a two-electrode detector tube, as it contains a platinum grid as well, to which the incoming antenna current is applied. It was named "audion" from mixing "audio" and "ionize", [2] page 21-22.. 1

BJT Bipolar Junction Transistor. 24, 25, 31, 35, 81, 82, 86, 87, 89, 90, 92, 106, 107, 116, 131, 136

CEA Common Emitter Amplifier. 30, 32–35, 37, 87, 89

EMC Electromagnetic compatibility. 122

FFT Fast Fourier Transform. 28, 29, 51, 70, 90, 91, 103, 104, 106, 107, 111, 119, 120, 124, 200–203

FPO Fixed Pitch Oscillator. 8, 9

GBP Gain Bandwidth Product. 32

Hi-Fi High fidelity. 17

Hi-Fi amplifier High fidelity amplifiers. 18, 27, 109, 130

HLS High Level Specification. 52, 53, 108, 109

HTD mixing heterodyne mixing. 15

I-V curve Current-Voltage Characteristic. 24, 25, 116, 131

IC Integrated Circuit. i, 11, 55, 67, 81, 82, 128, 136, 138, 139

IF Intermediate frequency. 17

LO Local Oscillator. 15, 16

MOSFET Metal-Oxide-Semiconductor Field-Effect Transistor. 16, 25–27, 83, 84, 131

OPAMP Operational Amplifier. 12, 13, 18, 82, 83, 128, 136, 138

PCB Printed Circuit Board. 44, 57, 61, 71, 76, 94–97, 100, 112, 113, 128

PWM Pulse Width Modulation. 25

RCA Radio Corporation of America. 2

RF Radio Frequency. 6, 16

RMS Root Mean Square. 21

Superhet Super Heterodyne. 15–17, 56

THD Total Harmonic Distortion. 28, 29, 92, 107, 111, 113, 114, 116, 131, 136

VCA Voltage Controlled Amplifier. 108

VPO Variable Pitch Oscillator. 8, 9, 15, 16

A Appendix

A.1 Antenna Capacitance Raw Data Table

Posture 1						Posture 2					
Distance	Measured by dewster	Calculated-ArmArea	Deviation	Calculated+ArmArea	Deviation	Distance	Measured by dewster	Calculated-ArmArea	Deviation	Calculated+ArmArea	Deviation
0,05	1,255964137	2,255796156	79,61%	4,379114082	248,67%	0,05	1,255964137	2,164963268	72,37%	4,288281196	241,43%
0,75	0,926308652	1,503864104	62,35%	2,919409388	215,17%	0,75	0,926308652	1,443308845	55,81%	2,858854131	208,63%
0,1	0,720016549	1,127898078	56,65%	2,189557041	204,10%	0,1	0,720016549	1,082481634	50,34%	2,144140598	197,79%
0,125	0,585750961	0,902318462	54,04%	1,751645633	199,04%	0,125	0,585750961	0,865985307	47,84%	1,715312478	192,84%
0,15	0,490843257	0,751932052	53,19%	1,459704694	197,39%	0,15	0,490843257	0,721654423	47,02%	1,429427065	191,22%
0,175	0,418076953	0,644513187	54,16%	1,251175452	199,27%	0,175	0,418076953	0,618560934	47,95%	1,225223199	193,06%
0,2	0,367630512	0,563949039	53,40%	1,09477852	197,79%	0,2	0,367630512	0,541240817	47,22%	1,072070299	191,62%
0,225	0,327055161	0,501288035	53,27%	0,973136463	197,55%	0,225	0,327055161	0,481102948	47,10%	0,952951377	191,37%
0,25	0,295947411	0,451159231	52,45%	0,875822816	195,94%	0,25	0,295947411	0,432992654	46,31%	0,857656239	189,80%
0,3	0,250914537	0,375966026	49,84%	0,729852347	190,88%	0,3	0,250914537	0,360827211	43,80%	0,714713533	184,84%
0,35	0,222847729	0,322256594	44,61%	0,625587726	180,72%	0,35	0,222847729	0,309280467	38,79%	0,612611599	174,90%
0,4	0,204145521	0,28197452	38,12%	0,54738926	168,14%	0,4	0,204145521	0,270620409	32,56%	0,53603515	162,58%
0,45	0,191985473	0,250644017	30,55%	0,486568231	153,44%	0,45	0,191985473	0,240551474	25,30%	0,476475688	148,18%
0,5	0,185967363	0,225579616	21,30%	0,437911408	135,48%	0,5	0,185967363	0,216496327	16,42%	0,42882812	130,59%

Table A.1: Raw data table used for graphs in figures: A.1, A.2, A.3, and A.4.

Posture 3						Posture 4					
Distance	Measured by dewster	Calculated-ArmArea	Deviation	Calculated+ArmArea	Deviation	Distance	Measured by dewster	Calculated-ArmArea	Deviation	Calculated+ArmArea	Deviation
0,05	1,255964137	1,962973804	56,29%	4,08629173	225,35%	0,05	1,255964137	2,224323098	77,10%	4,347641026	246,16%
0,75	0,926308652	1,308649203	41,28%	2,724194487	194,09%	0,75	0,926308652	1,482882065	60,09%	2,898427351	212,90%
0,1	0,720016549	0,981486902	36,31%	2,043145865	183,76%	0,1	0,720016549	1,112161549	54,46%	2,173820513	201,91%
0,125	0,585750961	0,785189522	34,05%	1,634516692	179,05%	0,125	0,585750961	0,889729239	51,90%	1,73905641	196,89%
0,15	0,490843257	0,654324601	33,31%	1,362097243	177,50%	0,15	0,490843257	0,741441033	51,05%	1,449213675	195,25%
0,175	0,418076953	0,560849658	34,15%	1,167511923	179,26%	0,175	0,418076953	0,635520885	52,01%	1,24218315	197,12%
0,2	0,367630512	0,490743451	33,49%	1,021572932	177,88%	0,2	0,367630512	0,556080775	51,26%	1,086910256	195,65%
0,225	0,327055161	0,436216401	33,38%	0,908064829	177,65%	0,225	0,327055161	0,494294022	51,13%	0,96614245	195,41%
0,25	0,295947411	0,392594761	32,66%	0,817258346	176,15%	0,25	0,295947411	0,44486462	50,32%	0,869528205	193,81%
0,3	0,250914537	0,327162301	30,39%	0,681048622	171,43%	0,3	0,250914537	0,370720516	47,75%	0,724606838	188,79%
0,35	0,222847729	0,280424829	25,84%	0,583755961	161,95%	0,35	0,222847729	0,317760443	42,59%	0,621091575	178,71%
0,4	0,204145521	0,245371726	20,19%	0,510786466	150,21%	0,4	0,204145521	0,278040387	36,20%	0,543455128	166,21%
0,45	0,191985473	0,2181082	13,61%	0,454032414	136,49%	0,45	0,191985473	0,247147011	28,73%	0,483071225	151,62%
0,5	0,185967363	0,19629738	5,55%	0,408629173	119,73%	0,5	0,185967363	0,22243231	19,61%	0,434764103	133,79%

Table A.2: Raw data table used for graphs in figures: A.5, A.6, A.7, and A.8.

Posture 5						Posture 6					
Distance	Measured by dewster	Calculated-ArmArea	Deviation	Calculated+ArmArea	Deviation	Distance	Measured by dewster	Calculated-ArmArea	Deviation	Calculated+ArmArea	Deviation
0,05	1,255964137	1,898538714	51,16%	4,02185664	220,22%	0,05	1,255964137	2,51183397	99,99%	4,635151898	269,05%
0,75	0,926308652	1,265692476	36,64%	2,68123776	189,45%	0,75	0,926308652	1,67455598	80,78%	3,090101265	233,59%
0,1	0,720016549	0,949269357	31,84%	2,01092832	179,29%	0,1	0,720016549	1,255916985	74,43%	2,317575949	221,88%
0,125	0,585750961	0,759415485	29,65%	1,608742656	174,65%	0,125	0,585750961	1,004733588	71,53%	1,854060759	216,53%
0,15	0,490843257	0,632846238	28,93%	1,34061888	173,13%	0,15	0,490843257	0,83727799	70,58%	1,545050633	214,77%
0,175	0,418076953	0,542439633	29,75%	1,149101897	174,85%	0,175	0,418076953	0,717666849	71,66%	1,324329114	216,77%
0,2	0,367630512	0,474634678	29,11%	1,00546416	173,50%	0,2	0,367630512	0,627958493	70,81%	1,158787974	215,20%
0,225	0,327055161	0,421897492	29,00%	0,89374592	173,27%	0,225	0,327055161	0,558185327	70,67%	1,030033755	214,94%
0,25	0,295947411	0,379707743	28,30%	0,804371328	171,80%	0,25	0,295947411	0,502366794	69,75%	0,92703038	213,24%
0,3	0,250914537	0,316423119	26,11%	0,67030944	167,15%	0,3	0,250914537	0,418638995	66,85%	0,772525316	207,88%
0,35	0,222847729	0,271219816	21,71%	0,574550949	157,82%	0,35	0,222847729	0,358833424	61,02%	0,662164557	197,14%
0,4	0,204145521	0,237317339	16,25%	0,50273208	146,26%	0,4	0,204145521	0,313979246	53,80%	0,579393987	183,81%
0,45	0,191985473	0,210948746	9,88%	0,44687296	132,76%	0,45	0,191985473	0,279092663	45,37%	0,515016878	168,26%
0,5	0,185967363	0,189853871	2,09%	0,402185664	116,27%	0,5	0,185967363	0,251183397	35,07%	0,46351519	149,25%

Table A.3: Raw data table used for graphs in figures: A.9, A.10, A.11, and A.12.

A.2 Various Antenna Calculations

A.2.1 Area Calculations Rod Variations

$$A_{Hand} = Width_{Hand} \cdot Height_{Hand} \Rightarrow 0.01 \cdot 0.1 = 0.001 \left[m^2\right] \tag{A.1}$$

$$A_{D_1} = R_1 \cdot Height_{Hand} \Rightarrow 0.008 \cdot 0.1 = 0.0008 \left[m^2\right] \tag{A.2}$$

$$A_{D_2} = R_2 \cdot Height_{Hand} \Rightarrow 0.01 \cdot 0.1 = 0.001 \left[m^2\right] \tag{A.3}$$

$$Crescent_{Inner} = R_1 \cdot \pi \rightarrow \frac{0.008 \cdot \pi}{2} = 0.01256 \left[m^2\right] \tag{A.4}$$

$$Crescent_{Outer} = R_2 \cdot \pi \rightarrow \frac{0.01 \cdot \pi}{2} = 0.01571 \left[m^2\right] \tag{A.5}$$

$$A_{CrescentInner} = Crescent_{Inner} \cdot Height_{Hand} \Rightarrow 0.01256 \cdot 0.1 = 0.001257 \left[m^2\right] \tag{A.6}$$

$$A_{crescentOuter} = Crescent_{Outer} \cdot Height_{Hand} \Rightarrow 0.01256 \cdot 0.1 = 0.001571 \left[m^2\right] \tag{A.7}$$

$$A_{HalfMoon} = A_{CrescentInner} + A_{crescentOuter} \Rightarrow 0.001257 + 0.001571 = 0.002827 \left[m^2\right] \tag{A.8}$$

$$A_{FullMoon} = 2 \cdot A_{HalfMoon} \Rightarrow 2 \cdot 0.002827 = 0.005655 \left[m^2\right] \tag{A.9}$$

A.2.2 Capacitance Equations Using Varying Rod Area

$$\frac{A_{D_1} \cdot \varepsilon}{distance} = 14.15545284 \cdot 10^{-15}[F] \tag{A.10}$$

$$\frac{A_{D_2} \cdot \varepsilon}{distance} = 17.69431606 \cdot 10^{-15}[F] \tag{A.11}$$

$$\frac{A_{CrescentInner} \cdot \varepsilon}{distance} = 22.23533334 \cdot 10^{-15}[F] \tag{A.12}$$

$$\frac{A_{CrescentOuter} \cdot \varepsilon}{distance} = 27.79416666 \cdot 10^{-15}[F] \tag{A.13}$$

$$\frac{A_{HalfMoon} \cdot \varepsilon}{distance} = 50.02950002 \cdot 10^{-15}[F] \tag{A.14}$$

$$\frac{A_{FullMoon} \cdot \varepsilon}{distance} = 100.0590000 \cdot 10^{-15}[F] \tag{A.15}$$

where ε is given by $\varepsilon_0 \cdot \varepsilon_r$ with ε_0 being vacuum permittivity ($\frac{1}{36\pi} \cdot 10^{-}9$) and ε_r being the relative permittivity between the positive and negative sides of the capacitor.

A.2.3 Hand Posture Area Results

As mentioned in section 4.6.4, the areas are found using AutoCAD's area function.

$$Posture_1 = 12748.705mm^2 \Rightarrow 0.012748705m^2 \tag{A.16}$$

$$Posture_2 = 12235.360mm^2 \Rightarrow 0.012235360m^2 \tag{A.17}$$

$$Posture_3 = 11093.810mm^2 \Rightarrow 0.011093810m^2 \tag{A.18}$$

$$Posture_4 = 12570.834mm^2 \Rightarrow 0.012570834m^2 \tag{A.19}$$

$$Posture_5 = 10729.653mm^2 \Rightarrow 0.010729653m^2 \tag{A.20}$$

$$Posture_6 = 14195.711mm^2 \Rightarrow 0.014195711m^2 \tag{A.21}$$

A.3 Antenna Capacitance Graph Comparisons

Figure A.1: Line graph showing capacitance relations between distance and area. The blue line is "dewster"'s data, orange is without the "ArmArea" added and grey is with "ArmArea" added.

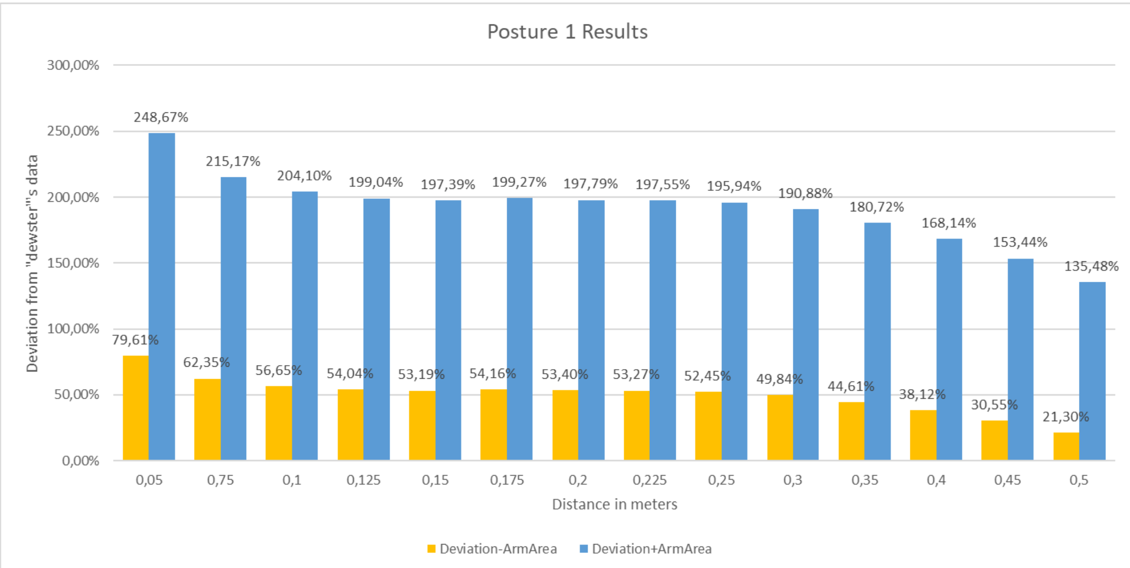


Figure A.2: Bar graph showing the deviation from "dewster"'s data in percent. The orange bars are without the "ArmArea" added and blue is with "ArmArea" added.

Figure A.3: Line graph showing capacitance relations between distance and area. The blue line is "dewster"'s data, orange is without the "ArmArea" added and grey is with "ArmArea" added.

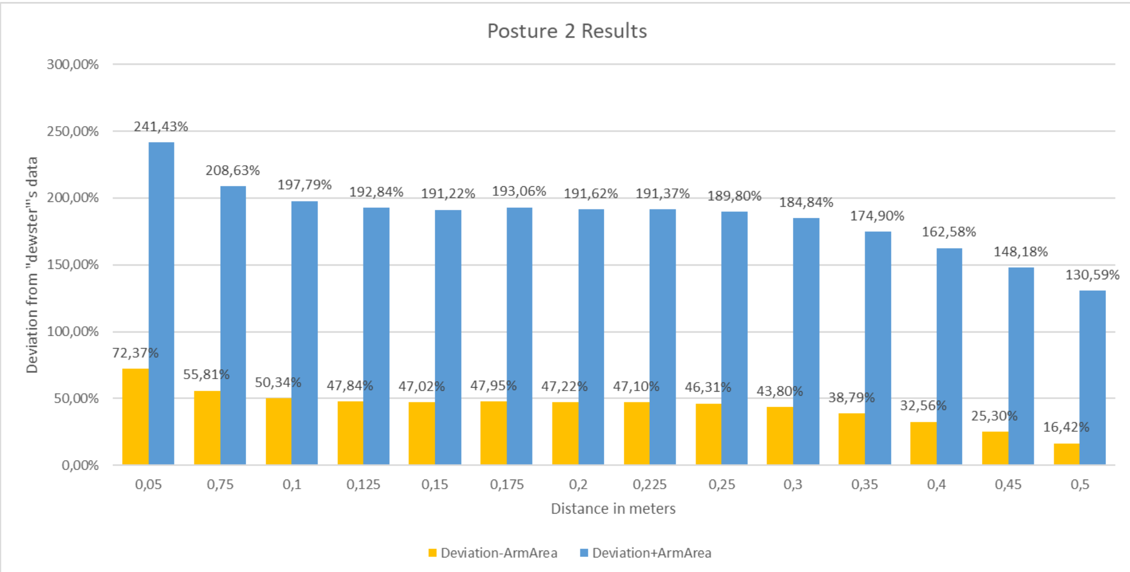


Figure A.4: Bar graph showing the deviation from "dewster"'s data in percent. The orange bars are without the "ArmArea" added and blue is with "ArmArea" added.

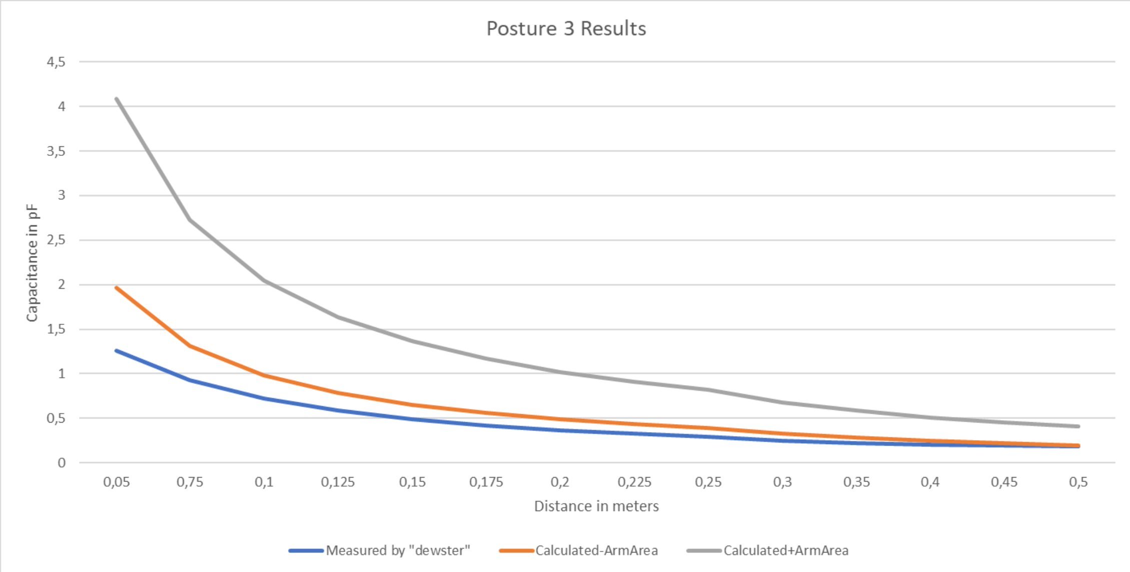


Figure A.5: Line graph showing capacitance relations between distance and area. The blue line is "dewster"'s data, orange is without the "ArmArea" added and grey is with "ArmArea" added.

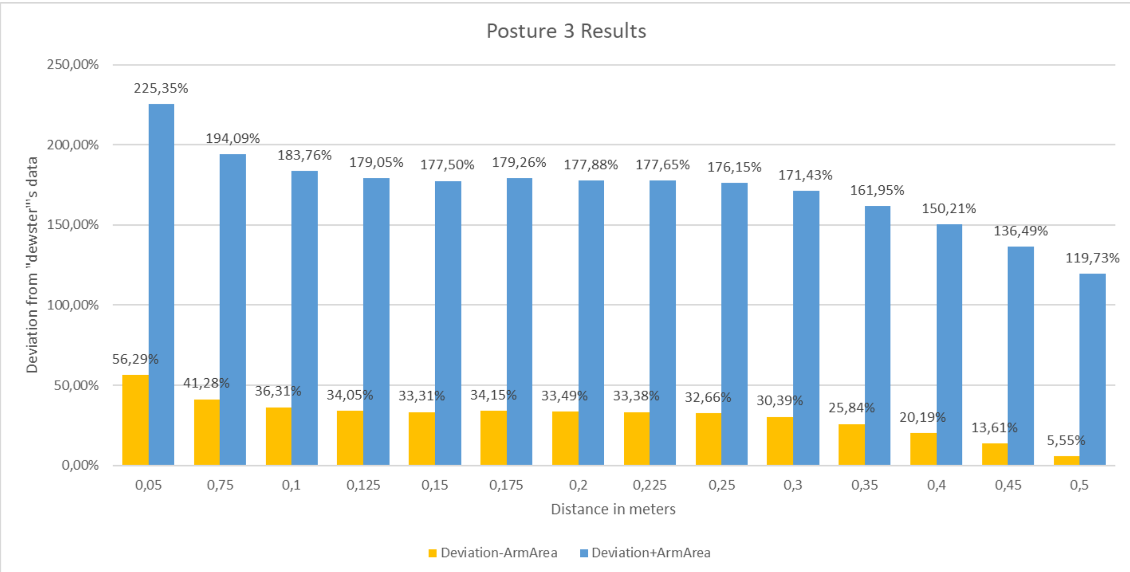


Figure A.6: Bar graph showing the deviation from "dewster"'s data in percent. The orange bars are without the "ArmArea" added and blue is with "ArmArea" added.

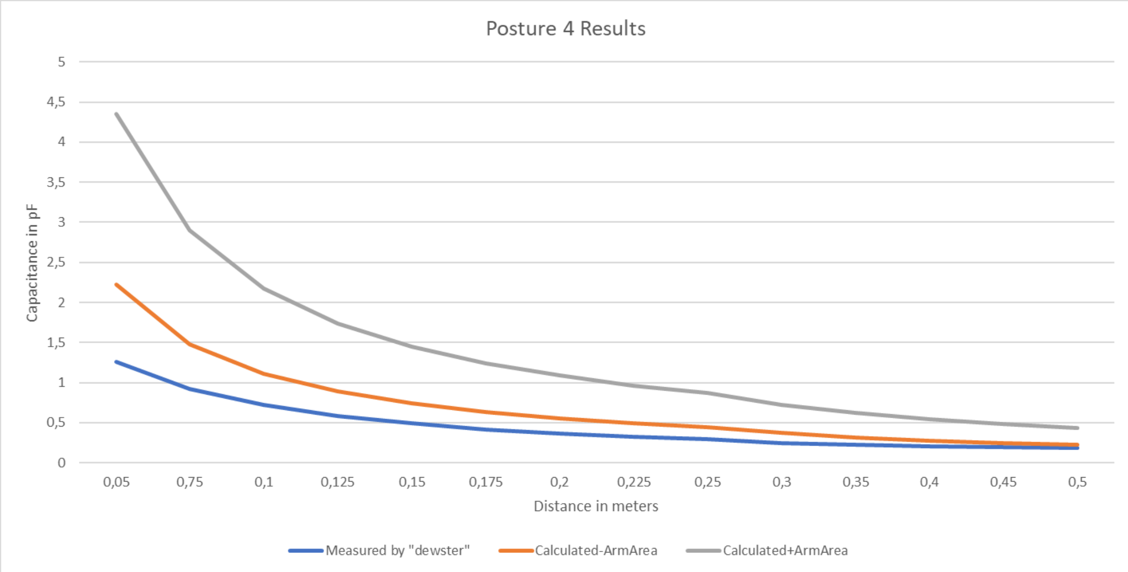


Figure A.7: Line graph showing capacitance relations between distance and area. The blue line is "dewster"'s data, orange is without the "ArmArea" added and grey is with "ArmArea" added.

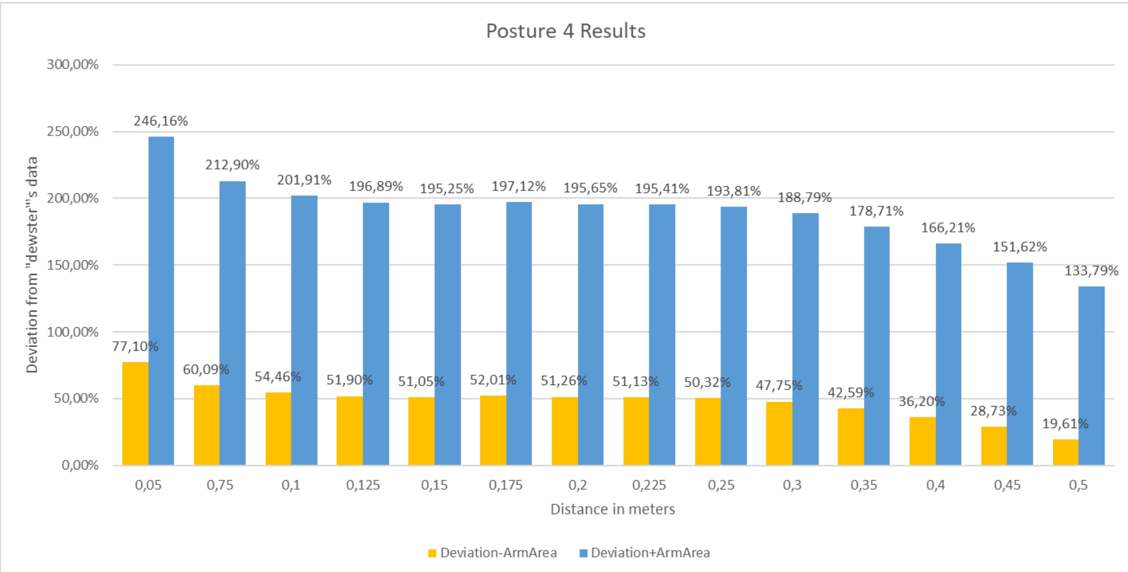


Figure A.8: Bar graph showing the deviation from "dewster"'s data in percent. The orange bars are without the "ArmArea" added and blue is with "ArmArea" added.

Figure A.9: Line graph showing capacitance relations between distance and area. The blue line is "dewster"'s data, orange is without the "ArmArea" added and grey is with "ArmArea" added.

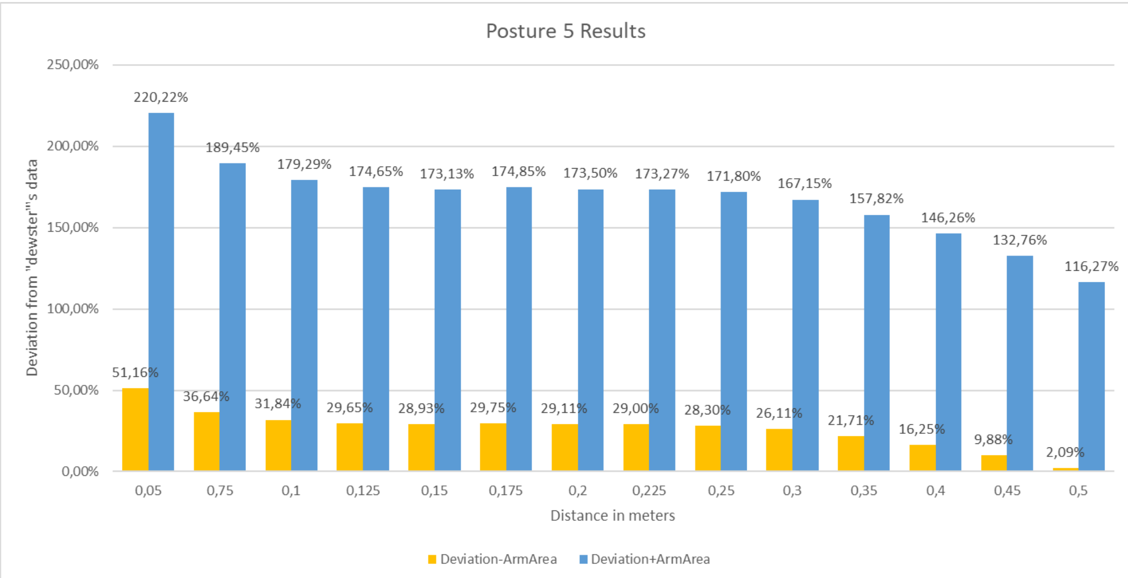


Figure A.10: Bar graph showing the deviation from "dewster"'s data in percent. The orange bars are without the "ArmArea" added and blue is with "ArmArea" added.

Figure A.11: Line graph showing capacitance relations between distance and area. The blue line is "dewster"'s data, orange is without the "ArmArea" added and grey is with "ArmArea" added.

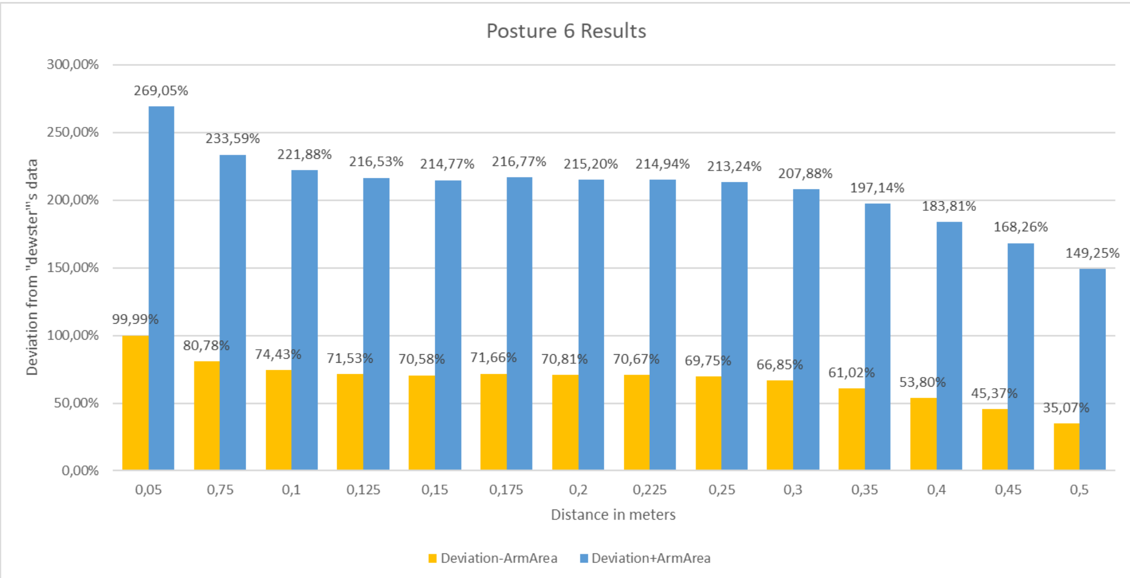


Figure A.12: Bar graph showing the deviation from "dewster"'s data in percent. The orange bars are without the "ArmArea" added and blue is with "ArmArea" added.

A.4 Antenna Capacitance Graph Comparisons With Constant "distance+0.6" added

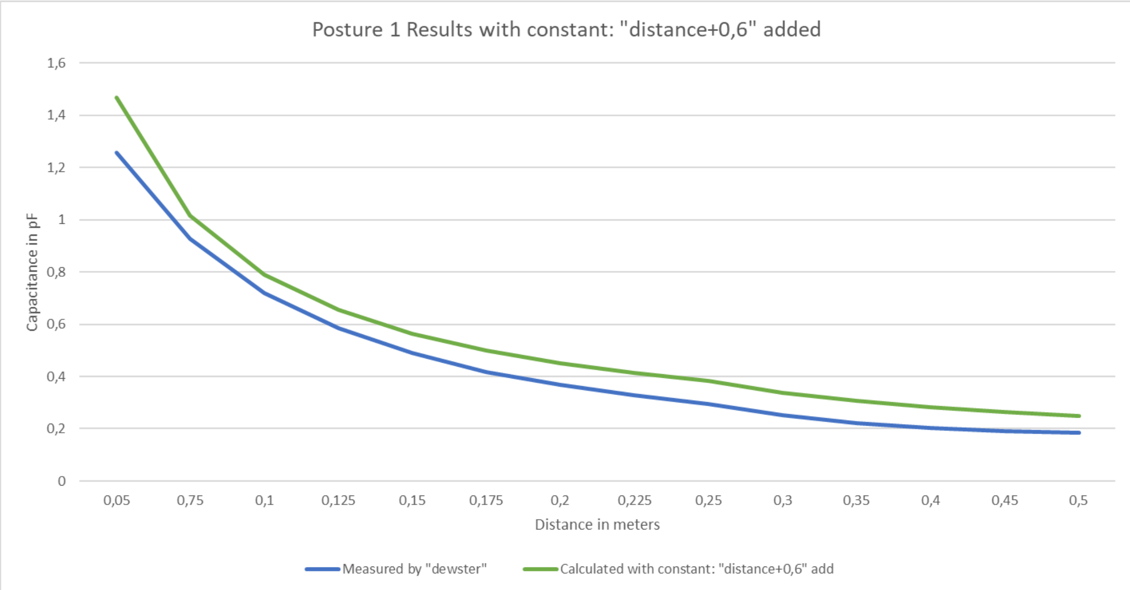


Figure A.13: Line graph showing that the addition of a constant *distance* + 0.6 yields a far better approximation for the 1st posture.

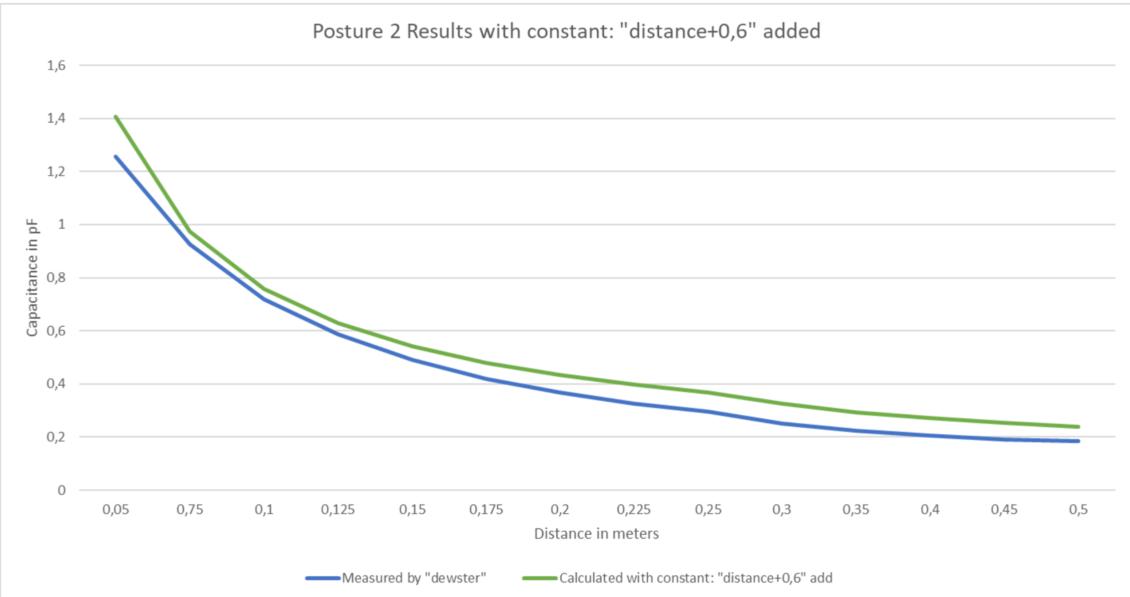


Figure A.14: Line graph showing that the addition of a constant *distance* + 0.6 yields a far better approximation for the 2nd posture.

Figure A.15: Line graph showing that the addition of a constant *distance* + 0.6 yields a far better approximation for the 3rd posture.

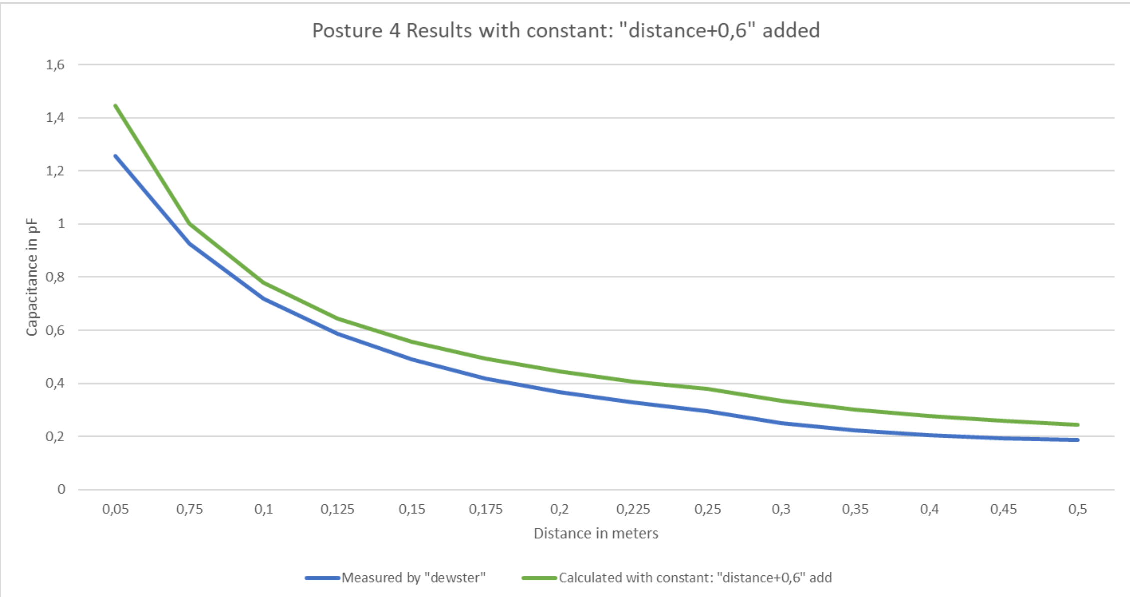


Figure A.16: Line graph showing that the addition of a constant *distance* + 0.6 yields a far better approximation for the 4th posture.

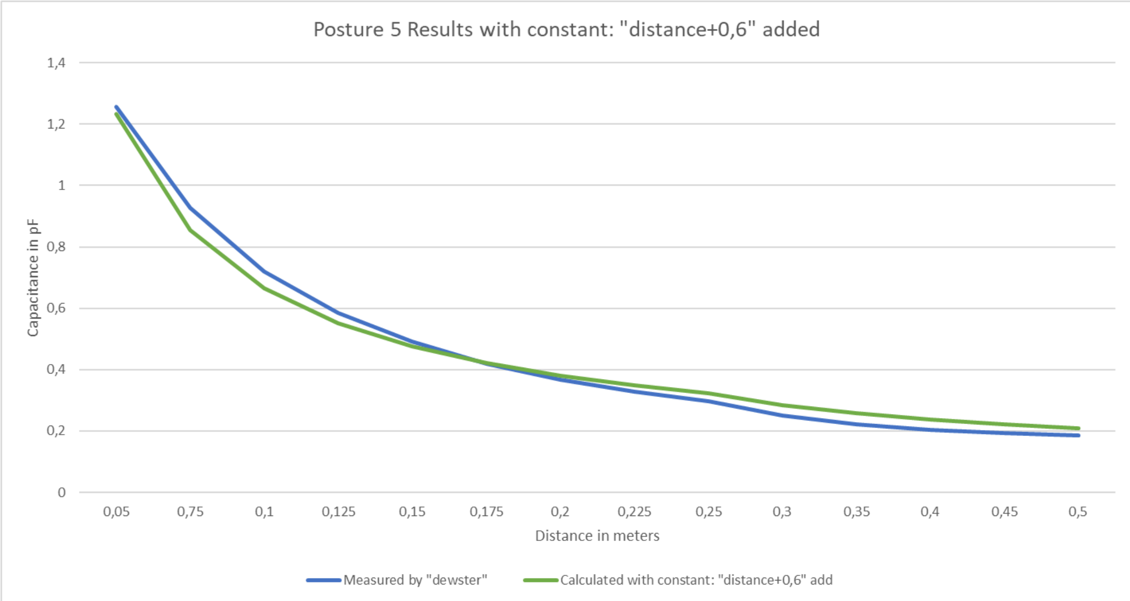


Figure A.17: Line graph showing that the addition of a constant *distance* + 0.6 yields a far better approximation for the 5th posture.

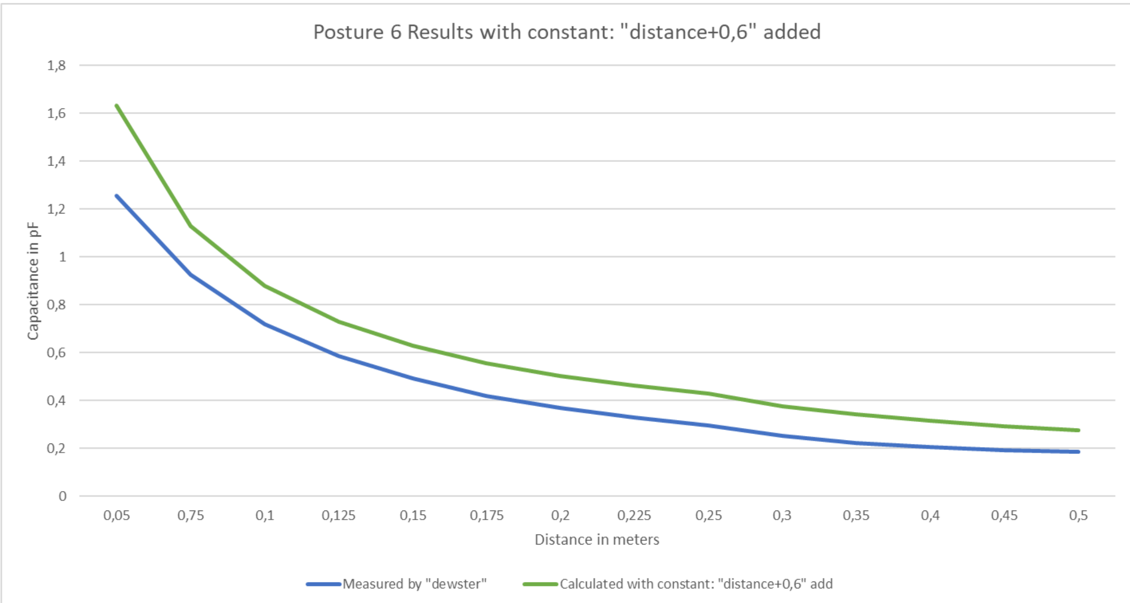


Figure A.18: Line graph showing that the addition of a constant *distance* + 0.6 yields a far better approximation for the 6th posture.

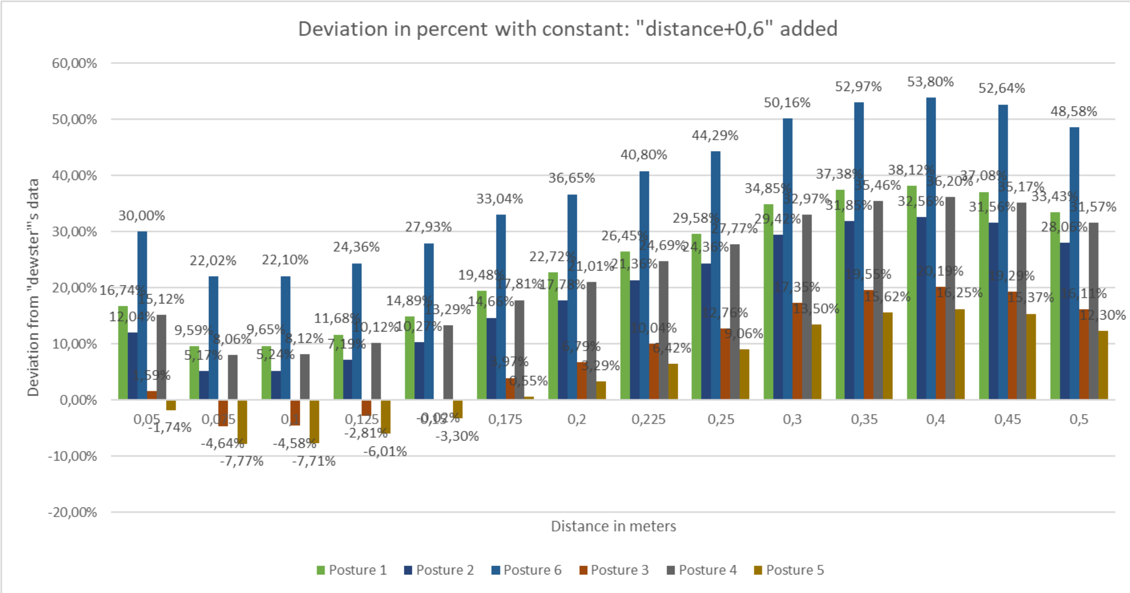
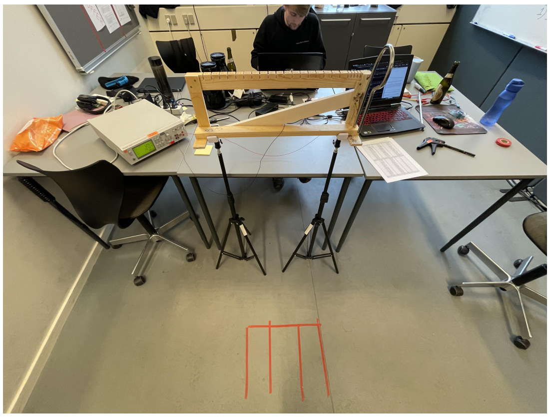
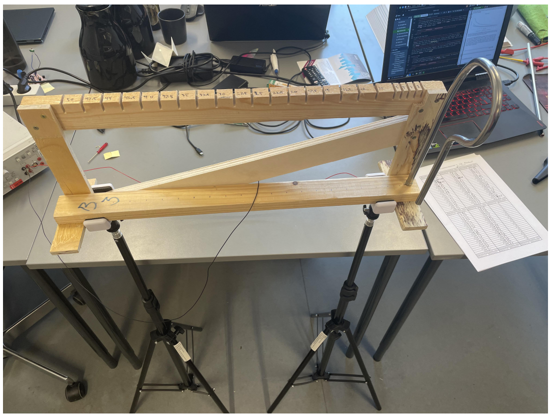


Figure A.19: Bar graph showing that the addition of a constant *distance* + 0.6 yields a far better approximation across all postures.

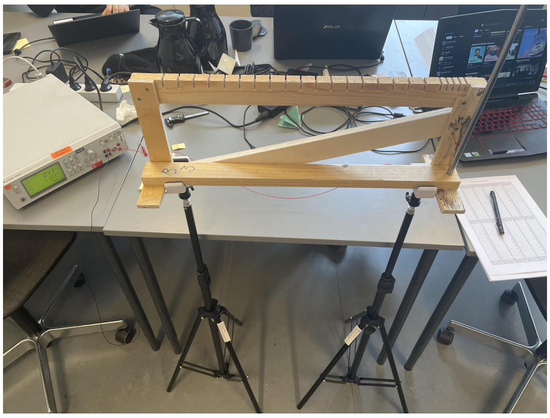
A.5 Antenna Capacitance Test Setup - Extra Photographs



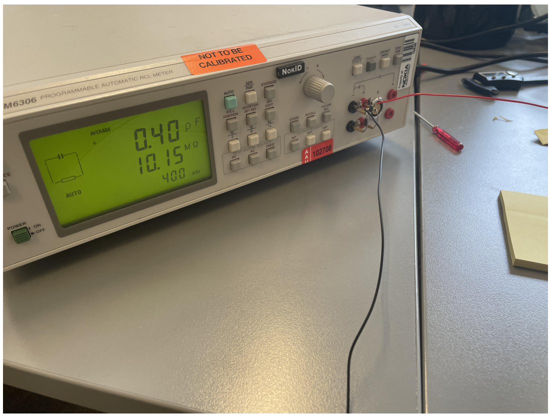
(a) Overview of noisy environment.



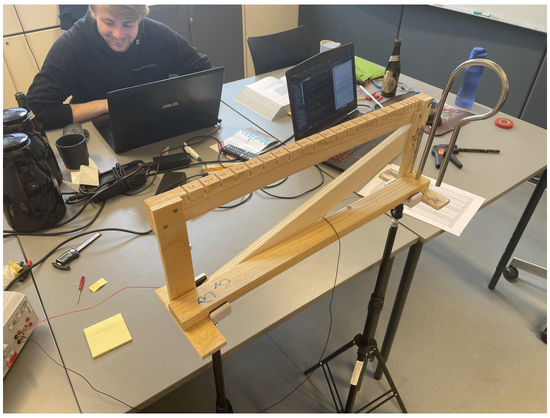
(b) Semi closeup of the jig.



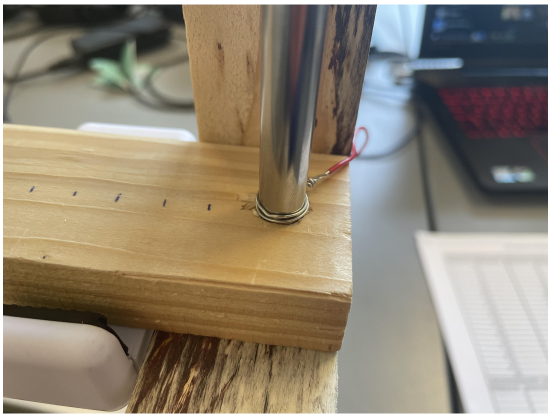
(c) Clear view of nearby "noise".



(d) Closeup of the Fluke RCL meter PM6306.



(e) More noisy environment.



(f) Connection between the RCL meter and antenna.

(g) Overview of test setup in clean environment.

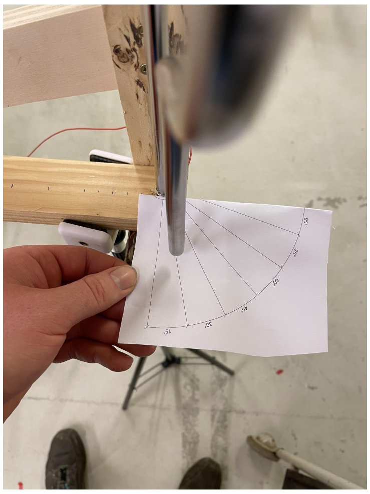
(h) Closeup of test setup in clean environment.

(i) The table used to hold test paper. Unfortunately made of a metal body with wooden boards.

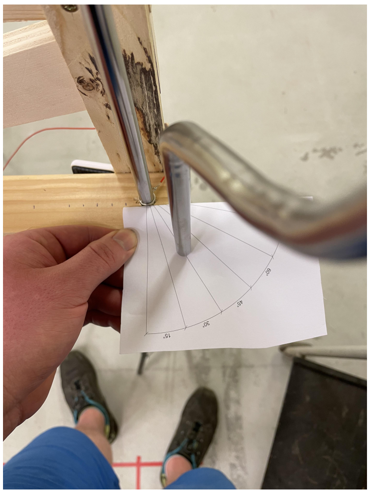
(j) Overview of test setup in clean environment - seen from the back with more background.

(k) Overview of test setup in clean environment - seen from the back.

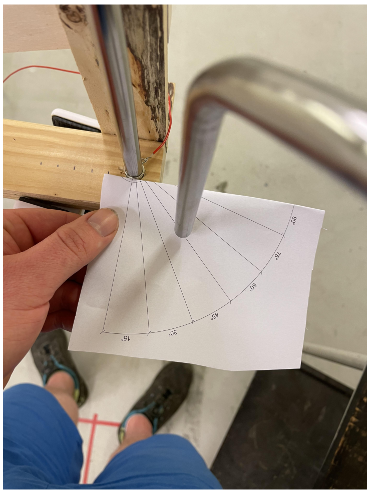
(l) Overview of test setup in clean environment.



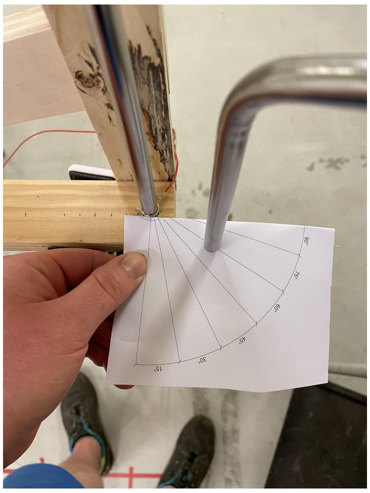
(m) Volume antenna angled 15°w.r.t. the jig - for omnidirectionality tests.



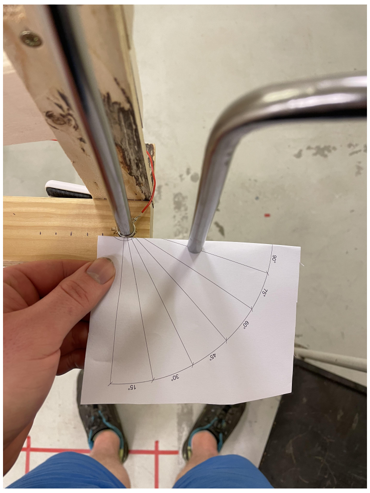
(n) Volume antenna angled 30°w.r.t. the jig - for omnidirectionality tests.



(o) Volume antenna angled 45°w.r.t. the jig - for omnidirectionality tests.

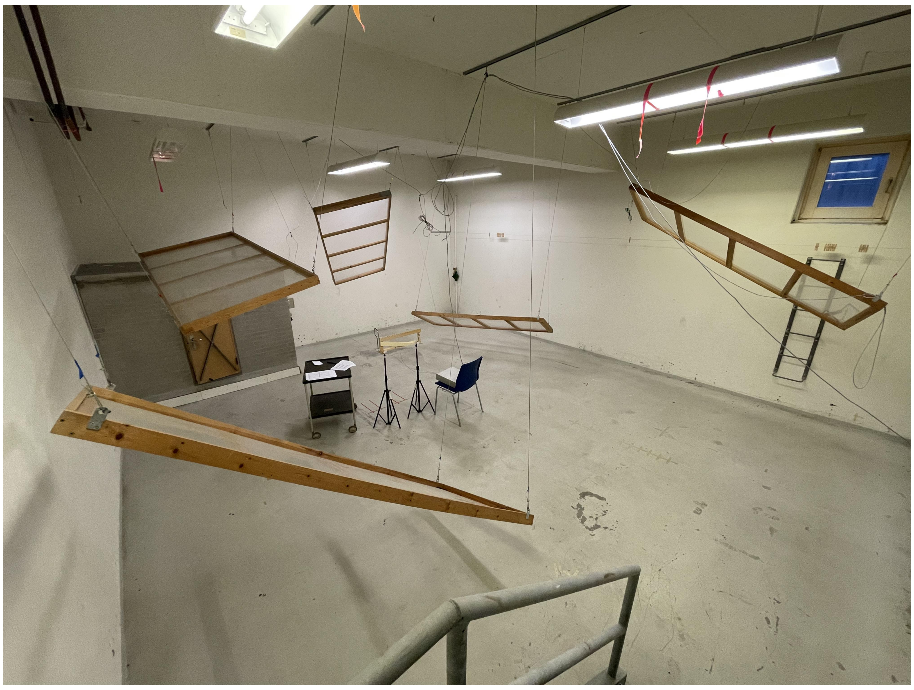


(p) Volume antenna angled 60°w.r.t. the jig - for omnidirectionality tests.



(q) Volume antenna angled 75°w.r.t. the jig - for omnidirectionality tests.

(r) Volume antenna angled 90°w.r.t. the jig - for omnidirectionality tests.



(s) Overview of the reverberation chamber.

Figure A.20: A collection of various pictures from testing.

A.6 Test Results From Actual Testing

NE Pitch - Test 1				NE Pitch - Test 2				NE Pitch - Test 3			
Dista	Measurement	Static C	2,75	Dista	Measurement	Static C	2,75	Dista	Measurement	Static C	2,75
1	8,03	5,28		1	8,1	5,35		1	7,68	4,93	
2	7,01	4,26		2	6,95	4,2		2	6,84	4,09	
3	6,34	3,59		3	6,43	3,68		3	6,12	3,37	
4	5,86	3,11		4	5,97	3,22		4	5,89	3,14	
5	5,03	2,28		5	5,68	2,93		5	5,66	2,91	
7,5	4,85	2,1		7,5	5,12	2,37		7,5	5,11	2,36	
10	4,55	1,8		10	4,87	2,12		10	4,85	2,1	
12,5	4,28	1,53		12,5	4,57	1,82		12,5	4,56	1,81	
15	4,22	1,47		15	4,39	1,64		15	4,4	1,65	
17,5	4,05	1,3		17,5	4,26	1,51		17,5	4,23	1,48	
20	3,89	1,14		20	4,15	1,4		20	4,13	1,38	
22,5	3,85	1,1		22,5	4,03	1,28		22,5	4,05	1,3	
25	3,78	1,03		25	3,9	1,15		25	3,86	1,11	
27,5	3,72	0,97		27,5	3,88	1,13		27,5	3,75	1	
30	3,67	0,92		30	3,8	1,05		30	3,69	0,94	
32,5	3,59	0,84		32,5	3,72	0,97		32,5	3,77	1,02	
35	3,59	0,84		35	3,68	0,93		35	3,56	0,81	
37,5	3,54	0,79		37,5	3,58	0,83		37,5	3,59	0,84	
40	3,48	0,73		40	3,57	0,82		40	3,58	0,83	
42,5	3,45	0,7		42,5	3,54	0,79		42,5	3,53	0,78	
45	3,38	0,63		45	3,52	0,77		45	3,48	0,73	
47,5	3,41	0,66		47,5	3,5	0,75		47,5	3,44	0,69	
50	3,37	0,62		50	3,44	0,69		50	3,46	0,71	

NE Pitch - Test 4				NE Pitch - Test 5				NE Pitch - Average			
Dista	Measurement	Static C	2,75	Dista	Measurement	Static C	2,75	Dista	Measurement	Static C	2,75
1	7,9	5,15		1	8,29	5,54		1	8	5,25	
2	7	4,25		2	7,09	4,34		2	6,978	4,228	
3	6,25	3,5		3	6,29	3,54		3	6,286	3,536	
4	5,95	3,2		4	6,03	3,28		4	5,94	3,19	
5	5,66	2,91		5	5,59	2,84		5	5,524	2,774	
7,5	5,11	2,36		7,5	5,14	2,39		7,5	5,066	2,316	
10	4,79	2,04		10	4,86	2,11		10	4,784	2,034	
12,5	4,63	1,88		12,5	4,62	1,87		12,5	4,532	1,782	
15	4,43	1,68		15	4,44	1,69		15	4,376	1,626	
17,5	4,25	1,5		17,5	4,26	1,51		17,5	4,21	1,46	
20	4,1	1,35		20	4,1	1,35		20	4,074	1,324	
22,5	3,99	1,24		22,5	3,99	1,24		22,5	3,982	1,232	
25	3,88	1,13		25	3,83	1,08		25	3,85	1,1	
27,5	3,83	1,08		27,5	3,84	1,09		27,5	3,804	1,054	
30	3,75	1		30	3,74	0,99		30	3,73	0,98	
32,5	3,68	0,93		32,5	3,67	0,92		32,5	3,686	0,936	
35	3,64	0,89		35	3,6	0,85		35	3,614	0,864	
37,5	3,58	0,83		37,5	3,58	0,83		37,5	3,574	0,824	
40	3,49	0,74		40	3,55	0,8		40	3,534	0,784	
42,5	3,53	0,78		42,5	3,49	0,74		42,5	3,508	0,758	
45	3,48	0,73		45	3,49	0,74		45	3,47	0,72	
47,5	3,5	0,75		47,5	3,44	0,69		47,5	3,458	0,708	
50	3,41	0,66		50	3,4	0,65		50	3,416	0,666	

Figure A.21

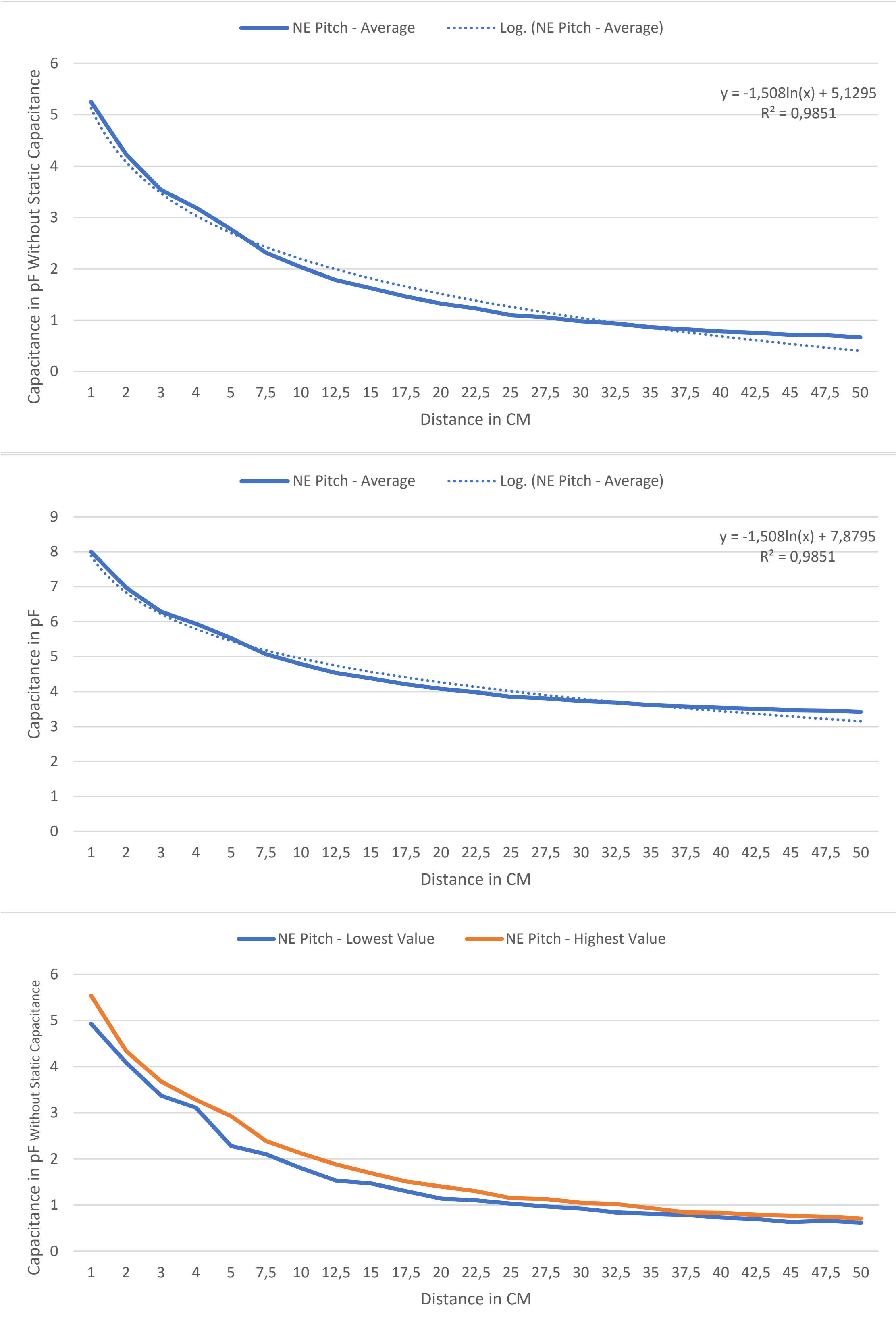

NE Pitch - Average
Log. (NE Pitch - Average)
y = -1,508ln(x) + 5,1295
R² = 0,9851
Capacitance in pF Without Static Capacitance
0 1 2 3 4 5 6
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
NE Pitch - Average
Log. (NE Pitch - Average)
y = -1,508ln(x) + 7,8795
R² = 0,9851
Capacitance in pF
0 1 2 3 4 5 6 7 8 9
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
NE Pitch - Lowest Value
NE Pitch - Highest Value
Capacitance in pF Without Static Capacitance
0 1 2 3 4 5 6
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

Figure A.22

NE Volume - Test 1				NE Volume - Test 2				NE Volume - Test 3			
Distar	Measurement	Static C	2,75	Distar	Measurement	Static C	2,75	Distar	Measurement	Static C	2,75
1	11,13	8,38		1	11,58	8,83		1	11,5	8,75	
2	9,65	6,9		2	10,03	7,28		2	9,96	7,21	
3	8,11	5,36		3	8,6	5,85		3	8,71	5,96	
4	7,38	4,63		4	7,9	5,15		4	7,72	4,97	
5	6,89	4,14		5	7,18	4,43		5	7,4	4,65	
7,5	5,75	3		7,5	6,16	3,41		7,5	6,28	3,53	
10	5,24	2,49		10	5,79	3,04		10	5,64	2,89	
12,5	4,89	2,14		12,5	5,14	2,39		12,5	5,37	2,62	
15	4,71	1,96		15	4,91	2,16		15	4,88	2,13	
17,5	4,52	1,77		17,5	4,71	1,96		17,5	4,83	2,08	
20	4,31	1,56		20	4,54	1,79		20	4,72	1,97	
22,5	4,2	1,45		22,5	4,44	1,69		22,5	4,56	1,81	
25	4,09	1,34		25	4,35	1,6		25	4,37	1,62	
27,5	3,98	1,23		27,5	4,28	1,53		27,5	4,33	1,58	
30	3,95	1,2		30	4,19	1,44		30	4,13	1,38	
32,5	4,03	1,28		32,5	4,08	1,33		32,5	4,04	1,29	
35	3,94	1,19		35	4,13	1,38		35	4,11	1,36	
37,5	3,9	1,15		37,5	4,04	1,29		37,5	4,05	1,3	
40	3,77	1,02		40	4,02	1,27		40	3,97	1,22	
42,5	3,76	1,01		42,5	3,97	1,22		42,5	4	1,25	
45	3,92	1,17		45	3,92	1,17		45	3,89	1,14	
47,5	3,79	1,04		47,5	3,92	1,17		47,5	3,94	1,19	
50	3,69	0,94		50	3,85	1,1		50	3,91	1,16	
NE Volume - Test 4				NE Volume - Test 5				NE Volume - Average			
Distar	Measurement	Static C	2,75	Distar	Measurement	Static C	2,75	Distar	Measurement	Static C	2,75
1	11,28	8,53		1	10,98	8,23		1	11,294	8,544	
2	9,29	6,54		2	9,39	6,64		2	9,664	6,914	
3	8,71	5,96		3	8,47	5,72		3	8,52	5,77	
4	7,4	4,65		4	7,93	5,18		4	7,666	4,916	
5	6,72	3,97		5	7,7	4,95		5	7,178	4,428	
7,5	6,27	3,52		7,5	6,54	3,79		7,5	6,2	3,45	
10	5,74	2,99		10	5,67	2,92		10	5,616	2,866	
12,5	5,21	2,46		12,5	5,44	2,69		12,5	5,21	2,46	
15	5,06	2,31		15	5,06	2,31		15	4,924	2,174	
17,5	4,87	2,12		17,5	4,85	2,1		17,5	4,756	2,006	
20	4,68	1,93		20	4,72	1,97		20	4,594	1,844	
22,5	4,59	1,84		22,5	4,53	1,78		22,5	4,464	1,714	
25	4,39	1,64		25	4,46	1,71		25	4,332	1,582	
27,5	4,33	1,58		27,5	4,36	1,61		27,5	4,256	1,506	
30	4,22	1,47		30	4,29	1,54		30	4,156	1,406	
32,5	4,1	1,35		32,5	4,17	1,42		32,5	4,084	1,334	
35	4,01	1,26		35	4,07	1,32		35	4,052	1,302	
37,5	3,98	1,23		37,5	4,02	1,27		37,5	3,998	1,248	
40	3,97	1,22		40	3,93	1,18		40	3,932	1,182	
42,5	3,93	1,18		42,5	3,91	1,16		42,5	3,914	1,164	
45	3,93	1,18		45	3,84	1,09		45	3,9	1,15	
47,5	3,85	1,1		47,5	3,87	1,12		47,5	3,874	1,124	
50	3,8	1,05		50	3,79	1,04		50	3,808	1,058	

Figure A.23

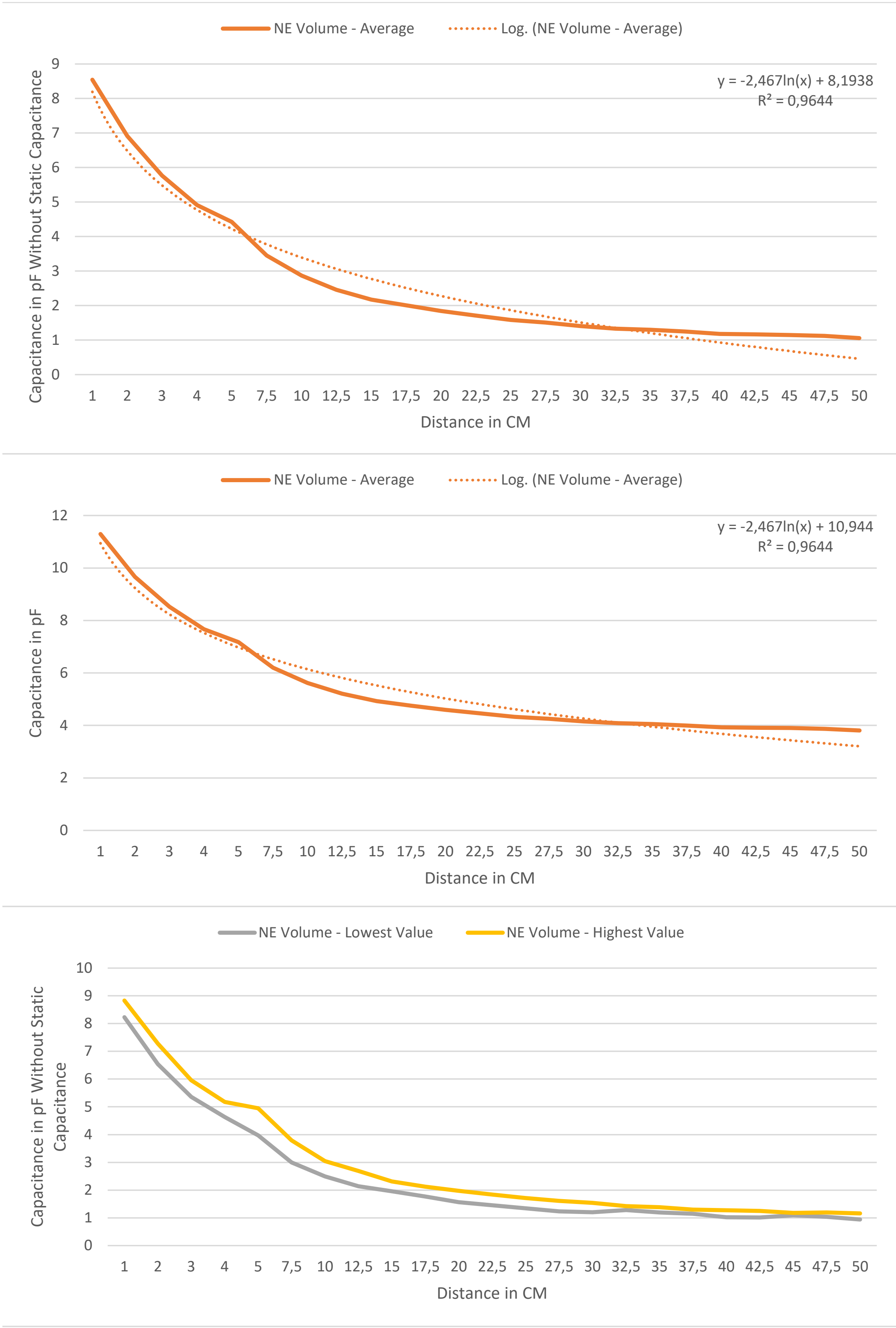

NE Volume - Average
Log. (NE Volume - Average)
y = -2,467ln(x) + 8,1938
R² = 0,9644
Capacitance in pF Without Static Capacitance
Distance in CM
NE Volume - Average
Log. (NE Volume - Average)
y = -2,467ln(x) + 10,944
R² = 0,9644
Capacitance in pF
Distance in CM
NE Volume - Lowest Value
NE Volume - Highest Value
Capacitance in pF Without Static Capacitance
Distance in CM

Figure A.24

CE Pitch - Test 1			CE Pitch - Test 2			CE Pitch - Test 3		
Distar	Measurement	Static C 3,53	Distar	Measurement	Static C 3,53	Distar	Measurement	Static C 3,53
1	9,07	5,54	1	9,09	5,56	1	8,78	5,25
2	7,37	3,84	2	7,51	3,98	2	7,25	3,72
3	6,86	3,33	3	6,72	3,19	3	6,94	3,41
4	6,46	2,93	4	6,51	2,98	4	6,64	3,11
5	6,19	2,66	5	6,23	2,7	5	6,24	2,71
7,5	5,73	2,2	7,5	5,75	2,22	7,5	5,68	2,15
10	5,39	1,86	10	5,41	1,88	10	5,49	1,96
12,5	5,23	1,7	12,5	5,27	1,74	12,5	5,38	1,85
15	4,98	1,45	15	4,99	1,46	15	5,03	1,5
17,5	4,87	1,34	17,5	4,92	1,39	17,5	4,93	1,4
20	4,73	1,2	20	4,85	1,32	20	4,83	1,3
22,5	4,65	1,12	22,5	4,68	1,15	22,5	4,69	1,16
25	4,6	1,07	25	4,6	1,07	25	4,62	1,09
27,5	4,58	1,05	27,5	4,53	1	27,5	4,55	1,02
30	4,56	1,03	30	4,48	0,95	30	4,46	0,93
32,5	4,43	0,9	32,5	4,45	0,92	32,5	4,42	0,89
35	4,39	0,86	35	4,34	0,81	35	4,44	0,91
37,5	4,35	0,82	37,5	4,26	0,73	37,5	4,28	0,75
40	4,33	0,8	40	4,29	0,76	40	4,32	0,79
42,5	4,3	0,77	42,5	4,23	0,7	42,5	4,28	0,75
45	4,28	0,75	45	4,28	0,75	45	4,2	0,67
47,5	4,21	0,68	47,5	4,22	0,69	47,5	4,18	0,65
50	4,15	0,62	50	4,21	0,68	50	4,18	0,65

CE Pitch - Test 4			CE Pitch - Test 5			CE Pitch - Average		
Distar	Measurement	Static C 3,53	Distar	Measurement	Static C 3,53	Distar	Measurement	Static C 3,53
1	8,26	4,73	1	9,2	5,67	1	8,88	5,35
2	7,44	3,91	2	7,44	3,91	2	7,402	3,872
3	6,92	3,39	3	6,54	3,01	3	6,796	3,266
4	6,77	3,24	4	6,55	3,02	4	6,586	3,056
5	6,22	2,69	5	6,12	2,59	5	6,2	2,67
7,5	5,88	2,35	7,5	5,71	2,18	7,5	5,75	2,22
10	5,62	2,09	10	5,41	1,88	10	5,464	1,934
12,5	5,43	1,9	12,5	5,25	1,72	12,5	5,312	1,782
15	5,21	1,68	15	5,03	1,5	15	5,048	1,518
17,5	5,09	1,56	17,5	4,94	1,41	17,5	4,95	1,42
20	4,91	1,38	20	4,76	1,23	20	4,816	1,286
22,5	4,82	1,29	22,5	4,74	1,21	22,5	4,716	1,186
25	4,62	1,09	25	4,65	1,12	25	4,618	1,088
27,5	4,62	1,09	27,5	4,59	1,06	27,5	4,574	1,044
30	4,53	1	30	4,51	0,98	30	4,508	0,978
32,5	4,58	1,05	32,5	4,54	1,01	32,5	4,484	0,954
35	4,51	0,98	35	4,47	0,94	35	4,43	0,9
37,5	4,46	0,93	37,5	4,43	0,9	37,5	4,356	0,826
40	4,45	0,92	40	4,31	0,78	40	4,34	0,81
42,5	4,34	0,81	42,5	4,29	0,76	42,5	4,288	0,758
45	4,33	0,8	45	4,26	0,73	45	4,27	0,74
47,5	4,26	0,73	47,5	4,24	0,71	47,5	4,222	0,692
50	4,19	0,66	50	4,14	0,61	50	4,174	0,644

Figure A.25

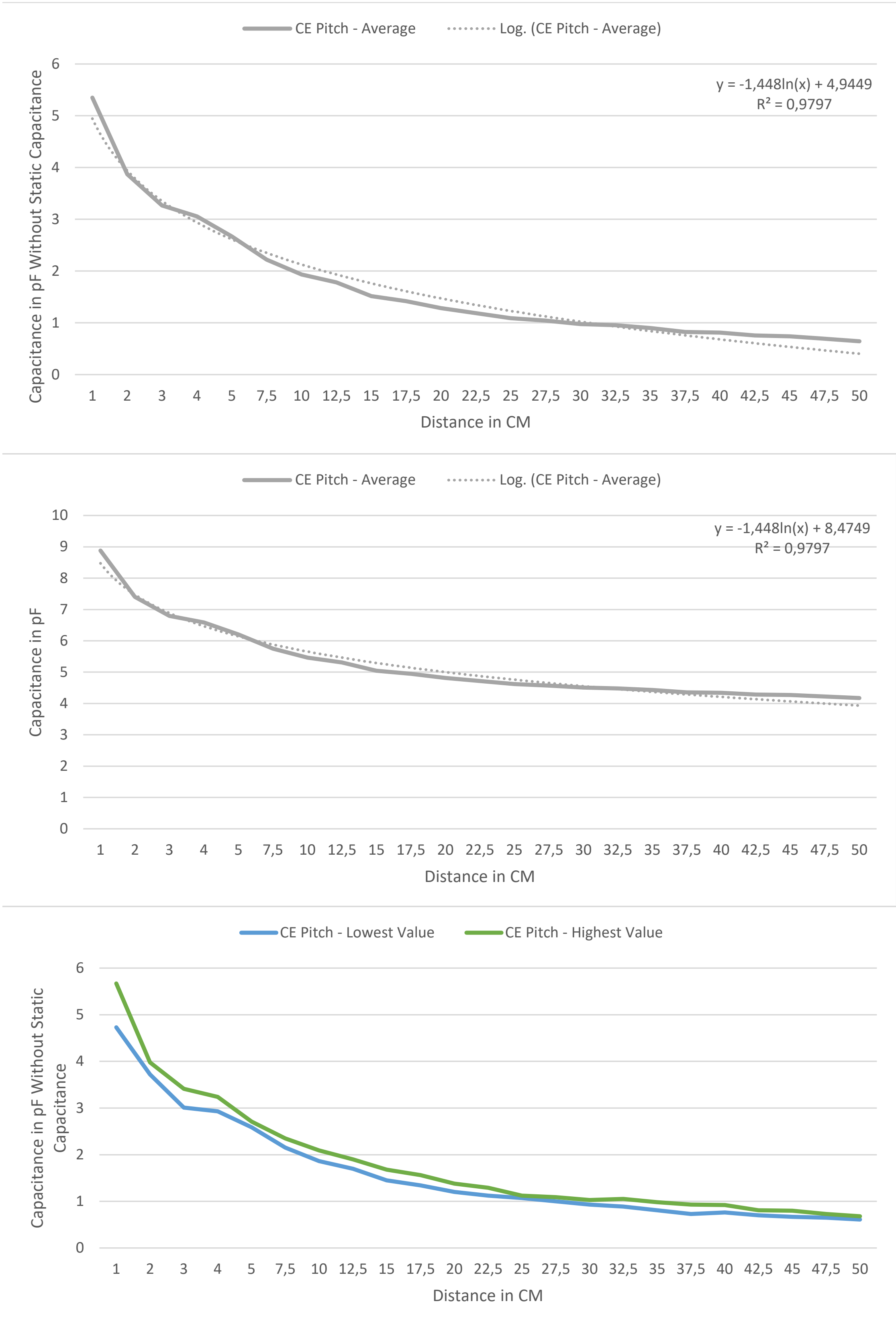

CE Pitch - Average
Log. (CE Pitch - Average)
y = -1,448ln(x) + 4,9449
R² = 0,9797
Capacitance in pF Without Static Capacitance
6
5
4
3
2
1
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
CE Pitch - Average
Log. (CE Pitch - Average)
y = -1,448ln(x) + 8,4749
R² = 0,9797
Capacitance in pF
10
9
8
7
6
5
4
3
2
1
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
CE Pitch - Lowest Value
CE Pitch - Highest Value
Capacitance in pF Without Static Capacitance
6
5
4
3
2
1
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

Figure A.26

CE Volume - Test 1				CE Volume - Test 2				CE Volume - Test 3			
Distar	Measurement	Static C	3,54	Distai	Measurement	Static C	3,54	Distar	Measurement	Static C	3,54
1	12,14	8,6		1	12,28	8,74		1	11,73	8,19	
2	10,51	6,97		2	11	7,46		2	10,15	6,61	
3	9,09	5,55		3	9,28	5,74		3	9,29	5,75	
4	8,24	4,7		4	8,76	5,22		4	8,45	4,91	
5	7,68	4,14		5	7,68	4,14		5	7,7	4,16	
7,5	6,8	3,26		7,5	6,8	3,26		7,5	6,87	3,33	
10	6,07	2,53		10	6,17	2,63		10	6,22	2,68	
12,5	5,73	2,19		12,5	5,84	2,3		12,5	5,89	2,35	
15	5,39	1,85		15	5,47	1,93		15	5,54	2	
17,5	5,18	1,47		17,5	5,33	1,79		17,5	5,72	2,18	
20	5,01	1,37		20	5,04	1,5		20	5,13	1,59	
22,5	4,91	1,25		22,5	4,99	1,45		22,5	5,01	1,47	
25	4,79	1,23		25	4,88	1,34		25	4,96	1,42	
27,5	4,77	1,12		27,5	4,78	1,24		27,5	4,77	1,23	
30	4,66	1,13		30	4,64	1,1		30	4,73	1,19	
32,5	4,67	0,99		32,5	4,56	1,02		32,5	4,62	1,08	
35	4,53	0,95		35	4,48	0,94		35	4,6	1,06	
37,5	4,49	0,93		37,5	4,54	1		37,5	4,57	1,03	
40	4,47	0,82		40	4,37	0,83		40	4,45	0,91	
42,5	4,36	0,84		42,5	4,44	0,9		42,5	4,49	0,95	
45	4,38	0,84		45	4,36	0,82		45	4,35	0,81	
47,5	4,31	0,77		47,5	4,32	0,78		47,5	4,3	0,76	
50	4,29	0,75		50	4,29	0,75		50	4,27	0,73	
CE Volume - Test 4				CE Volume - Test 5				CE Volume - Average			
Distar	Measurement	Static C	3,54	Distai	Measurement	Static C	3,54	Distar	Measurement	Static C	3,54
1	11,57	8,03		1	12,37	8,83		1	12,018	8,478	
2	10,76	7,22		2	10,52	6,98		2	10,588	7,048	
3	8,8	5,26		3	8,8	5,26		3	9,052	5,512	
4	8,45	4,91		4	8,31	4,77		4	8,442	4,902	
5	7,43	3,89		5	7,77	4,23		5	7,652	4,112	
7,5	6,48	2,94		7,5	6,71	3,17		7,5	6,732	3,192	
10	5,96	2,42		10	6,17	2,63		10	6,118	2,578	
12,5	5,64	2,1		12,5	5,8	2,26		12,5	5,78	2,24	
15	5,42	1,88		15	5,48	1,94		15	5,46	1,92	
17,5	5,23	1,69		17,5	5,32	1,78		17,5	5,322	1,782	
20	5,03	1,49		20	5,14	1,6		20	5,05	1,51	
22,5	4,94	1,4		22,5	4,94	1,4		22,5	4,934	1,394	
25	4,84	1,3		25	4,82	1,28		25	4,854	1,314	
27,5	4,8	1,26		27,5	4,73	1,19		27,5	4,748	1,208	
30	4,65	1,11		30	4,62	1,08		30	4,662	1,122	
32,5	4,56	1,02		32,5	4,64	1,1		32,5	4,582	1,042	
35	4,5	0,96		35	4,53	0,99		35	4,52	0,98	
37,5	4,51	0,97		37,5	4,46	0,92		37,5	4,51	0,97	
40	4,43	0,89		40	4,39	0,85		40	4,4	0,86	
42,5	4,42	0,88		42,5	4,37	0,83		42,5	4,42	0,88	
45	4,39	0,85		45	4,33	0,79		45	4,362	0,822	
47,5	4,33	0,79		47,5	4,3	0,76		47,5	4,312	0,772	
50	4,31	0,77		50	4,26	0,72		50	4,284	0,744	

Figure A.27

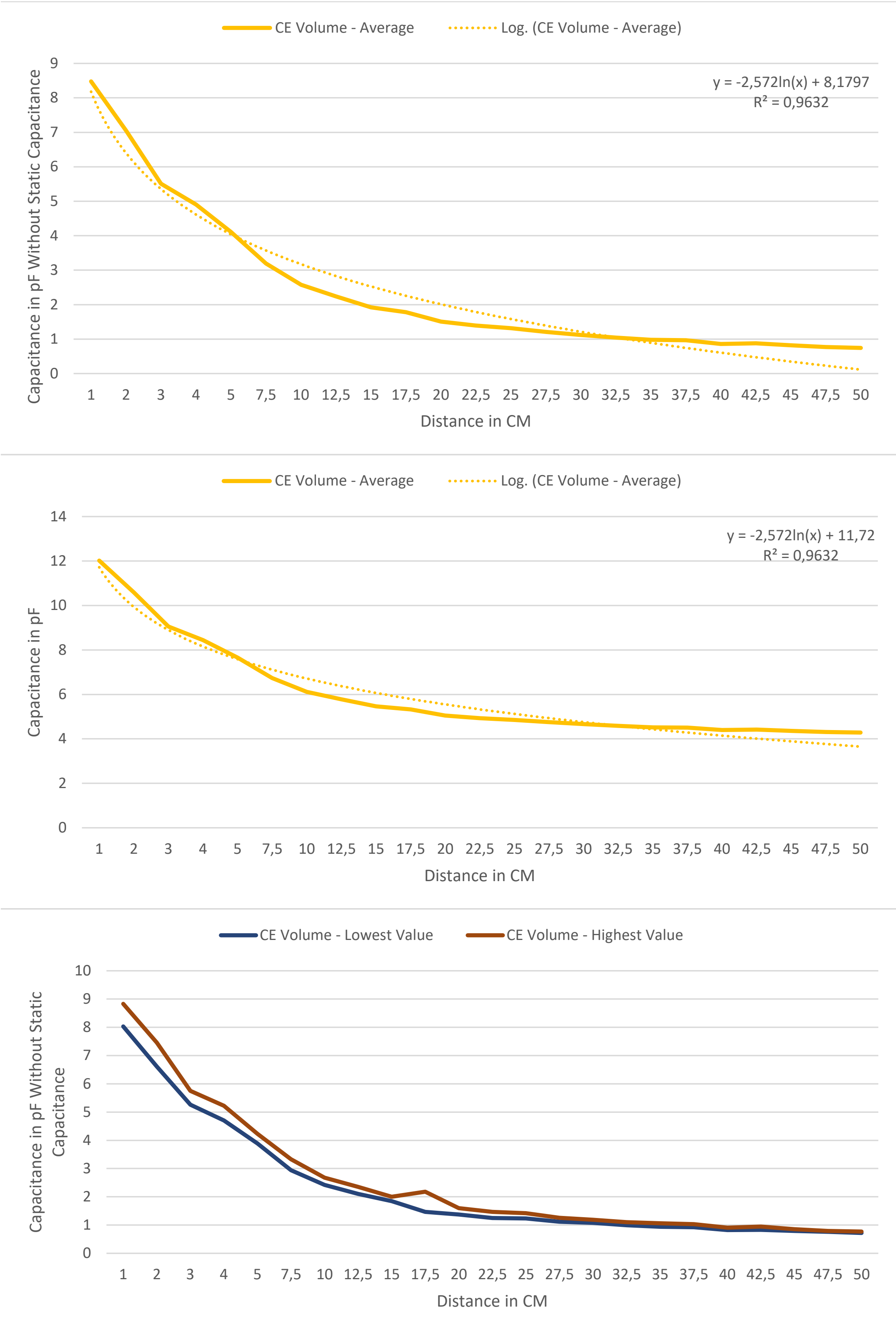

CE Volume - Average
Log. (CE Volume - Average)
y = -2,572ln(x) + 8,1797
R² = 0,9632
Capacitance in pF Without Static Capacitance
0 1 2 3 4 5 6 7 8 9
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
CE Volume - Average
Log. (CE Volume - Average)
y = -2,572ln(x) + 11,72
R² = 0,9632
Capacitance in pF
0 2 4 6 8 10 12 14
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
CE Volume - Lowest Value
CE Volume - Highest Value
Capacitance in pF Without Static Capacitance
0 1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

Figure A.28

CE Pitch Mikkel - Test 1				CE Pitch Mikkel - Test 2				CE Pitch Mikkel - Test 3			
Distar	Measurement	Static C	2,75	Distar	Measurement	Static C	2,75	Distar	Measurement	Static C	2,75
1	8,1	5,35		1	7,15	4,4		1	8,06	5,31	
2	7,54	4,79		2	6,85	4,1		2	6,9	4,15	
3	6,98	4,23		3	6,42	3,67		3	6,47	3,72	
4	6,67	3,92		4	6,2	3,45		4	6,09	3,34	
5	6,22	3,47		5	5,92	3,17		5	6,04	3,29	
7,5	5,73	2,98		7,5	5,44	2,69		7,5	5,54	2,79	
10	5,4	2,65		10	5,09	2,34		10	5,25	2,5	
12,5	5,13	2,38		12,5	4,83	2,08		12,5	4,9	2,15	
15	4,91	2,16		15	4,7	1,95		15	4,72	1,97	
17,5	4,62	1,87		17,5	4,61	1,86		17,5	4,58	1,83	
20	4,45	1,7		20	4,42	1,67		20	4,36	1,61	
22,5	4,27	1,52		22,5	4,33	1,58		22,5	4,23	1,48	
25	4,12	1,37		25	4,15	1,4		25	4,23	1,48	
27,5	4,01	1,26		27,5	4,11	1,36		27,5	4,23	1,48	
30	3,87	1,12		30	4,02	1,27		30	4,18	1,43	
32,5	4,04	1,29		32,5	3,95	1,2		32,5	4,06	1,31	
35	3,88	1,13		35	3,86	1,11		35	4,09	1,34	
37,5	3,89	1,14		37,5	3,92	1,17		37,5	4,03	1,28	
40	3,77	1,02		40	3,9	1,15		40	3,98	1,23	
42,5	3,85	1,1		42,5	3,83	1,08		42,5	3,95	1,2	
45	3,77	1,02		45	3,86	1,11		45	3,9	1,15	
47,5	3,88	1,13		47,5	3,8	1,05		47,5	3,89	1,14	
50	3,82	1,07		50	3,84	1,09		50	3,83	1,08	

CE Pitch Mikkel - Test 4				CE Pitch Mikkel - Test 5				CE Pitch Mikkel - Average			
Distar	Measurement	Static C	2,75	Distar	Measurement	Static C	2,75	Distar	Measurement	Static C	2,75
1	7,6	4,85		1	7,78	5,03		1	7,738	4,988	
2	6,93	4,18		2	7,06	4,31		2	7,056	4,306	
3	6,19	3,44		3	6,46	3,71		3	6,504	3,754	
4	5,99	3,24		4	6,14	3,39		4	6,218	3,468	
5	5,93	3,18		5	5,92	3,17		5	6,006	3,256	
7,5	5,56	2,81		7,5	5,34	2,59		7,5	5,522	2,772	
10	5,17	2,42		10	5,19	2,44		10	5,22	2,47	
12,5	4,96	2,21		12,5	4,97	2,22		12,5	4,958	2,208	
15	4,75	2		15	4,89	2,14		15	4,794	2,044	
17,5	4,63	1,88		17,5	4,69	1,94		17,5	4,626	1,876	
20	4,44	1,69		20	4,52	1,77		20	4,438	1,688	
22,5	4,35	1,6		22,5	4,42	1,67		22,5	4,32	1,57	
25	4,31	1,56		25	4,29	1,54		25	4,22	1,47	
27,5	4,24	1,49		27,5	4,24	1,49		27,5	4,166	1,416	
30	4,17	1,42		30	4,15	1,4		30	4,078	1,328	
32,5	4,1	1,35		32,5	4,07	1,32		32,5	4,044	1,294	
35	4,04	1,29		35	4,04	1,29		35	3,982	1,232	
37,5	4,03	1,28		37,5	3,99	1,24		37,5	3,972	1,222	
40	4	1,25		40	3,99	1,24		40	3,928	1,178	
42,5	3,99	1,24		42,5	4,04	1,29		42,5	3,932	1,182	
45	3,96	1,21		45	4,04	1,29		45	3,906	1,156	
47,5	4,09	1,34		47,5	4,03	1,28		47,5	3,938	1,188	
50	4,03	1,28		50	3,91	1,16		50	3,886	1,136	

Figure A.29

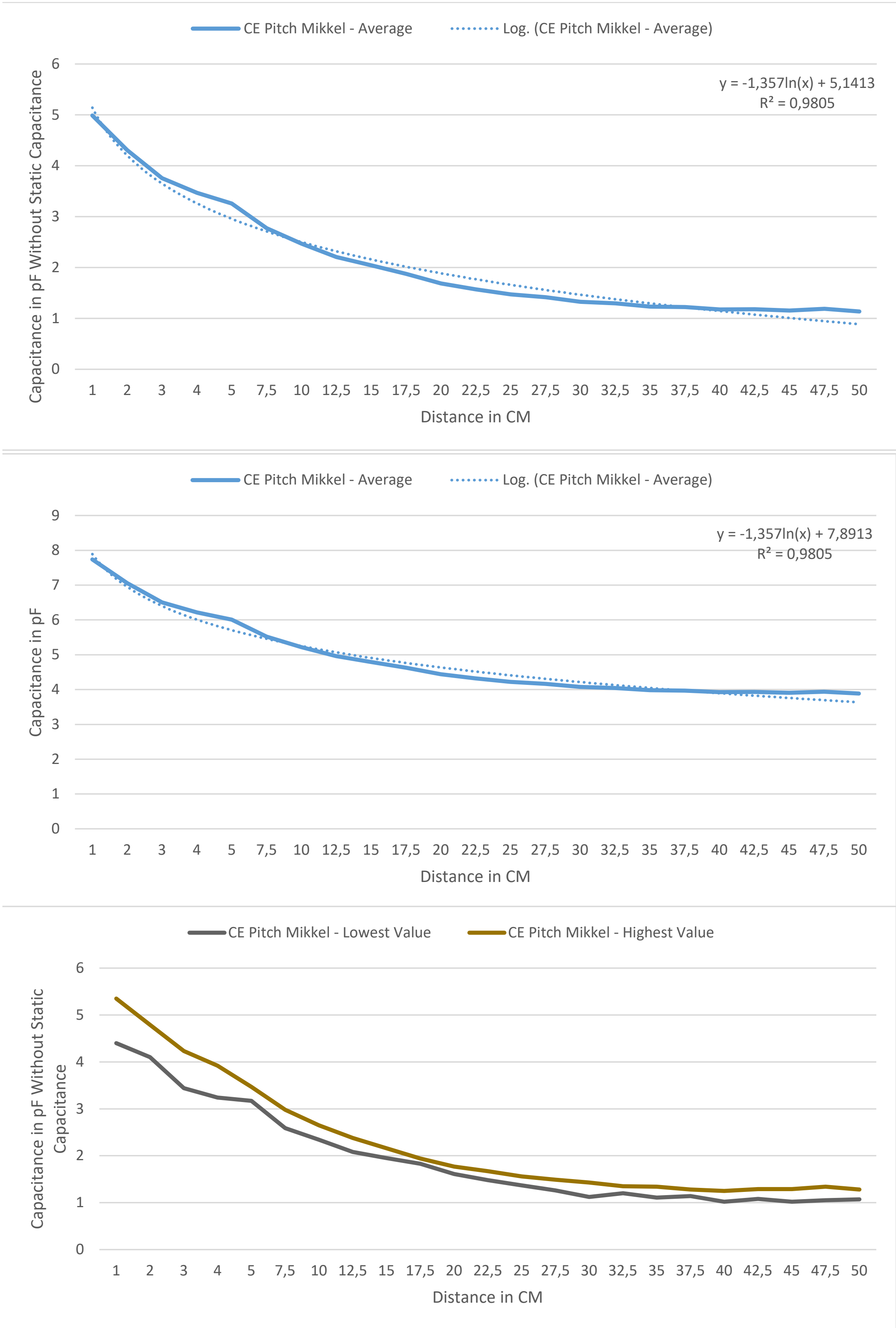
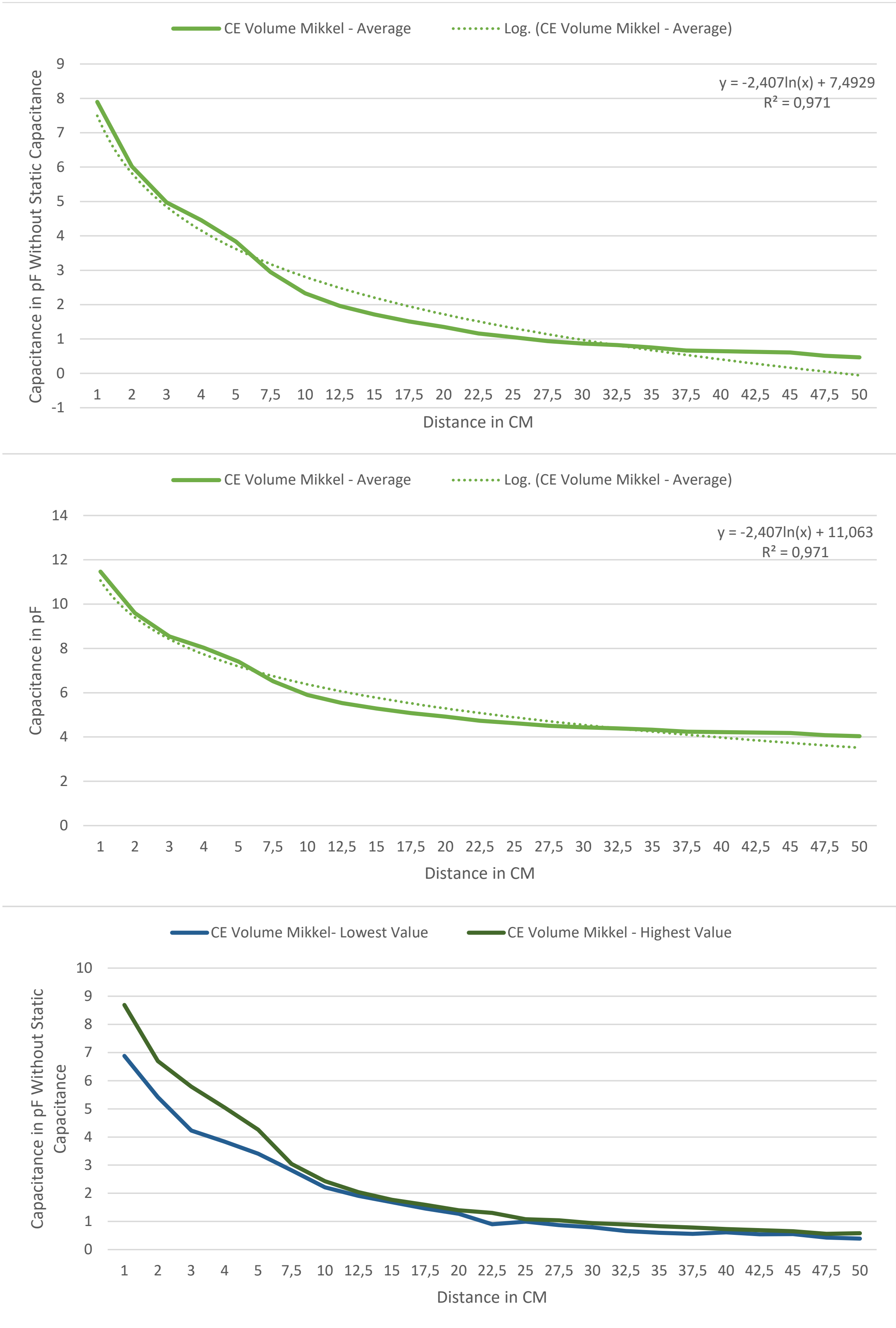

CE Pitch Mikkel - Average
Log. (CE Pitch Mikkel - Average)
y = -1,357ln(x) + 5,1413
R² = 0,9805
Capacitance in pF Without Static Capacitance
0
1
2
3
4
5
6
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
CE Pitch Mikkel - Average
Log. (CE Pitch Mikkel - Average)
y = -1,357ln(x) + 7,8913
R² = 0,9805
Capacitance in pF
0
1
2
3
4
5
6
7
8
9
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
CE Pitch Mikkel - Lowest Value
CE Pitch Mikkel - Highest Value
Capacitance in pF Without Static Capacitance
0
1
2
3
4
5
6
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

Figure A.30

CE Volume Mikkel - Test 1				CE Volume Mikkel - Test 2				CE Volume Mikkel - Test 3			
Distar	Measurement	Static C	3,57	Distar	Measurement	Static C	3,57	Distar	Measurement	Static C	3,57
1	11,35	7,78		1	12,12	8,55		1	12,26	8,69	
2	10,27	6,7		2	10,24	6,67		2	9,3	5,73	
3	8,51	4,94		3	9,36	5,79		3	8,94	5,37	
4	7,98	4,41		4	8,61	5,04		4	8,5	4,93	
5	7,35	3,78		5	7,83	4,26		5	7,44	3,87	
7,5	6,57	3		7,5	6,61	3,04		7,5	6,59	3,02	
10	5,92	2,35		10	5,94	2,37		10	6	2,43	
12,5	5,54	1,97		12,5	5,54	1,97		12,5	5,61	2,04	
15	5,31	1,74		15	5,27	1,7		15	5,34	1,77	
17,5	5,08	1,51		17,5	5,04	1,47		17,5	5,16	1,59	
20	4,97	1,4		20	4,84	1,27		20	4,97	1,4	
22,5	4,87	1,3		22,5	4,76	1,19		22,5	4,8	1,23	
25	4,62	1,05		25	4,62	1,05		25	4,65	1,08	
27,5	4,52	0,95		27,5	4,61	1,04		27,5	4,44	0,87	
30	4,5	0,93		30	4,51	0,94		30	4,36	0,79	
32,5	4,44	0,87		32,5	4,41	0,84		32,5	4,46	0,89	
35	4,34	0,77		35	4,36	0,79		35	4,36	0,79	
37,5	4,21	0,64		37,5	4,26	0,69		37,5	4,23	0,66	
40	4,18	0,61		40	4,22	0,65		40	4,18	0,61	
42,5	4,11	0,54		42,5	4,26	0,69		42,5	4,22	0,65	
45	4,12	0,55		45	4,22	0,65		45	4,15	0,58	
47,5	4,13	0,56		47,5	4,12	0,55		47,5	4,06	0,49	
50	4	0,43		50	4,15	0,58		50	4,04	0,47	
CE Volume Mikkel - Test 4				CE Volume Mikkel - Test 5				CE Volume Mikkel - Average			
Distar	Measurement	Static C	3,57	Distar	Measurement	Static C	3,57	Distar	Measurement	Static C	3,57
1	11,15	7,58		1	10,45	6,88		1	11,466	7,896	
2	9,15	5,58		2	8,99	5,42		2	9,59	6,02	
3	8,1	4,53		3	7,8	4,23		3	8,542	4,972	
4	7,4	3,83		4	7,64	4,07		4	8,026	4,456	
5	6,98	3,41		5	7,42	3,85		5	7,404	3,834	
7,5	6,43	2,86		7,5	6,39	2,82		7,5	6,518	2,948	
10	5,86	2,29		10	5,78	2,21		10	5,9	2,33	
12,5	5,48	1,91		12,5	5,5	1,93		12,5	5,534	1,964	
15	5,26	1,69		15	5,25	1,68		15	5,286	1,716	
17,5	5,08	1,51		17,5	5,03	1,46		17,5	5,078	1,508	
20	4,94	1,37		20	4,89	1,32		20	4,922	1,352	
22,5	4,75	1,18		22,5	4,47	0,9		22,5	4,73	1,16	
25	4,65	1,08		25	4,56	0,99		25	4,62	1,05	
27,5	4,51	0,94		27,5	4,46	0,89		27,5	4,508	0,938	
30	4,45	0,88		30	4,37	0,8		30	4,438	0,868	
32,5	4,42	0,85		32,5	4,23	0,66		32,5	4,392	0,822	
35	4,4	0,83		35	4,17	0,6		35	4,326	0,756	
37,5	4,35	0,78		37,5	4,13	0,56		37,5	4,236	0,666	
40	4,3	0,73		40	4,2	0,63		40	4,216	0,646	
42,5	4,23	0,66		42,5	4,16	0,59		42,5	4,196	0,626	
45	4,21	0,64		45	4,19	0,62		45	4,178	0,608	
47,5	4,09	0,52		47,5	4	0,43		47,5	4,08	0,51	
50	4,03	0,46		50	3,96	0,39		50	4,036	0,466	

Figure A.31



CE Volume Mikkel - Average
Log. (CE Volume Mikkel - Average)
y = -2,407ln(x) + 7,4929
R² = 0,971
Capacitance in pF Without Static Capacitance
Distance in CM
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
CE Volume Mikkel - Average
Log. (CE Volume Mikkel - Average)
y = -2,407ln(x) + 11,063
R² = 0,971
Capacitance in pF
Distance in CM
CE Volume Mikkel- Lowest Value
CE Volume Mikkel - Highest Value
Capacitance in pF Without Static Capacitance
Distance in CM

Figure A.32

CE Pitch Johan - Test 1			
Distar	Measurement	Static C	3,3
1	8,16	4,86	
2	6,8	3,5	
3	6,3	3	
4	5,9	2,6	
5	5,7	2,4	
7,5	5,35	2,05	
10	5	1,7	
12,5	4,8	1,5	
15	4,6	1,3	
17,5	4,4	1,1	
20	4,35	1,05	
22,5	4,2	0,9	
25	4,1	0,8	
27,5	4	0,7	
30	3,9	0,6	
32,5	4	0,7	
35	3,95	0,65	
37,5	3,85	0,55	
40	3,8	0,5	
42,5	3,8	0,5	
45	3,75	0,45	
47,5	3,65	0,35	
50	3,6	0,3	

CE Pitch Johan - Test 2			
Distar	Measurement	Static C	3,3
1	7,5	4,2	
2	6,55	3,25	
3	6,2	2,9	
4	5,9	2,6	
5	5,65	2,35	
7,5	5,3	2	
10	5	1,7	
12,5	4,8	1,5	
15	4,6	1,3	
17,5	4,4	1,1	
20	4,3	1	
22,5	4,15	0,85	
25	4	0,7	
27,5	3,95	0,65	
30	3,9	0,6	
32,5	3,85	0,55	
35	3,8	0,5	
37,5	3,75	0,45	
40	3,8	0,5	
42,5	3,75	0,45	
45	3,65	0,35	
47,5	3,75	0,45	
50	3,75	0,45	

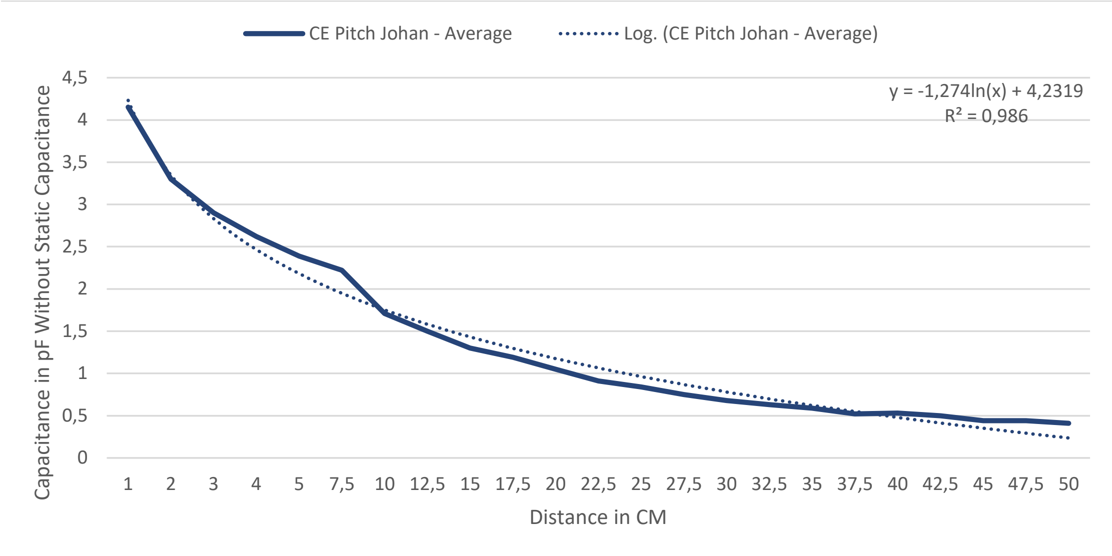
CE Pitch Johan - Test 3			
Distar	Measurement	Static C	3,3
1	7,2	3,9	
2	6,55	3,25	
3	6,2	2,9	
4	5,85	2,55	
5	5,6	2,3	
7,5	5,25	1,95	
10	4,95	1,65	
12,5	4,75	1,45	
15	4,6	1,3	
17,5	4,45	1,15	
20	4,3	1	
22,5	4,15	0,85	
25	4,2	0,9	
27,5	4,1	0,8	
30	4,05	0,75	
32,5	3,9	0,6	
35	3,85	0,55	
37,5	3,8	0,5	
40	3,8	0,5	
42,5	3,75	0,45	
45	3,7	0,4	
47,5	3,75	0,45	
50	3,7	0,4	

CE Pitch Johan - Test 4			
Distar	Measurement	Static C	3,3
1	7,2	3,9	
2	6,45	3,15	
3	6,1	2,8	
4	5,9	2,6	
5	5,7	2,4	
7,5	5,35	2,05	
10	5,1	1,8	
12,5	4,85	1,55	
15	4,6	1,3	
17,5	4,65	1,35	
20	4,4	1,1	
22,5	4,3	1	
25	4,2	0,9	
27,5	4,1	0,8	
30	4,05	0,75	
32,5	3,95	0,65	
35	3,9	0,6	
37,5	3,85	0,55	
40	3,95	0,65	
42,5	3,9	0,6	
45	3,85	0,55	
47,5	3,8	0,5	
50	3,75	0,45	

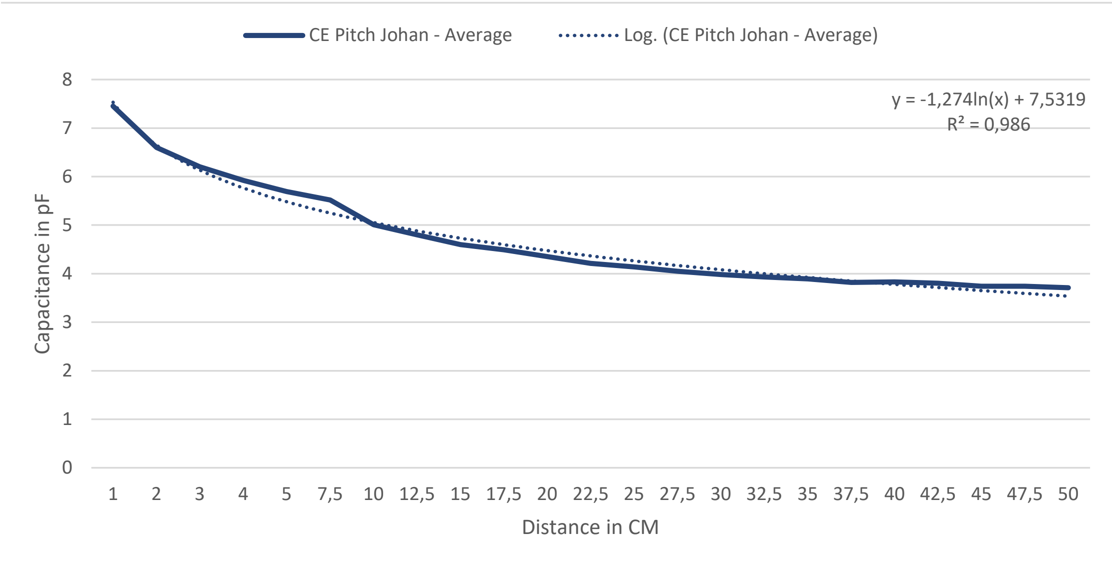
CE Pitch Johan - Test 5			
Distar	Measurement	Static C	3,3
1	7,2	3,9	
2	6,65	3,35	
3	6,2	2,9	
4	6,05	2,75	
5	5,8	2,5	
7,5	6,35	3,05	
10	5	1,7	
12,5	4,8	1,5	
15	4,6	1,3	
17,5	4,55	1,25	
20	4,4	1,1	
22,5	4,25	0,95	
25	4,2	0,9	
27,5	4,1	0,8	
30	4	0,7	
32,5	3,95	0,65	
35	3,95	0,65	
37,5	3,85	0,55	
40	3,8	0,5	
42,5	3,8	0,5	
45	3,75	0,45	
47,5	3,75	0,45	
50	3,75	0,45	

CE Pitch Johan - Average			
Distar	Measurement	Static C	3,3
1	7,452	4,152	
2	6,6	3,3	
3	6,2	2,9	
4	5,92	2,62	
5	5,69	2,39	
7,5	5,52	2,22	
10	5,01	1,71	
12,5	4,8	1,5	
15	4,6	1,3	
17,5	4,49	1,19	
20	4,35	1,05	
22,5	4,21	0,91	
25	4,14	0,84	
27,5	4,05	0,75	
30	3,98	0,68	
32,5	3,93	0,63	
35	3,89	0,59	
37,5	3,82	0,52	
40	3,83	0,53	
42,5	3,8	0,5	
45	3,74	0,44	
47,5	3,74	0,44	
50	3,71	0,41	

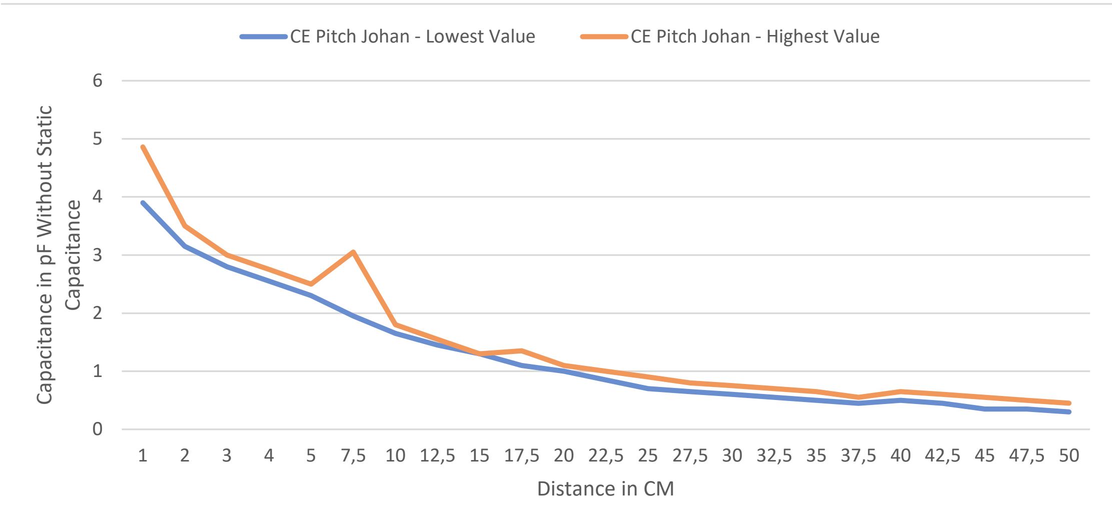
Figure A.33



CE Pitch Johan - Average
Log. (CE Pitch Johan - Average)
y = -1,274ln(x) + 4,2319
R² = 0,986
Capacitance in pF Without Static Capacitance
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM



CE Pitch Johan - Average
Log. (CE Pitch Johan - Average)
y = -1,274ln(x) + 7,5319
R² = 0,986
Capacitance in pF
8
7
6
5
4
3
2
1
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM



CE Pitch Johan - Lowest Value
CE Pitch Johan - Highest Value
Capacitance in pF Without Static Capacitance
6
5
4
3
2
1
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

Figure A.34

CE Volume Johan - Test 1				CE Volume Johan - Test 2				CE Volume Johan - Test 3			
Distar	Measurement	Static C	3,3	Distar	Measurement	Static C	3,3	Distar	Measurement	Static C	3,3
1	10,4	7,1		1	10,28	6,98		1	10,05	6,75	
2	8,5	5,2		2	9,4	6,1		2	9,1	5,8	
3	7,5	4,2		3	8,2	4,9		3	7,65	4,35	
4	7,05	3,75		4	7,8	4,5		4	7,2	3,9	
5	6,87	3,57		5	7	3,7		5	6,85	3,55	
7,5	5,4	2,1		7,5	6,05	2,75		7,5	6,15	2,85	
10	5,45	2,15		10	5,55	2,25		10	5,5	2,2	
12,5	5,05	1,75		12,5	5,15	1,85		12,5	5,2	1,9	
15	4,81	1,51		15	4,95	1,65		15	4,95	1,65	
17,5	4,63	1,33		17,5	4,7	1,4		17,5	4,7	1,4	
20	4,44	1,14		20	4,5	1,2		20	4,55	1,25	
22,5	4,25	0,95		22,5	4,45	1,15		22,5	4,45	1,15	
25	4,13	0,83		25	4,35	1,05		25	4,4	1,1	
27,5	4	0,7		27,5	4,3	1		27,5	4,35	1,05	
30	3,93	0,63		30	4,2	0,9		30	4,3	1	
32,5	3,99	0,69		32,5	4,15	0,85		32,5	4,2	0,9	
35	3,88	0,58		35	4,15	0,85		35	4,2	0,9	
37,5	3,43	0,13		37,5	4,1	0,8		37,5	4,15	0,85	
40	3,88	0,58		40	4,05	0,75		40	4	0,7	
42,5	3,79	0,49		42,5	4,05	0,75		42,5	3,95	0,65	
45	3,88	0,58		45	4	0,7		45	3,75	0,45	
47,5	3,88	0,58		47,5	3,85	0,55		47,5	3,7	0,4	
50	3,83	0,53		50	3,85	0,55		50	3,5	0,2	

CE Volume Johan - Test 4				CE Volume Johan - Test 5				CE Volume Johan - Average			
Distar	Measurement	Static C	3,3	Distar	Measurement	Static C	3,3	Distar	Measurement	Static C	3,3
1	10,15	6,85		1	9,75	6,45		1	10,126	6,826	
2	9,3	6		2	8,75	5,45		2	9,01	5,71	
3	8,25	4,95		3	8,05	4,75		3	7,93	4,63	
4	7,4	4,1		4	7,45	4,15		4	7,38	4,08	
5	6,85	3,55		5	6,9	3,6		5	6,894	3,594	
7,5	6,1	2,8		7,5	6,15	2,85		7,5	5,97	2,67	
10	5,45	2,15		10	5,55	2,25		10	5,5	2,2	
12,5	5,15	1,85		12,5	5,2	1,9		12,5	5,15	1,85	
15	4,85	1,55		15	5	1,7		15	4,912	1,612	
17,5	4,7	1,4		17,5	4,2	0,9		17,5	4,586	1,286	
20	4,55	1,25		20	4,5	1,2		20	4,508	1,208	
22,5	4,4	1,1		22,5	4,4	1,1		22,5	4,39	1,09	
25	4,3	1		25	4,36	1,06		25	4,308	1,008	
27,5	4,2	0,9		27,5	4,3	1		27,5	4,23	0,93	
30	4,1	0,8		30	4,2	0,9		30	4,146	0,846	
32,5	4,2	0,9		32,5	4,2	0,9		32,5	4,148	0,848	
35	4,15	0,85		35	4,1	0,8		35	4,096	0,796	
37,5	4,1	0,8		37,5	4,06	0,76		37,5	3,968	0,668	
40	4,05	0,75		40	3,9	0,6		40	3,976	0,676	
42,5	3,95	0,65		42,5	3,9	0,6		42,5	3,928	0,628	
45	3,95	0,65		45	3,85	0,55		45	3,886	0,586	
47,5	3,65	0,35		47,5	3,7	0,4		47,5	3,756	0,456	
50	3,6	0,3		50	3,7	0,4		50	3,696	0,396	

Figure A.35

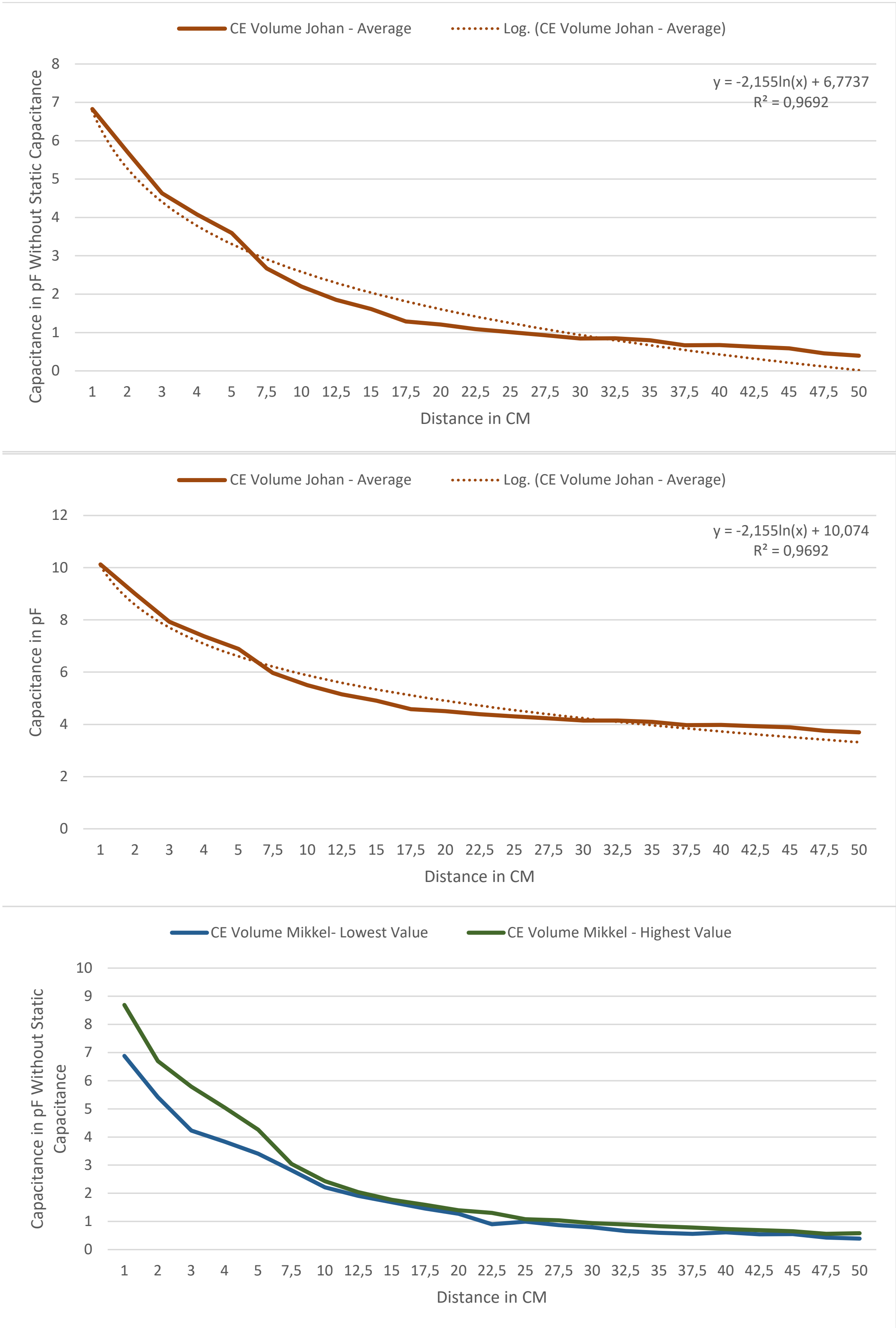

CE Volume Johan - Average
Log. (CE Volume Johan - Average)
y = -2,155ln(x) + 6,7737
R² = 0,9692
Capacitance in pF Without Static Capacitance
Distance in CM
CE Volume Johan - Average
Log. (CE Volume Johan - Average)
y = -2,155ln(x) + 10,074
R² = 0,9692
Capacitance in pF
Distance in CM
CE Volume Mikkel- Lowest Value
CE Volume Mikkel - Highest Value
Capacitance in pF Without Static Capacitance
Distance in CM

Figure A.36

nnidirectionality 15 CE Volume - Tes				nnidirectionality 15 CE Volume - Tes				nnidirectionality 15 CE Volume - Tes			
Distar	Measurement	Static C	3,54	Distar	Measurement	Static C	3,54	Distar	Measurement	Static C	3,54
1	8,97	5,43		1	9,66	6,12		1	10,22	6,68	
2	8,63	5,09		2	8,39	4,85		2	9,11	5,57	
3	7,78	4,24		3	7,95	4,41		3	7,88	4,34	
4	7,41	3,87		4	7,6	4,06		4	8,09	4,55	
5	7,05	3,51		5	7,04	3,5		5	7,18	3,64	
7,5	6,36	2,82		7,5	6,35	2,81		7,5	6,33	2,79	
10	5,83	2,29		10	6	2,46		10	5,86	2,32	
12,5	5,53	1,99		12,5	5,66	2,12		12,5	5,58	2,04	
15	5,18	1,64		15	5,35	1,81		15	5,35	1,81	
17,5	5,02	1,48		17,5	5,17	1,63		17,5	5,21	1,67	
20	4,94	1,4		20	5,09	1,55		20	5,13	1,59	
22,5	4,75	1,21		22,5	4,92	1,38		22,5	4,99	1,45	
25	4,72	1,18		25	4,81	1,27		25	4,87	1,33	
27,5	4,62	1,08		27,5	4,72	1,18		27,5	4,79	1,25	
30	4,55	1,01		30	4,63	1,09		30	4,61	1,07	
32,5	4,47	0,93		32,5	4,56	1,02		32,5	4,6	1,06	
35	4,37	0,83		35	4,52	0,98		35	4,49	0,95	
37,5	4,46	0,92		37,5	4,62	1,08		37,5	4,49	0,95	
40	4,41	0,87		40	4,42	0,88		40	4,51	0,97	
42,5	4,35	0,81		42,5	4,45	0,91		42,5	4,53	0,99	
45	4,31	0,77		45	4,37	0,83		45	4,33	0,79	
47,5	4,26	0,72		47,5	4,34	0,8		47,5	4,37	0,83	
50	4,18	0,64		50	4,27	0,73		50	4,28	0,74	

nnidirectionality 15 CE Volume - Tes				nnidirectionality 15 CE Volume - Tes				mnidirectionality 15 CE Volume - AV			
Distar	Measurement	Static C	3,54	Distar	Measurement	Static C	3,54	Distar	Measurement	Static C	3,54
1	9,94	6,4		1	10,02	6,48		1	9,762	6,222	
2	9,13	5,59		2	9,13	5,59		2	8,878	5,338	
3	7,96	4,42		3	8,61	5,07		3	8,036	4,496	
4	7,73	4,19		4	7,96	4,42		4	7,758	4,218	
5	6,99	3,45		5	7,41	3,87		5	7,134	3,594	
7,5	6,59	3,05		7,5	6,58	3,04		7,5	6,442	2,902	
10	5,88	2,34		10	6,02	2,48		10	5,918	2,378	
12,5	5,71	2,17		12,5	5,69	2,15		12,5	5,634	2,094	
15	5,54	2		15	5,59	2,05		15	5,402	1,862	
17,5	5,19	1,65		17,5	5,35	1,81		17,5	5,188	1,648	
20	5,05	1,51		20	5,22	1,68		20	5,086	1,546	
22,5	4,97	1,43		22,5	4,99	1,45		22,5	4,924	1,384	
25	4,87	1,33		25	4,91	1,37		25	4,836	1,296	
27,5	4,66	1,12		27,5	4,79	1,25		27,5	4,716	1,176	
30	4,72	1,18		30	4,77	1,23		30	4,656	1,116	
32,5	4,7	1,16		32,5	4,75	1,21		32,5	4,616	1,076	
35	4,57	1,03		35	4,65	1,11		35	4,52	0,98	
37,5	4,64	1,1		37,5	4,65	1,11		37,5	4,572	1,032	
40	4,5	0,96		40	4,59	1,05		40	4,486	0,946	
42,5	4,45	0,91		42,5	4,6	1,06		42,5	4,476	0,936	
45	4,42	0,88		45	4,57	1,03		45	4,4	0,86	
47,5	4,38	0,84		47,5	4,52	0,98		47,5	4,374	0,834	
50	4,33	0,79		50	4,37	0,83		50	4,286	0,746	

Figure A.37

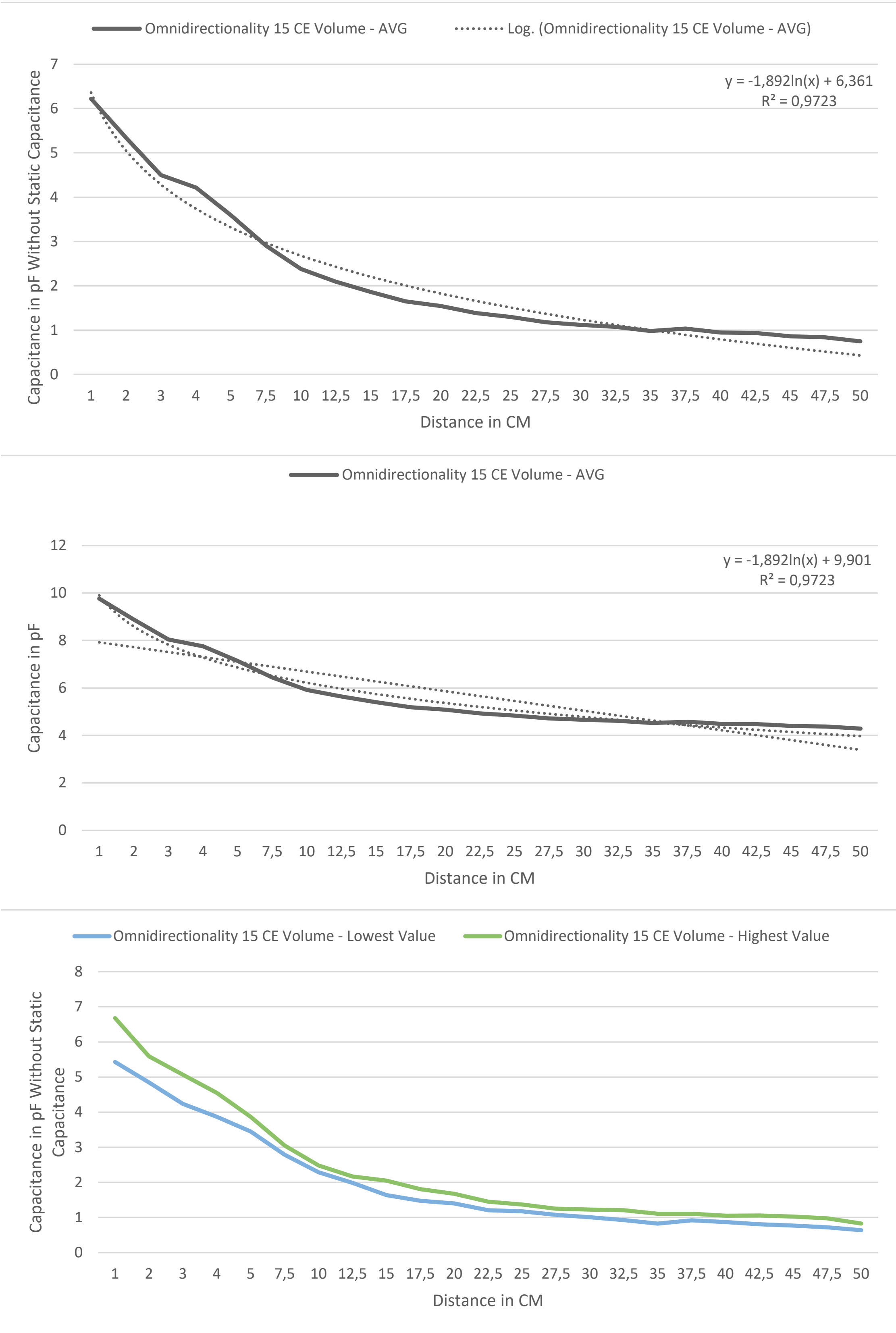

Omnidirectionality 15 CE Volume - AVG
Log. (Omnidirectionality 15 CE Volume - AVG)
y = -1,892ln(x) + 6,361
R² = 0,9723
Capacitance in pF Without Static Capacitance
Distance in CM
Omnidirectionality 15 CE Volume - AVG
y = -1,892ln(x) + 9,901
R² = 0,9723
Capacitance in pF
Distance in CM
Omnidirectionality 15 CE Volume - Lowest Value
Omnidirectionality 15 CE Volume - Highest Value
Capacitance in pF Without Static Capacitance
Distance in CM

Figure A.38

nnidirectionality 30 CE Volume - Tes			
Distar	Measurement	Static C	3,67
1	9,05	5,38	
2	8,4	4,73	
3	7,57	3,9	
4	7,15	3,48	
5	6,67	3	
7,5	6,05	2,38	
10	5,66	1,99	
12,5	5,4	1,73	
15	5,27	1,6	
17,5	5,17	1,5	
20	5,05	1,38	
22,5	4,93	1,26	
25	4,78	1,11	
27,5	4,6	0,93	
30	4,53	0,86	
32,5	4,49	0,82	
35	4,52	0,85	
37,5	4,37	0,7	
40	4,37	0,7	
42,5	4,32	0,65	
45	4,37	0,7	
47,5	4,31	0,64	
50	4,35	0,68	

nnidirectionality 30 CE Volume - Tes			
Distar	Measurement	Static C	3,67
1	8,67	5	
2	8,38	4,71	
3	7,59	3,92	
4	7,3	3,63	
5	6,95	3,28	
7,5	6,21	2,54	
10	5,8	2,13	
12,5	5,5	1,83	
15	5,26	1,59	
17,5	5,13	1,46	
20	5,08	1,41	
22,5	4,87	1,2	
25	4,79	1,12	
27,5	4,78	1,11	
30	4,65	0,98	
32,5	4,54	0,87	
35	4,52	0,85	
37,5	4,51	0,84	
40	4,46	0,79	
42,5	4,34	0,67	
45	4,38	0,71	
47,5	4,43	0,76	
50	4,3	0,63	

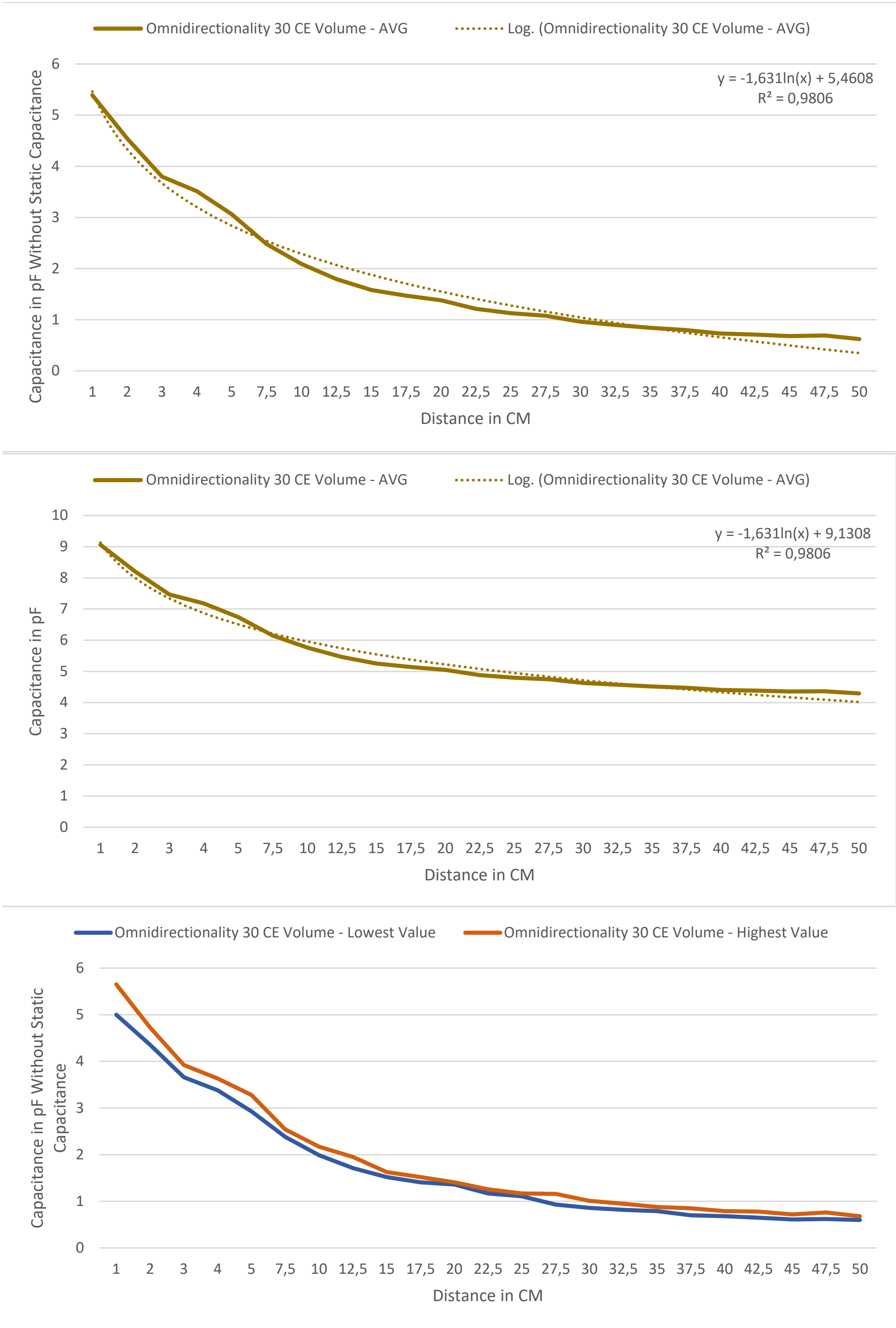
nnidirectionality 30 CE Volume - Tes			
Distar	Measurement	Static C	3,67
1	9,07	5,4	
2	8,11	4,44	
3	7,44	3,77	
4	7,21	3,54	
5	6,76	3,09	
7,5	6,13	2,46	
10	5,69	2,02	
12,5	5,42	1,75	
15	5,3	1,63	
17,5	5,08	1,41	
20	5,04	1,37	
22,5	4,88	1,21	
25	4,8	1,13	
27,5	4,83	1,16	
30	4,68	1,01	
32,5	4,61	0,94	
35	4,52	0,85	
37,5	4,46	0,79	
40	4,37	0,7	
42,5	4,45	0,78	
45	4,34	0,67	
47,5	4,29	0,62	
50	4,27	0,6	

nnidirectionality 30 CE Volume - Tes			
Distar	Measurement	Static C	3,67
1	9,32	5,65	
2	8,13	4,46	
3	7,41	3,74	
4	7,05	3,38	
5	6,69	3,02	
7,5	6,21	2,54	
10	5,81	2,14	
12,5	5,62	1,95	
15	5,23	1,56	
17,5	5,19	1,52	
20	5,03	1,36	
22,5	4,84	1,17	
25	4,84	1,17	
27,5	4,77	1,1	
30	4,63	0,96	
32,5	4,62	0,95	
35	4,46	0,79	
37,5	4,52	0,85	
40	4,35	0,68	
42,5	4,37	0,7	
45	4,28	0,61	
47,5	4,35	0,68	
50	4,27	0,6	

nnidirectionality 30 CE Volume - Tes			
Distar	Measurement	Static C	3,67
1	9,19	5,52	
2	8,03	4,36	
3	7,33	3,66	
4	7,19	3,52	
5	6,6	2,93	
7,5	6,15	2,48	
10	5,84	2,17	
12,5	5,38	1,71	
15	5,19	1,52	
17,5	5,14	1,47	
20	5,05	1,38	
22,5	4,89	1,22	
25	4,78	1,11	
27,5	4,75	1,08	
30	4,66	0,99	
32,5	4,58	0,91	
35	4,55	0,88	
37,5	4,49	0,82	
40	4,45	0,78	
42,5	4,42	0,75	
45	4,39	0,72	
47,5	4,43	0,76	
50	4,27	0,6	

mnidirectionality 30 CE Volume - AV			
Distar	Measurement	Static C	3,67
1	9,06	5,39	
2	8,21	4,54	
3	7,468	3,798	
4	7,18	3,51	
5	6,734	3,064	
7,5	6,15	2,48	
10	5,76	2,09	
12,5	5,464	1,794	
15	5,25	1,58	
17,5	5,142	1,472	
20	5,05	1,38	
22,5	4,882	1,212	
25	4,798	1,128	
27,5	4,746	1,076	
30	4,63	0,96	
32,5	4,568	0,898	
35	4,514	0,844	
37,5	4,47	0,8	
40	4,4	0,73	
42,5	4,38	0,71	
45	4,352	0,682	
47,5	4,362	0,692	
50	4,292	0,622	

Figure A.39



Omnidirectionality 30 CE Volume - AVG
Log. (Omnidirectionality 30 CE Volume - AVG)
y = -1,631ln(x) + 5,4608
R² = 0,9806
Capacitance in pF Without Static Capacitance
0 1 2 3 4 5 6
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
Omnidirectionality 30 CE Volume - AVG
Log. (Omnidirectionality 30 CE Volume - AVG)
y = -1,631ln(x) + 9,1308
R² = 0,9806
Capacitance in pF
0 1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM
Omnidirectionality 30 CE Volume - Lowest Value
Omnidirectionality 30 CE Volume - Highest Value
Capacitance in pF Without Static Capacitance
0 1 2 3 4 5 6
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

Figure A.40

nnidirectionality 45 CE Volume - Tes				nnidirectionality 45 CE Volume - Tes				nnidirectionality 45 CE Volume - Tes			
Distar	Measurement	Static C	3,55	Distar	Measurement	Static C	3,55	Distar	Measurement	Static C	3,55
1	8,58	5,03		1	8,77	5,22		1	8,46	4,91	
2	7,43	3,88		2	7,8	4,25		2	7,69	4,14	
3	7,07	3,52		3	7,36	3,81		3	7,14	3,59	
4	6,64	3,09		4	6,83	3,28		4	6,7	3,15	
5	6,49	2,94		5	6,48	2,93		5	6,43	2,88	
7,5	5,87	2,32		7,5	6,28	2,73		7,5	6,05	2,5	
10	5,6	2,05		10	5,64	2,09		10	5,62	2,07	
12,5	5,29	1,74		12,5	5,46	1,91		12,5	5,48	1,93	
15	5,19	1,64		15	5,25	1,7		15	5,25	1,7	
17,5	5,07	1,52		17,5	5,03	1,48		17,5	5,21	1,66	
20	4,96	1,41		20	4,96	1,41		20	5,05	1,5	
22,5	4,79	1,24		22,5	4,83	1,28		22,5	4,87	1,32	
25	4,76	1,21		25	4,77	1,22		25	4,75	1,2	
27,5	4,64	1,09		27,5	4,68	1,13		27,5	4,69	1,14	
30	4,65	1,1		30	4,64	1,09		30	4,68	1,13	
32,5	4,66	1,11		32,5	4,52	0,97		32,5	4,57	1,02	
35	4,54	0,99		35	4,51	0,96		35	4,56	1,01	
37,5	4,45	0,9		37,5	4,44	0,89		37,5	4,48	0,93	
40	4,45	0,9		40	4,41	0,86		40	4,48	0,93	
42,5	4,39	0,84		42,5	4,39	0,84		42,5	4,3	0,75	
45	4,41	0,86		45	4,31	0,76		45	4,26	0,71	
47,5	4,35	0,8		47,5	4,22	0,67		47,5	4,23	0,68	
50	4,18	0,63		50	4,24	0,69		50	4,21	0,66	

nnidirectionality 45 CE Volume - Tes				nnidirectionality 45 CE Volume - Tes				mnidirectionality 45 CE Volume - AV			
Distar	Measurement	Static C	3,55	Distar	Measurement	Static C	3,55	Distar	Measurement	Static C	3,55
1	8,81	5,26		1	8,56	5,01		1	8,636	5,086	
2	7,53	3,98		2	8,18	4,63		2	7,726	4,176	
3	7	3,45		3	7,27	3,72		3	7,168	3,618	
4	6,63	3,08		4	6,81	3,26		4	6,722	3,172	
5	6,42	2,87		5	6,52	2,97		5	6,468	2,918	
7,5	5,93	2,38		7,5	5,96	2,41		7,5	6,018	2,468	
10	5,57	2,02		10	5,59	2,04		10	5,604	2,054	
12,5	5,32	1,77		12,5	5,4	1,85		12,5	5,39	1,84	
15	5,18	1,63		15	5,1	1,55		15	5,194	1,644	
17,5	4,98	1,43		17,5	5,03	1,48		17,5	5,064	1,514	
20	4,83	1,28		20	4,93	1,38		20	4,946	1,396	
22,5	4,65	1,1		22,5	4,85	1,3		22,5	4,798	1,248	
25	4,56	1,01		25	4,71	1,16		25	4,71	1,16	
27,5	4,57	1,02		27,5	4,63	1,08		27,5	4,642	1,092	
30	4,58	1,03		30	4,55	1		30	4,62	1,07	
32,5	4,45	0,9		32,5	4,54	0,99		32,5	4,548	0,998	
35	4,4	0,85		35	4,5	0,95		35	4,502	0,952	
37,5	4,39	0,84		37,5	4,54	0,99		37,5	4,46	0,91	
40	4,39	0,84		40	4,48	0,93		40	4,442	0,892	
42,5	4,29	0,74		42,5	4,39	0,84		42,5	4,352	0,802	
45	4,24	0,69		45	4,36	0,81		45	4,316	0,766	
47,5	4,23	0,68		47,5	4,33	0,78		47,5	4,272	0,722	
50	4,18	0,63		50	4,28	0,73		50	4,218	0,668	

Figure A.41

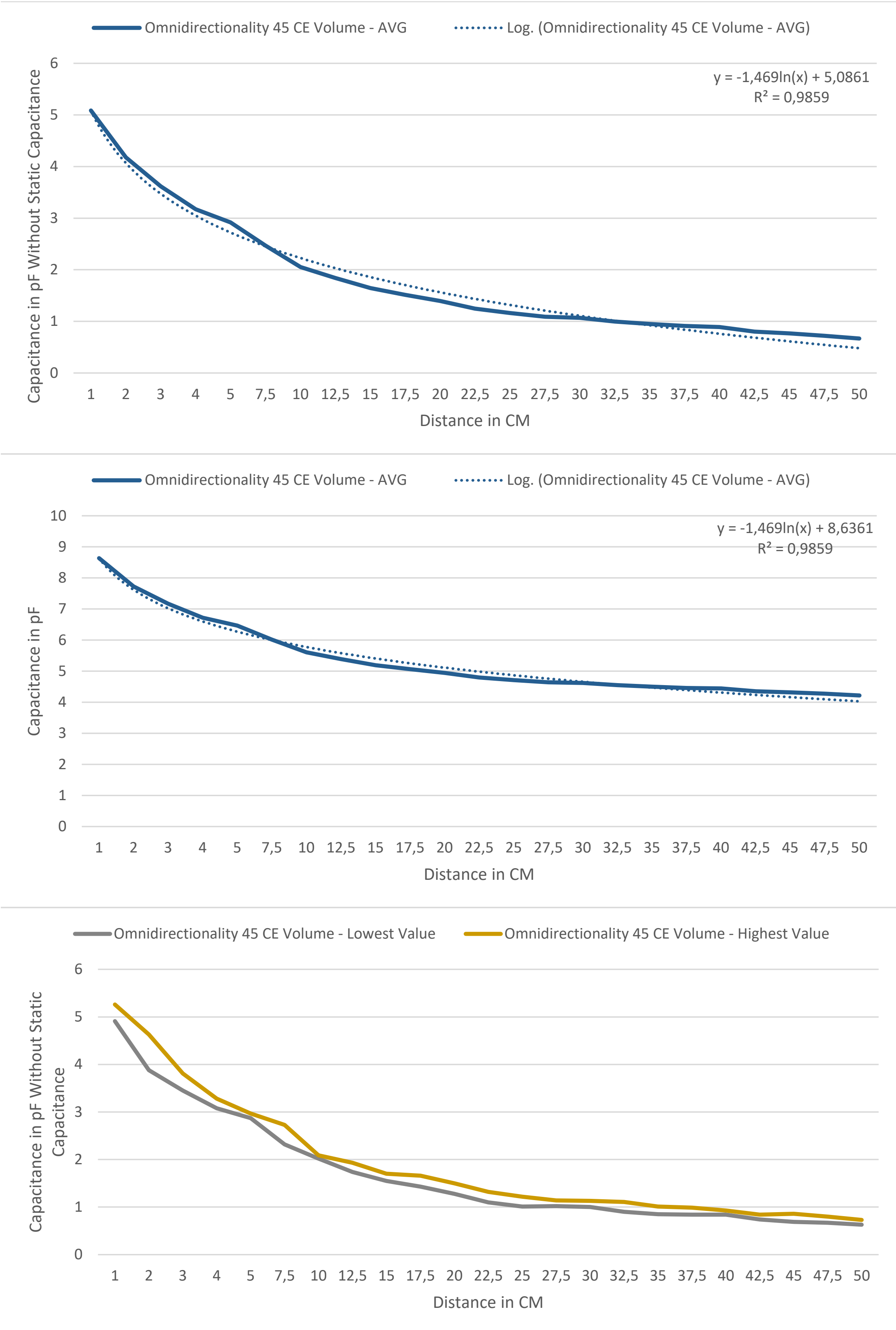

Omnidirectionality 45 CE Volume - AVG
Log. (Omnidirectionality 45 CE Volume - AVG)
y = -1,469ln(x) + 5,0861
R² = 0,9859
Capacitance in pF Without Static Capacitance
Distance in CM
Omnidirectionality 45 CE Volume - AVG
Log. (Omnidirectionality 45 CE Volume - AVG)
y = -1,469ln(x) + 8,6361
R² = 0,9859
Capacitance in pF
Distance in CM
Omnidirectionality 45 CE Volume - Lowest Value
Omnidirectionality 45 CE Volume - Highest Value
Capacitance in pF Without Static Capacitance
Distance in CM

Figure A.42

nnidirectionality 60 CE Volume - Tes				nnidirectionality 60 CE Volume - Tes				nnidirectionality 60 CE Volume - Tes			
Distar	Measurement	Static C	3,48	Distar	Measurement	Static C	3,48	Distar	Measurement	Static C	3,48
1	8,07	4,59		1	8,42	4,94		1	8,22	4,74	
2	7,46	3,98		2	7,68	4,2		2	7,69	4,21	
3	6,78	3,3		3	7,03	3,55		3	7,17	3,69	
4	6,43	2,95		4	6,76	3,28		4	6,81	3,33	
5	6,22	2,74		5	6,4	2,92		5	6,64	3,16	
7,5	5,72	2,24		7,5	5,94	2,46		7,5	5,99	2,51	
10	5,5	2,02		10	5,6	2,12		10	5,64	2,16	
12,5	5,24	1,76		12,5	5,33	1,85		12,5	5,34	1,86	
15	5,07	1,59		15	5,19	1,71		15	5,16	1,68	
17,5	4,92	1,44		17,5	4,98	1,5		17,5	5,02	1,54	
20	4,76	1,28		20	4,91	1,43		20	4,89	1,41	
22,5	4,76	1,28		22,5	4,74	1,26		22,5	4,86	1,38	
25	4,64	1,16		25	4,68	1,2		25	4,68	1,2	
27,5	4,58	1,1		27,5	4,64	1,16		27,5	4,59	1,11	
30	4,51	1,03		30	4,55	1,07		30	4,53	1,05	
32,5	4,57	1,09		32,5	4,42	0,94		32,5	4,46	0,98	
35	4,44	0,96		35	4,34	0,86		35	4,47	0,99	
37,5	4,38	0,9		37,5	4,35	0,87		37,5	4,32	0,84	
40	4,35	0,87		40	4,43	0,95		40	4,35	0,87	
42,5	4,41	0,93		42,5	4,4	0,92		42,5	4,3	0,82	
45	4,4	0,92		45	4,42	0,94		45	4,24	0,76	
47,5	4,32	0,84		47,5	4,24	0,76		47,5	4,31	0,83	
50	4,33	0,85		50	4,29	0,81		50	4,25	0,77	

nnidirectionality 60 CE Volume - Tes				nnidirectionality 60 CE Volume - Tes				mnidirectionality 60 CE Volume - AV			
Distar	Measurement	Static C	3,48	Distar	Measurement	Static C	3,48	Distar	Measurement	Static C	3,48
1	8,28	4,8		1	8,18	4,7		1	8,234	4,754	
2	7,22	3,74		2	7,42	3,94		2	7,494	4,014	
3	7,07	3,59		3	7,21	3,73		3	7,052	3,572	
4	6,66	3,18		4	6,67	3,19		4	6,666	3,186	
5	6,41	2,93		5	6,28	2,8		5	6,39	2,91	
7,5	6,09	2,61		7,5	5,87	2,39		7,5	5,922	2,442	
10	5,54	2,06		10	5,57	2,09		10	5,57	2,09	
12,5	5,28	1,8		12,5	5,44	1,96		12,5	5,326	1,846	
15	5,13	1,65		15	5,16	1,68		15	5,142	1,662	
17,5	4,97	1,49		17,5	4,99	1,51		17,5	4,976	1,496	
20	4,9	1,42		20	4,83	1,35		20	4,858	1,378	
22,5	4,82	1,34		22,5	4,78	1,3		22,5	4,792	1,312	
25	4,72	1,24		25	4,66	1,18		25	4,676	1,196	
27,5	4,7	1,22		27,5	4,58	1,1		27,5	4,618	1,138	
30	4,63	1,15		30	4,57	1,09		30	4,558	1,078	
32,5	4,56	1,08		32,5	4,5	1,02		32,5	4,502	1,022	
35	4,47	0,99		35	4,41	0,93		35	4,426	0,946	
37,5	4,41	0,93		37,5	4,45	0,97		37,5	4,382	0,902	
40	4,46	0,98		40	4,41	0,93		40	4,4	0,92	
42,5	4,37	0,89		42,5	4,38	0,9		42,5	4,372	0,892	
45	4,27	0,79		45	4,28	0,8		45	4,322	0,842	
47,5	4,25	0,77		47,5	4,25	0,77		47,5	4,274	0,794	
50	4,25	0,77		50	4,25	0,77		50	4,274	0,794	

Figure A.43

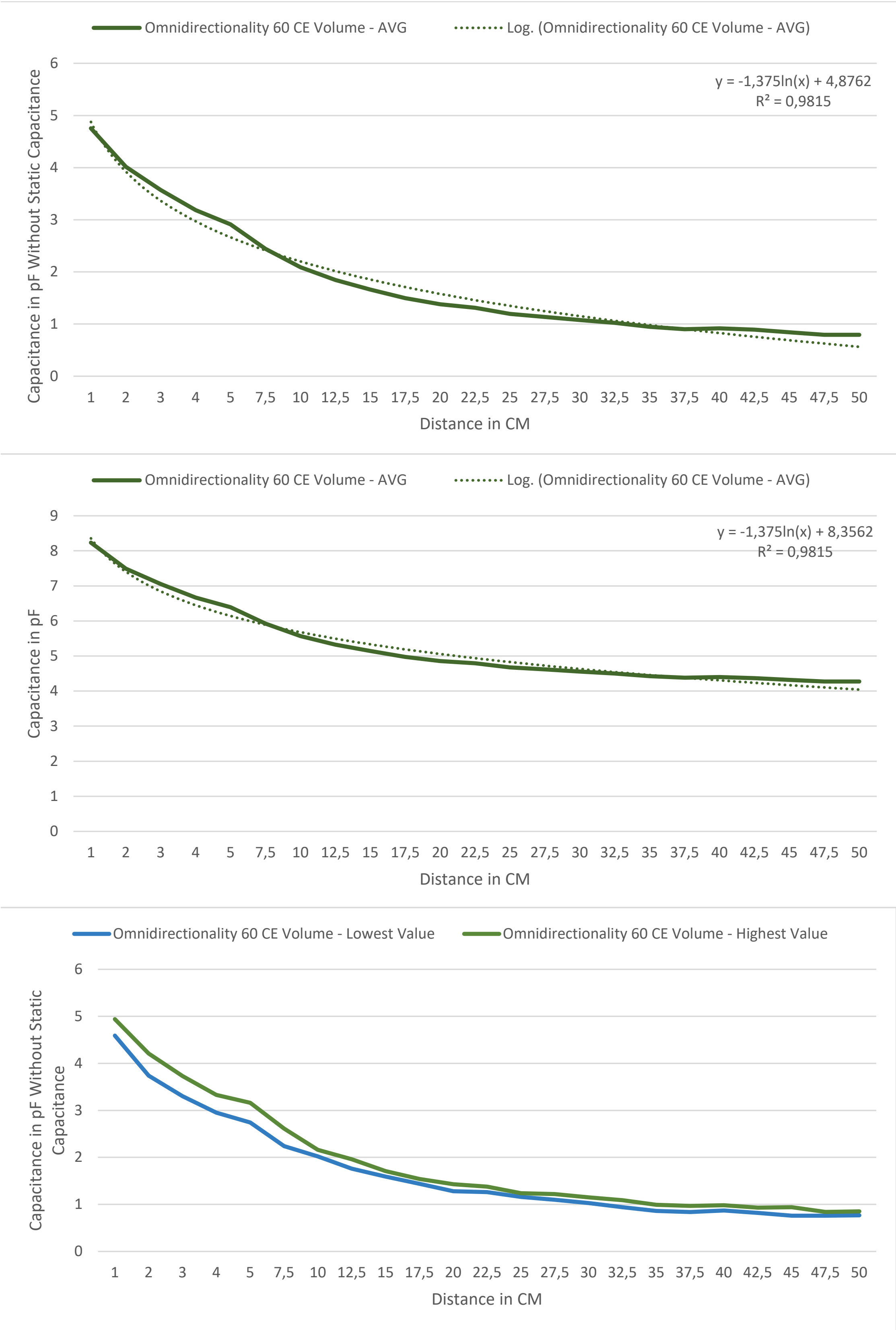
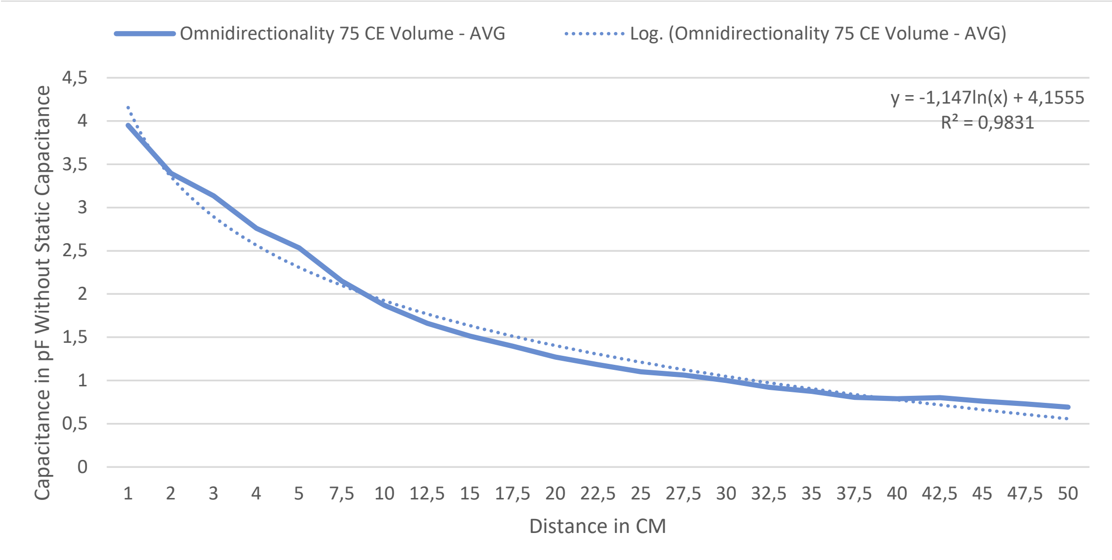

Omnidirectionality 60 CE Volume - AVG
Log. (Omnidirectionality 60 CE Volume - AVG)
y = -1,375ln(x) + 4,8762
R² = 0,9815
Capacitance in pF Without Static Capacitance
Distance in CM
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Omnidirectionality 60 CE Volume - AVG
Log. (Omnidirectionality 60 CE Volume - AVG)
y = -1,375ln(x) + 8,3562
R² = 0,9815
Capacitance in pF
Distance in CM
Omnidirectionality 60 CE Volume - Lowest Value
Omnidirectionality 60 CE Volume - Highest Value
Capacitance in pF Without Static Capacitance
Distance in CM

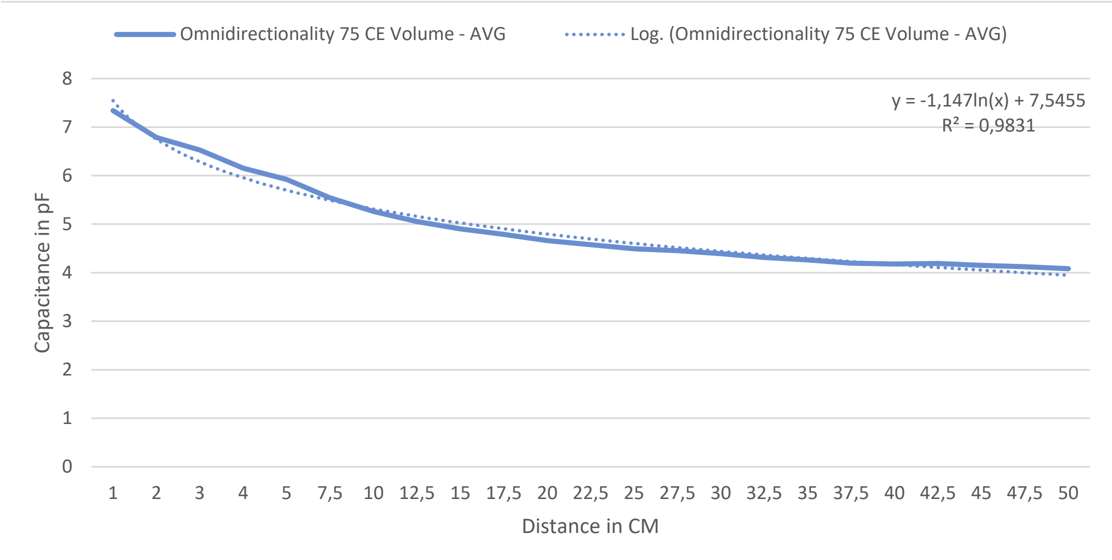
Figure A.44

nnidirectionality 75 CE Volume - Tes				nnidirectionality 75 CE Volume - Tes				nnidirectionality 75 CE Volume - Tes			
Distar	Measurement	Static C	3,39	Distar	Measurement	Static C	3,39	Distar	Measurement	Static C	3,39
1	7,73	4,34		1	7,4	4,01		1	7,13	3,74	
2	6,79	3,4		2	6,82	3,43		2	6,74	3,35	
3	6,41	3,02		3	6,42	3,03		3	6,4	3,01	
4	6,14	2,75		4	6,16	2,77		4	6,14	2,75	
5	5,87	2,48		5	5,98	2,59		5	5,99	2,6	
7,5	5,54	2,15		7,5	5,64	2,25		7,5	5,52	2,13	
10	5,31	1,92		10	5,28	1,89		10	5,22	1,83	
12,5	5,11	1,72		12,5	5,09	1,7		12,5	5,02	1,63	
15	4,92	1,53		15	4,96	1,57		15	4,89	1,5	
17,5	4,8	1,41		17,5	4,8	1,41		17,5	4,77	1,38	
20	4,66	1,27		20	4,66	1,27		20	4,65	1,26	
22,5	4,56	1,17		22,5	4,6	1,21		22,5	4,53	1,14	
25	4,46	1,07		25	4,54	1,15		25	4,38	0,99	
27,5	4,45	1,06		27,5	4,48	1,09		27,5	4,36	0,97	
30	4,38	0,99		30	4,41	1,02		30	4,34	0,95	
32,5	4,31	0,92		32,5	4,37	0,98		32,5	4,21	0,82	
35	4,3	0,91		35	4,28	0,89		35	4,17	0,78	
37,5	4,24	0,85		37,5	4,17	0,78		37,5	4,09	0,7	
40	4,13	0,74		40	4,17	0,78		40	4,17	0,78	
42,5	4,17	0,78		42,5	4,23	0,84		42,5	4,19	0,8	
45	4,08	0,69		45	4,16	0,77		45	4,11	0,72	
47,5	4,11	0,72		47,5	4,15	0,76		47,5	4,09	0,7	
50	4,1	0,71		50	4,12	0,73		50	4,01	0,62	

nnidirectionality 75 CE Volume - Tes				nnidirectionality 75 CE Volume - Tes				mnidirectionality 75 CE Volume - AV			
Distar	Measurement	Static C	3,39	Distar	Measurement	Static C	3,39	Distar	Measurement	Static C	3,39
1	7,14	3,75		1	7,3	3,91		1	7,34	3,95	
2	6,85	3,46		2	6,73	3,34		2	6,786	3,396	
3	6,97	3,58		3	6,43	3,04		3	6,526	3,136	
4	6,13	2,74		4	6,18	2,79		4	6,15	2,76	
5	5,94	2,55		5	5,84	2,45		5	5,924	2,534	
7,5	5,51	2,12		7,5	5,49	2,1		7,5	5,54	2,15	
10	5,26	1,87		10	5,22	1,83		10	5,258	1,868	
12,5	5,06	1,67		12,5	4,98	1,59		12,5	5,052	1,662	
15	4,89	1,5		15	4,86	1,47		15	4,904	1,514	
17,5	4,79	1,4		17,5	4,78	1,39		17,5	4,788	1,398	
20	4,7	1,31		20	4,64	1,25		20	4,662	1,272	
22,5	4,61	1,22		22,5	4,57	1,18		22,5	4,574	1,184	
25	4,54	1,15		25	4,53	1,14		25	4,49	1,1	
27,5	4,5	1,11		27,5	4,47	1,08		27,5	4,452	1,062	
30	4,44	1,05		30	4,38	0,99		30	4,39	1	
32,5	4,37	0,98		32,5	4,3	0,91		32,5	4,312	0,922	
35	4,26	0,87		35	4,31	0,92		35	4,264	0,874	
37,5	4,23	0,84		37,5	4,24	0,85		37,5	4,194	0,804	
40	4,18	0,79		40	4,24	0,85		40	4,178	0,788	
42,5	4,2	0,81		42,5	4,17	0,78		42,5	4,192	0,802	
45	4,23	0,84		45	4,17	0,78		45	4,15	0,76	
47,5	4,12	0,73		47,5	4,13	0,74		47,5	4,12	0,73	
50	4,1	0,71		50	4,08	0,69		50	4,082	0,692	

Figure A.45


Omnidirectionality 75 CE Volume - AVG
Log. (Omnidirectionality 75 CE Volume - AVG)
y = -1,147ln(x) + 4,1555
R² = 0,9831
Capacitance in pF Without Static Capacitance
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM


Omnidirectionality 75 CE Volume - AVG
Log. (Omnidirectionality 75 CE Volume - AVG)
y = -1,147ln(x) + 7,5455
R² = 0,9831
Capacitance in pF
8
7
6
5
4
3
2
1
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

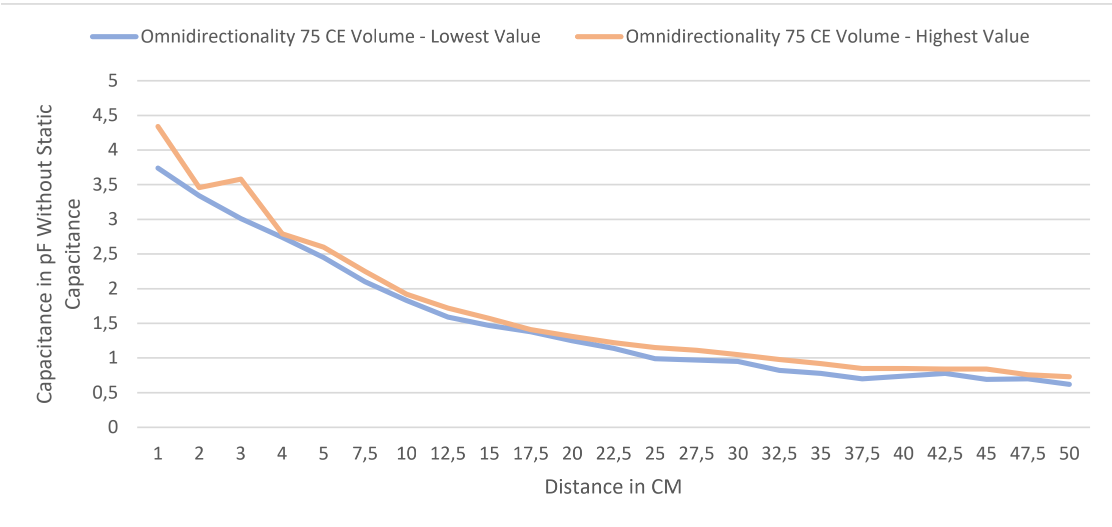

Omnidirectionality 75 CE Volume - Lowest Value
Omnidirectionality 75 CE Volume - Highest Value
Capacitance in pF Without Static Capacitance
5
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

Figure A.46

nnidirectionality 90 CE Volume - Tes			
Distar	Measurement	Static C	3,48
1	7,21	3,73	
2	6,6	3,12	
3	6,35	2,87	
4	6,15	2,67	
5	5,93	2,45	
7,5	5,52	2,04	
10	5,2	1,72	
12,5	5,01	1,53	
15	4,91	1,43	
17,5	4,73	1,25	
20	4,6	1,12	
22,5	4,55	1,07	
25	4,45	0,97	
27,5	4,4	0,92	
30	4,38	0,9	
32,5	4,3	0,82	
35	4,25	0,77	
37,5	4,23	0,75	
40	4,29	0,81	
42,5	4,19	0,71	
45	4,13	0,65	
47,5	4,21	0,73	
50	4,17	0,69	

nnidirectionality 90 CE Volume - Tes			
Distar	Measurement	Static C	3,48
1	7,2	3,72	
2	6,49	3,01	
3	6,39	2,91	
4	6,03	2,55	
5	5,81	2,33	
7,5	5,52	2,04	
10	5,23	1,75	
12,5	5,02	1,54	
15	4,95	1,47	
17,5	4,71	1,23	
20	4,61	1,13	
22,5	4,61	1,13	
25	4,47	0,99	
27,5	4,35	0,87	
30	4,33	0,85	
32,5	4,25	0,77	
35	4,19	0,71	
37,5	4,15	0,67	
40	4,1	0,62	
42,5	4,16	0,68	
45	4,08	0,6	
47,5	4,05	0,57	
50	4,06	0,58	

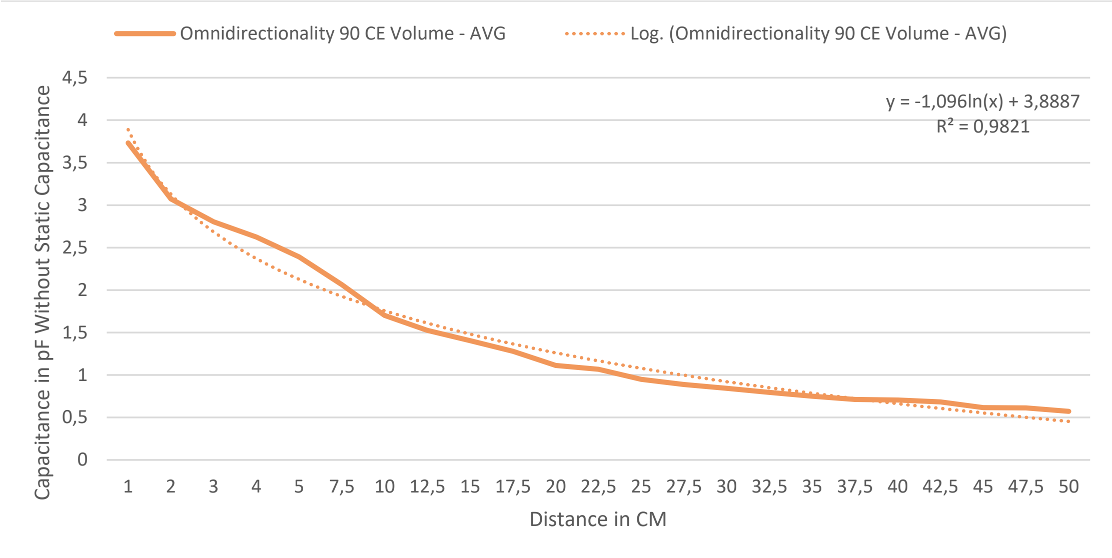
nnidirectionality 90 CE Volume - Tes			
Distar	Measurement	Static C	3,48
1	6,98	3,5	
2	6,49	3,01	
3	6,21	2,73	
4	6,12	2,64	
5	5,86	2,38	
7,5	5,4	1,92	
10	5,16	1,68	
12,5	4,97	1,49	
15	4,79	1,31	
17,5	4,71	1,23	
20	4,53	1,05	
22,5	4,49	1,01	
25	4,37	0,89	
27,5	4,31	0,83	
30	4,32	0,84	
32,5	4,25	0,77	
35	4,23	0,75	
37,5	4,18	0,7	
40	4,2	0,72	
42,5	4,13	0,65	
45	4,04	0,56	
47,5	4,03	0,55	
50	4,04	0,56	

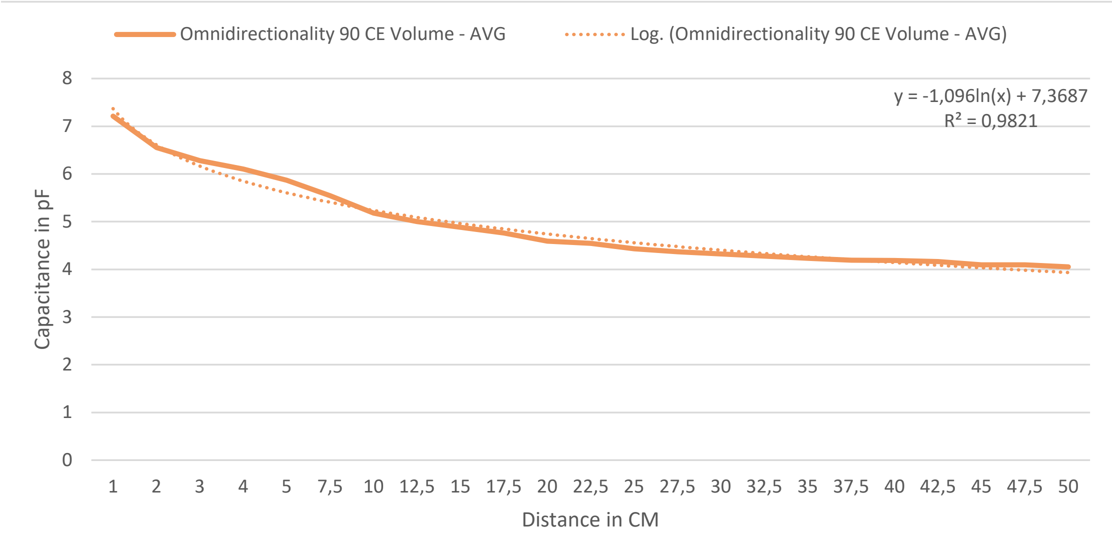
nnidirectionality 90 CE Volume - Tes			
Distar	Measurement	Static C	3,48
1	7,27	3,79	
2	6,54	3,06	
3	6,25	2,77	
4	6,12	2,64	
5	5,91	2,43	
7,5	5,39	1,91	
10	5,19	1,71	
12,5	5,03	1,55	
15	4,9	1,42	
17,5	4,82	1,34	
20	4,6	1,12	
22,5	4,59	1,11	
25	4,45	0,97	
27,5	4,38	0,9	
30	4,31	0,83	
32,5	4,31	0,83	
35	4,26	0,78	
37,5	4,21	0,73	
40	4,22	0,74	
42,5	4,18	0,7	
45	4,11	0,63	
47,5	4,1	0,62	
50	4,01	0,53	

nnidirectionality 90 CE Volume - Tes			
Distar	Measurement	Static C	3,48
1	7,4	3,92	
2	6,64	3,16	
3	6,21	2,73	
4	6,1	2,62	
5	5,84	2,36	
7,5	5,89	2,41	
10	5,12	1,64	
12,5	4,99	1,51	
15	4,87	1,39	
17,5	4,83	1,35	
20	4,62	1,14	
22,5	4,5	1,02	
25	4,41	0,93	
27,5	4,4	0,92	
30	4,27	0,79	
32,5	4,27	0,79	
35	4,22	0,74	
37,5	4,19	0,71	
40	4,12	0,64	
42,5	4,15	0,67	
45	4,12	0,64	
47,5	4,07	0,59	
50	3,98	0,5	

mnidirectionality 90 CE Volume - AV			
Distar	Measurement	Static C	3,48
1	7,212	3,732	
2	6,552	3,072	
3	6,282	2,802	
4	6,104	2,624	
5	5,87	2,39	
7,5	5,544	2,064	
10	5,18	1,7	
12,5	5,004	1,524	
15	4,884	1,404	
17,5	4,76	1,28	
20	4,592	1,112	
22,5	4,548	1,068	
25	4,43	0,95	
27,5	4,368	0,888	
30	4,322	0,842	
32,5	4,276	0,796	
35	4,23	0,75	
37,5	4,192	0,712	
40	4,186	0,706	
42,5	4,162	0,682	
45	4,096	0,616	
47,5	4,092	0,612	
50	4,052	0,572	

Figure A.47


Omnidirectionality 90 CE Volume - AVG
Log. (Omnidirectionality 90 CE Volume - AVG)
y = -1,096ln(x) + 3,8887
R² = 0,9821
Capacitance in pF Without Static Capacitance
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM


Omnidirectionality 90 CE Volume - AVG
Log. (Omnidirectionality 90 CE Volume - AVG)
y = -1,096ln(x) + 7,3687
R² = 0,9821
Capacitance in pF
8
7
6
5
4
3
2
1
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

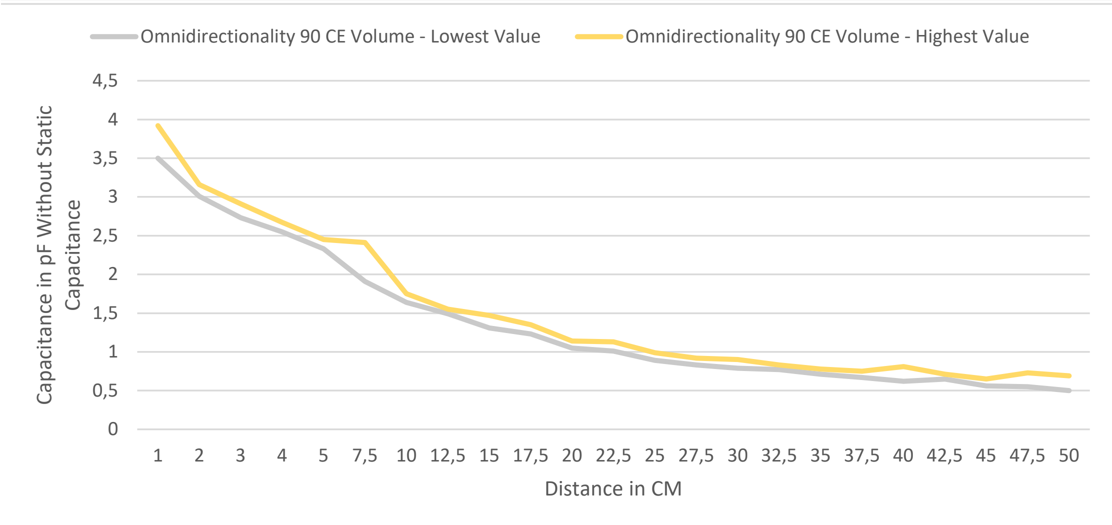

Omnidirectionality 90 CE Volume - Lowest Value
Omnidirectionality 90 CE Volume - Highest Value
Capacitance in pF Without Static Capacitance
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
1 2 3 4 5 7,5 10 12,5 15 17,5 20 22,5 25 27,5 30 32,5 35 37,5 40 42,5 45 47,5 50
Distance in CM

Figure A.48

A.7 Raw Data From Oscillator Stability Testing

W/O antenna	1	2	3	4	5	AVG
Low capacitance						
Frequency[kHz]	336,475	336,29	336,402	336,488	336,535	336,438
Amplitude [Pk-pK V]	11,5	11,5	11,5	11,5	11,5	11,5
Drift [Hz]	4	-2,5	-0,3	-4	-1,2	-0,8
Mid capacitance						
Frequency[kHz]	331,545	331.960	332,149	331,812	332,046	66657,5104
Amplitude [Pk-pK V]	11,1	11,2	11,2	11,1	11,2	11,16
Drift [Hz]	-8	1	-0,5	0,2	0,8	-1,3
High capacitance						
Frequency[kHz]	327,267	327,27	327,306	327,262	327,272	327,2754
Amplitude [Pk-pK V]	10,5	10,6	10,6	10,7	10,6	10,6
Drift [Hz]	2,3	0,5	-0,6	0,5	-2,3	0,08
W antenna	1	2	3	4	5	AVG
Low capacitance						
Frequency[kHz]	330,265	330,422	330,34	330,238	330,022	330,2574
Amplitude [Pk-pK V]	11,7	11,6	11,6	11,6	11,6	11,62
Drift [Hz]	0,7	0,8	1,1	-1,6	-1,4	-0,08
Mid capacitance						
Frequency[kHz]	326,053	325,846	326,178	326,014	326,008	326,0198
Amplitude [Pk-pK V]	11,3	11,3	11,3	11,3	11,3	11,3
Drift [Hz]	-1	0,3	-0,9	-1,8	-1,5	-0,98
High capacitance						
Frequency[kHz]	320,925	321,308	321,255	321,315	321,275	321,2156
Amplitude [Pk-pK V]	10,8	10,9	10,8	10,9	10,9	10,86
Drift [Hz]	-1,7	-1,2	1,4	0,7	1,4	0,12

Figure A.49: Raw data table from 5 observations of the oscillator both with and without the antenna, and with Cvar at low, middle, and high capacitance.

A.8 Raw Data From Frequency Range Testing

NE Frequency Range 1 - Cvar=High				NE Frequency Range 2 - Cvar=High				NE Frequency Range 3 - Cvar=High			
Distance i	Measured	Base Hz	321761	Distance i	Measured	Base Hz	321733	Distance i	Measured	Base Hz	321720
1	319950	-1811		1	319632	-2101		1	319225	-2495	
2	320400	-1361		2	320013	-1720		2	319815	-1905	
3	320852	-909		3	320437	-1296		3	320384	-1336	
4	320990	-771		4	320703	-1030		4	320629	-1091	
5	321233	-528		5	320865	-868		5	320819	-901	
7,5	321370	-391		7,5	321168	-565		7,5	321094	-626	
10	321455	-306		10	321303	-430		10	321283	-437	
12,5	321517	-244		12,5	321402	-331		12,5	321386	-334	
15	321558	-203		15	321485	-248		15	321458	-262	
17,5	321591	-170		17,5	321509	-224		17,5	321506	-214	
20	321614	-147		20	321553	-180		20	321546	-174	
22,5	321632	-129		22,5	321611	-122		22,5	321577	-143	
25	321649	-112		25	321602	-131		25	321596	-124	
27,5	321660	-101		27,5	321621	-112		27,5	321614	-106	
30	321670	-91		30	321633	-100		30	321628	-92	
32,5	321662	-99		32,5	321650	-83		32,5	321642	-78	
35	321670	-91		35	321657	-76		35	321648	-72	
37,5	321678	-83		37,5	321665	-68		37,5	321657	-63	
40	321684	-77		40	321669	-64		40	321662	-58	
42,5	321688	-73		42,5	321677	-56		42,5	321668	-52	
45	321718	-43		45	321682	-51		45	321673	-47	
47,5	321696	-65		47,5	321687	-46		47,5	321675	-45	
50	321698	-63		50	321707	-26		50	321681	-39	

NE Frequency Range 4 - Cvar=High				NE Frequency Range 5 - Cvar=High				NE Frequency Range Average - Cvar=High			
Distance i	Measured	Base Hz	321710	Distance i	Measured	Base Hz	321718	Distance i	Measured	Base Hz	321.728
1	319189	-2521		1	319073	-2645		1	319413,8	-2314,6	
2	319611	-2099		2	319609	-2109		2	319889,6	-1838,8	
3	320261	-1449		3	320269	-1449		3	320440,6	-1287,8	
4	320468	-1242		4	320551	-1167		4	320668,2	-1060,2	
5	320712	-998		5	320780	-938		5	320881,8	-846,6	
7,5	321042	-668		7,5	321075	-643		7,5	321149,8	-578,6	
10	321242	-468		10	321288	-430		10	321314,2	-414,2	
12,5	321354	-356		12,5	321374	-344		12,5	321406,6	-321,8	
15	321452	-258		15	321440	-278		15	321478,6	-249,8	
17,5	321480	-230		17,5	321493	-225		17,5	321515,8	-212,6	
20	321522	-188		20	321530	-188		20	321553	-175,4	
22,5	321564	-146		22,5	321566	-152		22,5	321590	-138,4	
25	321586	-124		25	321588	-130		25	321604,2	-124,2	
27,5	321602	-108		27,5	321606	-112		27,5	321620,6	-107,8	
30	321644	-66		30	321633	-85		30	321641,6	-86,8	
32,5	321633	-77		32,5	321637	-81		32,5	321644,8	-83,6	
35	321646	-64		35	321645	-73		35	321653,2	-75,2	
37,5	321651	-59		37,5	321655	-63		37,5	321661,2	-67,2	
40	321683	-27		40	321662	-56		40	321672	-56,4	
42,5	321664	-46		42,5	321667	-51		42,5	321672,8	-55,6	
45	321669	-41		45	321675	-43		45	321683,4	-45	
47,5	321672	-38		47,5	321677	-41		47,5	321681,4	-47	
50	321681	-29		50	321707	-11		50	321694,8	-33,6	

Figure A.50

NE Frequency Range 1 - Cvar=Mid			
Distance i	Measured	Base Hz	326491
1	323982	-2509	
2	324549	-1942	
3	324919	-1572	
4	325331	-1160	
5	325598	-893	
7,5	325881	-610	
10	326059	-432	
12,5	326155	-336	
15	326228	-263	
17,5	326280	-211	
20	326316	-175	
22,5	326343	-148	
25	326366	-125	
27,5	326383	-108	
30	326402	-89	
32,5	326413	-78	
35	326421	-70	
37,5	326427	-64	
40	326431	-60	
42,5	326433	-58	
45	326436	-55	
47,5	326442	-49	
50	326444	-47	

NE Frequency Range 2 - Cvar=Mid			
Distance i	Measured	Base Hz	326479
1	323810	-2669	
2	324615	-1864	
3	325047	-1432	
4	325408	-1071	
5	325585	-894	
7,5	325858	-621	
10	326026	-453	
12,5	326141	-338	
15	326212	-267	
17,5	326257	-222	
20	326296	-183	
22,5	326330	-149	
25	326349	-130	
27,5	326366	-113	
30	326379	-100	
32,5	326392	-87	
35	326409	-70	
37,5	326414	-65	
40	326420	-59	
42,5	326424	-55	
45	326430	-49	
47,5	326436	-43	
50	326438	-41	

NE Frequency Range 3 - Cvar=Mid			
Distance i	Measured	Base Hz	326478
1	323821	-2657	
2	324659	-1819	
3	325141	-1337	
4	325375	-1103	
5	325520	-958	
7,5	325853	-625	
10	326028	-450	
12,5	326125	-353	
15	326195	-283	
17,5	326251	-227	
20	326284	-194	
22,5	326314	-164	
25	326344	-134	
27,5	326356	-122	
30	326373	-105	
32,5	326391	-87	
35	326401	-77	
37,5	326406	-72	
40	326415	-63	
42,5	326420	-58	
45	326426	-52	
47,5	326431	-47	
50	326434	-44	

NE Frequency Range 4 - Cvar=Mid			
Distance i	Measured	Base Hz	326483
1	323709	-2774	
2	324460	-2023	
3	325072	-1411	
4	325383	-1100	
5	325601	-882	
7,5	325889	-594	
10	326040	-443	
12,5	326154	-329	
15	326206	-277	
17,5	326257	-226	
20	326303	-180	
22,5	326326	-157	
25	326354	-129	
27,5	326368	-115	
30	326387	-96	
32,5	326396	-87	
35	326406	-77	
37,5	326415	-68	
40	326426	-57	
42,5	326432	-51	
45	326437	-46	
47,5	326441	-42	
50	326445	-38	

NE Frequency Range 5 - Cvar=Mid			
Distance i	Measured	Base Hz	326481
1	323730	-2751	
2	324769	-1712	
3	325113	-1368	
4	325314	-1167	
5	325510	-971	
7,5	325814	-667	
10	325980	-501	
12,5	326100	-381	
15	326183	-298	
17,5	326235	-246	
20	326279	-202	
22,5	326317	-164	
25	326342	-139	
27,5	326361	-120	
30	326375	-106	
32,5	326391	-90	
35	326401	-80	
37,5	326409	-72	
40	326416	-65	
42,5	326425	-56	
45	326432	-49	
47,5	326435	-46	
50	326437	-44	

NE Frequency Range Average - Cvar=Mid			
Distance i	Measured	Base Hz	326.482
1	323810,4	-2672	
2	324610,4	-1872	
3	325058,4	-1424	
4	325362,2	-1120,2	
5	325562,8	-919,6	
7,5	325859	-623,4	
10	326026,6	-455,8	
12,5	326135	-347,4	
15	326204,8	-277,6	
17,5	326256	-226,4	
20	326295,6	-186,8	
22,5	326326	-156,4	
25	326351	-131,4	
27,5	326366,8	-115,6	
30	326383,2	-99,2	
32,5	326396,6	-85,8	
35	326407,6	-74,8	
37,5	326414,2	-68,2	
40	326421,6	-60,8	
42,5	326426,8	-55,6	
45	326432,2	-50,2	
47,5	326437	-45,4	
50	326439,6	-42,8	

Figure A.51

NE Frequency Range 1 - Cvar=Low			
Distance i	Measured	Base Hz	330671
1	328.288	-2383	
2	328851	-1820	
3	329352	-1319	
4	329588	-1083	
5	329739	-932	
7,5	330035	-636	
10	330204	-467	
12,5	330321	-350	
15	330393	-278	
17,5	330456	-215	
20	330499	-172	
22,5	330517	-154	
25	330545	-126	
27,5	330562	-109	
30	330576	-95	
32,5	330587	-84	
35	330600	-71	
37,5	330608	-63	
40	330623	-48	
42,5	330628	-43	
45	330626	-45	
47,5	330629	-42	
50	330632	-39	

NE Frequency Range 2 - Cvar=Low			
Distance i	Measured	Base Hz	330663
1	327321	-3342	
2	328512	-2151	
3	329204	-1459	
4	329421	-1242	
5	329691	-972	
7,5	330019	-644	
10	330219	-444	
12,5	330323	-340	
15	330430	-233	
17,5	330443	-220	
20	330484	-179	
22,5	330507	-156	
25	330537	-126	
27,5	330555	-108	
30	330571	-92	
32,5	330580	-83	
35	330590	-73	
37,5	330600	-63	
40	330602	-61	
42,5	330611	-52	
45	330614	-49	
47,5	330632	-31	
50	330619	-44	

NE Frequency Range 3 - Cvar=Low			
Distance i	Measured	Base Hz	330657
1	327519	-3138	
2	328405	-2252	
3	329120	-1537	
4	329483	-1174	
5	329688	-969	
7,5	330012	-645	
10	330198	-459	
12,5	330299	-358	
15	330375	-282	
17,5	330455	-202	
20	330498	-159	
22,5	330501	-156	
25	330525	-132	
27,5	330549	-108	
30	330562	-95	
32,5	330572	-85	
35	330580	-77	
37,5	330602	-55	
40	330619	-38	
42,5	330598	-59	
45	330603	-54	
47,5	330606	-51	
50	330618	-39	

NE Frequency Range 4 - Cvar=Low			
Distance i	Measured	Base Hz	330660
1	327980	-2680	
2	328858	-1802	
3	329353	-1307	
4	329666	-994	
5	329789	-871	
7,5	330070	-590	
10	330233	-427	
12,5	330331	-329	
15	330398	-262	
17,5	330450	-210	
20	330491	-169	
22,5	330545	-115	
25	330540	-120	
27,5	330581	-79	
30	330568	-92	
32,5	330583	-77	
35	330589	-71	
37,5	330600	-60	
40	330607	-53	
42,5	330613	-47	
45	330641	-19	
47,5	330620	-40	
50	330621	-39	

NE Frequency Range 5 - Cvar=Low			
Distance i	Measured	Base Hz	330661
1	328096	-2565	
2	328516	-2145	
3	329234	-1427	
4	329454	-1207	
5	329678	-983	
7,5	330010	-651	
10	330200	-461	
12,5	330285	-376	
15	330370	-291	
17,5	330425	-236	
20	330464	-197	
22,5	330495	-166	
25	330519	-142	
27,5	330542	-119	
30	330556	-105	
32,5	330569	-92	
35	330580	-81	
37,5	330592	-69	
40	330600	-61	
42,5	330604	-57	
45	330609	-52	
47,5	330616	-45	
50	330620	-41	

NE Frequency Range Average - Cvar=Low			
Distance i	Measured	Base Hz	330.662
1	327840,8	-2821,6	
2	328628,4	-2034	
3	329252,6	-1409,8	
4	329522,4	-1140	
5	329717	-945,4	
7,5	330029,2	-633,2	
10	330210,8	-451,6	
12,5	330311,8	-350,6	
15	330393,2	-269,2	
17,5	330445,8	-216,6	
20	330487,2	-175,2	
22,5	330513	-149,4	
25	330533,2	-129,2	
27,5	330557,8	-104,6	
30	330566,6	-95,8	
32,5	330578,2	-84,2	
35	330587,8	-74,6	
37,5	330600,4	-62	
40	330610,2	-52,2	
42,5	330610,8	-51,6	
45	330618,6	-43,8	
47,5	330620,6	-41,8	
50	330622	-40,4	

Figure A.52

A.9 Raw Data From Pitch Drift Testing

Pitch Drift Frequency Test - Cvar=Low								
Distance in cm	0 sec	10 sec	20 sec	30 sec	40 sec	50 sec	60 sec	Deviance
1	326380	327041	326846	326812	326716	326641	326452	661
2	327251	327074	327080	327076	327058	327033	327019	232
3	327649	327706	327696	327678	327664	327605	327558	148
4	327934	327905	327886	327859	327833	327840	327802	132
5	328079	328180	328156	328135	328160	328060	328062	120
7,5	328369	328383	328410	328410	328417	328418	328402	49
10	328553	328545	328545	328549	328567	328565	328573	28
12,5	328685	328686	328685	328682	328678	328672	328674	14
15	328753	328760	328761	328757	328756	328756	328757	8
17,5	328798	328802	328799	328798	328786	328787	328784	18
20	328830	328823	328823	328823	328822	328823	328822	8
22,5	328860	328866	328865	328863	328864	328865	328864	6
25	328884	328880	328876	328876	328876	328894	328870	24
27,5	328913	328906	328901	328905	328903	328908	328922	21
30	328905	328904	328905	328905	328905	328906	328906	2
32,5	328930	328925	328914	328914	328915	328917	328925	16
35	328933	328924	328922	328922	328921	328941	328939	20
37,5	328948	328943	328933	328933	328932	328932	328931	17
40	328939	328937	328940	328942	328938	328938	328940	5
42,5	328946	328943	328940	328940	328942	328940	328940	6
45	328951	328941	328955	328949	328943	328941	328943	14
47,5	328946	328946	328954	328957	328953	328951	328952	11
50	328970	328947	328946	328946	328943	328942	328946	28
Pitch Drift Frequency Test - Cvar=Mid								
Distance in cm	0 sec	10 sec	20 sec	30 sec	40 sec	50 sec	60 sec	Deviance
1	322407	322099	322082	321738	321445	321451	320730	1677
2	322370	322630	322520	322424	322359	322402	322337	293
3	322832	323114	323029	323015	322865	322890	322880	282
4	323181	323246	323182	323147	323128	323126	323093	153
5	324443	323428	323400	323371	323350	323349	323365	1094
7,5	324746	323776	323780	323683	323699	323704	323668	1078
10	323885	323899	323902	323879	323894	323880	323899	23
12,5	324013	324015	324010	324008	324011	324022	324024	16
15	324107	324081	324078	324074	324075	324084	324068	39
17,5	324154	324143	324135	324132	324132	324127	324129	27
20	324183	324169	324169	324173	324171	324168	324169	15
22,5	324203	324202	324222	324224	324224	324224	324225	23
25	324255	324248	324248	324246	324248	324242	324244	13
27,5	324265	324262	324261	324261	324254	324252	324248	17
30	324252	324275	324246	324272	324243	324270	324268	32
32,5	324265	324257	324293	324280	324280	324280	324282	36
35	324264	324264	324262	324262	324262	324263	324278	16
37,5	324282	324279	324283	324274	324277	324276	324278	9
40	324288	324280	324280	324281	324281	324305	324305	25
42,5	324285	324284	324283	324282	324282	324283	324279	6
45	324286	324286	324282	324282	324282	324280	324283	6
47,5	324290	324287	324286	324284	324283	324281	324288	9
50	324286	324308	324282	324283	324309	324294	324281	28

Figure A.53

Pitch Drift Frequency Test - Cvar=High								
Distance in cm	0 sec	10 sec	20 sec	30 sec	40 sec	50 sec	60 sec	Deviance
1	318176	317540	317692	317580	317577	317586	317436	740
2	318286	317488	317296	317671	317710	317638	317475	990
3	318670	318512	318421	318349	318259	318196	318177	493
4	319331	318903	318678	318608	318525	318507	318483	848
5	318940	318980	318980	318963	318928	318910	318873	107
7,5	319333	319271	319268	319264	319257	319254	319267	79
10	319512	319488	319466	319460	319451	319446	319445	67
12,5	319629	319601	319602	319593	319589	319587	319585	44
15	319682	319656	319652	319652	319650	319658	319657	32
17,5	319740	319728	319724	319720	319718	319718	319716	24
20	319769	319759	319755	319757	319754	319752	319750	19
22,5	319804	319803	319828	319819	319801	319793	319793	35
25	319819	319817	319817	319814	319814	319815	319816	5
27,5	319843	319840	319841	319839	319839	319838	319835	8
30	319855	319850	319847	319847	319850	319850	319848	8
32,5	319892	319862	319863	319862	319861	319860	319860	32
35	319873	319871	319870	319869	319869	319870	319870	4
37,5	319884	319877	319878	319878	319880	319880	319879	7
40	319884	319880	319880	319882	319880	319880	319880	4
42,5	319882	319883	319881	319880	319881	319882	319882	3
45	319891	319891	319891	319891	319895	319906	319911	20
47,5	319893	319886	319883	319911	319912	319911	319912	29
50	319892	319891	319892	319891	319891	319892	319891	1

Figure A.54

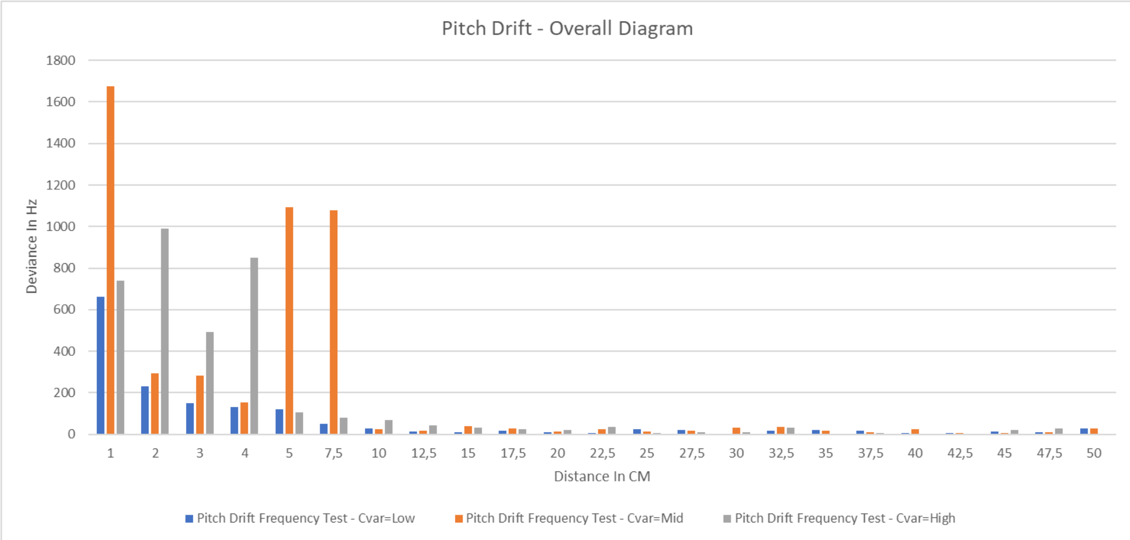


Figure A.55: Overall diagram of deviance data related to pitch drift. As mentioned earlier, the raw data can be seen on pages A.53 and A.54. It is worth mentioning that the deviance is total maximum deviance and not deviance between the first and last measurement.

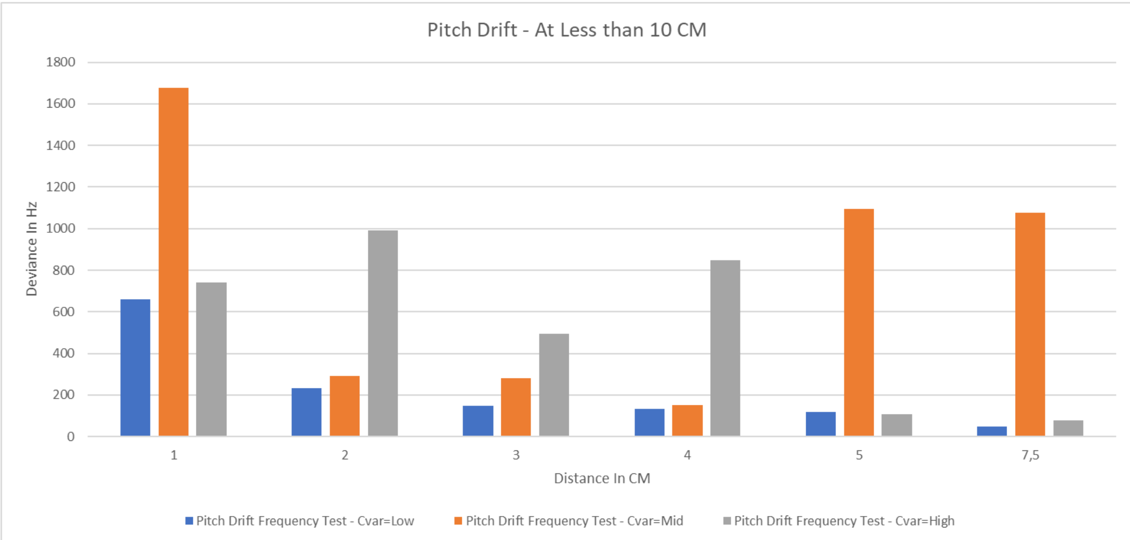


Figure A.56: Diagram over the first 10cm of deviance data related to pitch drift. As mentioned earlier, the raw data can be seen on pages A.53 and A.54. It is worth mentioning that the deviance is total maximum deviance and not deviance between the first and last measurement.

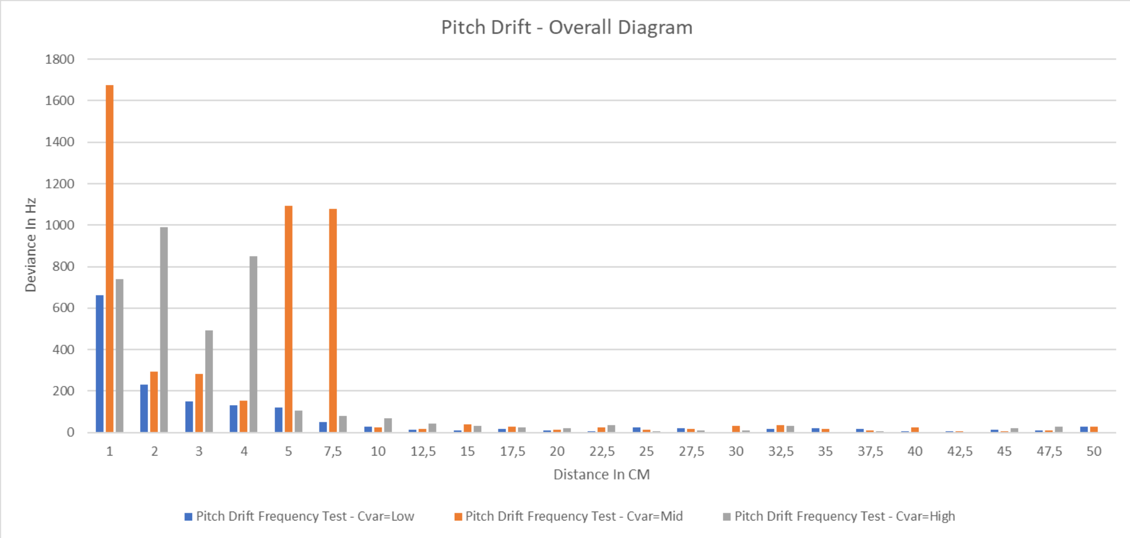
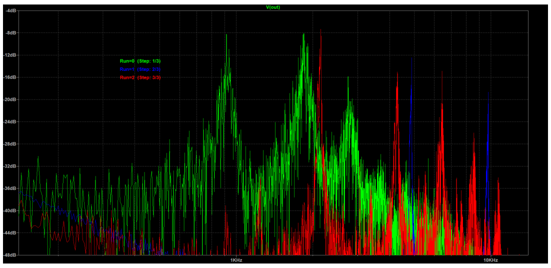


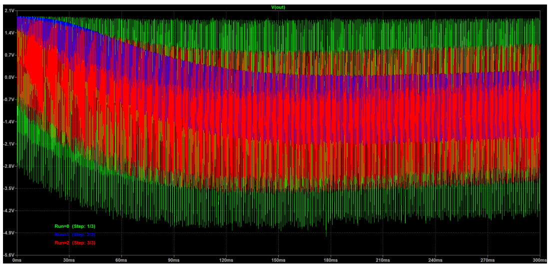
Figure A.57: Diagram over deviance found measured more than 10cm from the antenna related to pitch drift. As mentioned earlier, the raw data can be seen on pages A.53 and A.54. It is worth mentioning that the deviance is total maximum deviance and not deviance between the first and last measurement.

A.10 Component Tolerance Simulations With Resistors at 1%

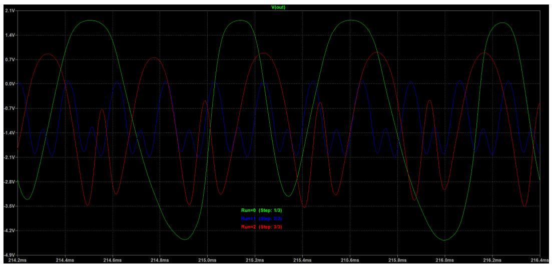
(a) Full Fourier transformation showing that either the system does not function at all, or has shifted severely.



(b) Closeup of the same Fourier transformation as in figure A.58a.



(c) Transient analysis of the complete system.



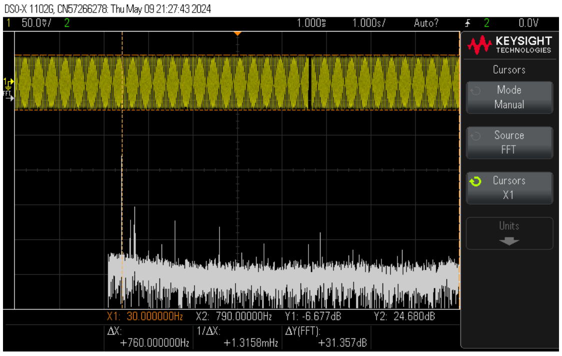
(d) Closeup of the transient analysis of the complete system, showcasing the far from ideal sinus waves.

Figure A.58: Lt-spice analysis showing deviances in the final system, with capacitor tolerances of 10%, resistors of 1%, and inductors of 5%. Run 0 (green) is with positive deviance for all components, run 1 (blue) is with negative deviance, and run 2 (red) is with ideal values.

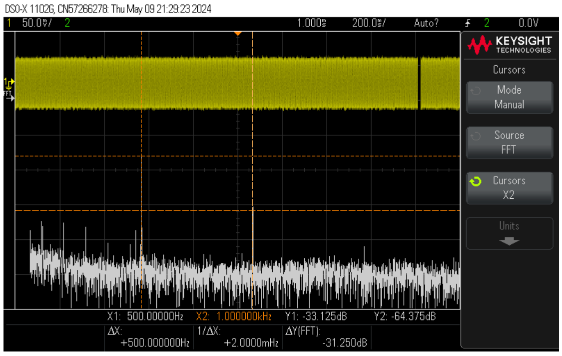
A.11 Mixer test Results

LOCAL f	PITCH f	M1	M2	M3	M4	M5	Mean	Desired	Deviation
240,000Hz	240,030Hz	30.397Hz	30.383Hz	30.016Hz	30.395Hz	30.751Hz	30.458Hz	30Hz	0.458Hz
240,000Hz	240,500Hz	500.499Hz	500.503Hz	500.498Hz	500.001Hz	500.488Hz	500.498Hz	500Hz	0.498Hz
240,000Hz	241,000Hz	1000.381Hz	1000.378Hz	1000.403Hz	1000.391Hz	1000.384Hz	1000.387Hz	1000Hz	0.387Hz
240,000Hz	241,500Hz	1500.401Hz	1500.419Hz	1500.404Hz	1500.416Hz	1500.416Hz	1500.411Hz	1500Hz	0.411Hz
240,000Hz	242,000Hz	2000.397Hz	2000.417Hz	2000.395Hz	2000.393Hz	2000.407Hz	2000.402Hz	2000Hz	0.402Hz
240,000Hz	242,500Hz	2499.405Hz	2497.408Hz	2499.993Hz	2500.73Hz	2500.093Hz	2499.394Hz	2500Hz	-0.605Hz
240,000Hz	243,000Hz	3000.003Hz	3000.001Hz	3000.005Hz	3000.002Hz	3000.005Hz	3000.003Hz	3000Hz	0.0032Hz

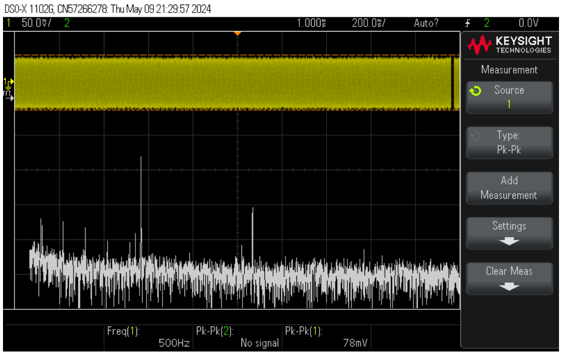
A.11.1 Scope images from end-to-end test



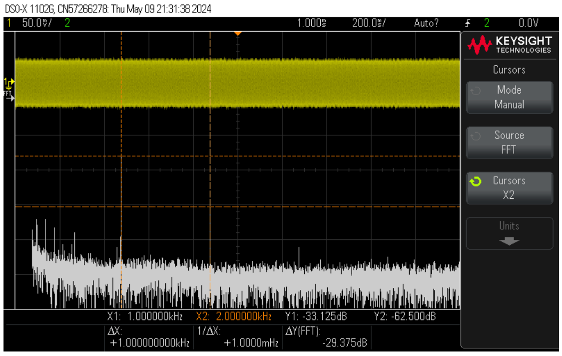
(a) Output FFT of 30Hz input frequency difference.



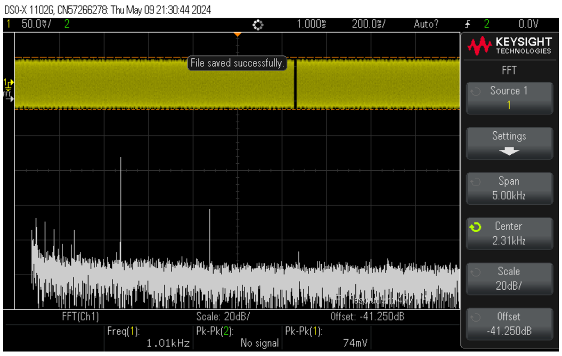
(b) Output FFT of 500Hz input frequency difference.



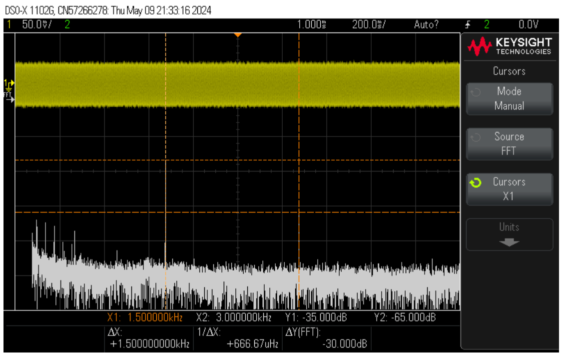
(c) Output amplitude of 500Hz input frequency difference.



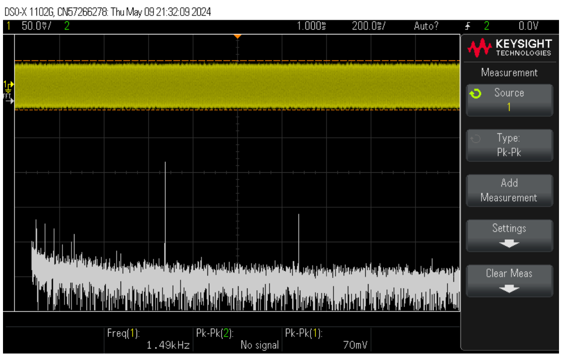
(d) Output FFT of 1000Hz input frequency difference.



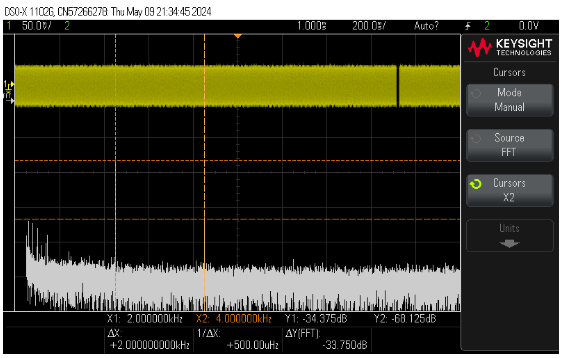
(e) Output amplitude of 1000Hz input frequency difference.



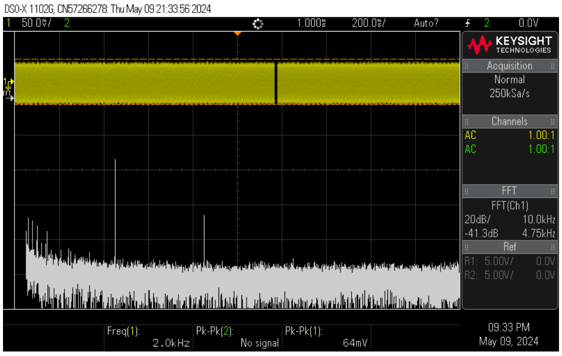
(f) Output FFT of 1500Hz input frequency difference.



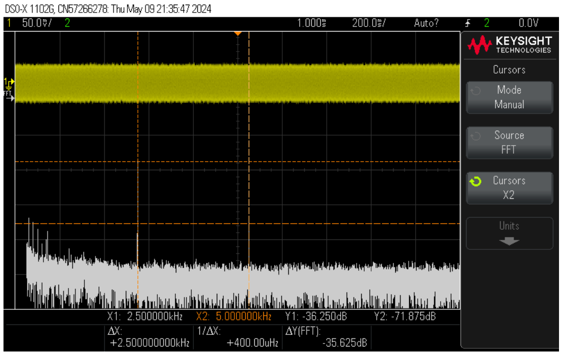
(g) Output amplitude of 1500Hz input frequency difference.



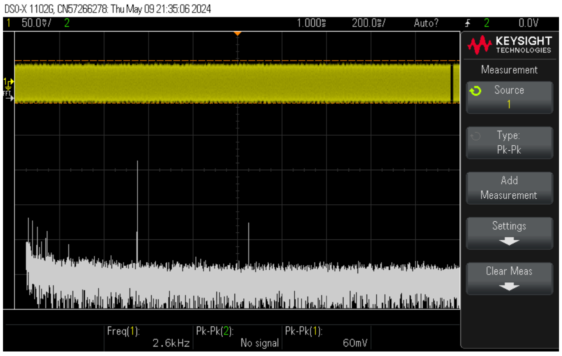
(h) Output FFT of 2000Hz input frequency difference.



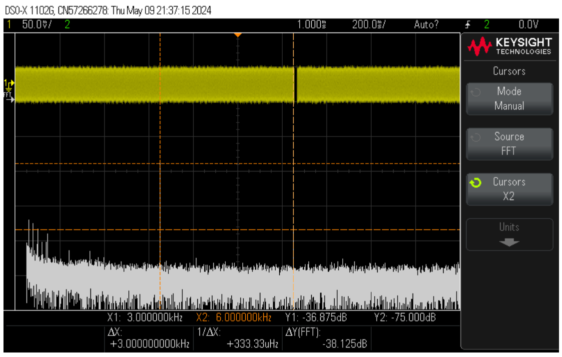
(i) Output amplitude of 2000Hz input frequency difference.



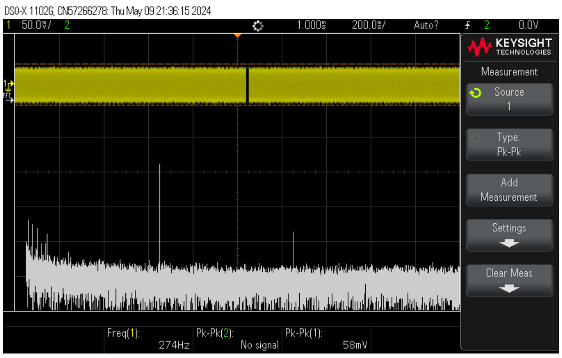
(j) Output FFT of 2500Hz input frequency difference.



(k) Output amplitude of 2500Hz input frequency difference.



(l) Output FFT of 3000Hz input frequency difference.

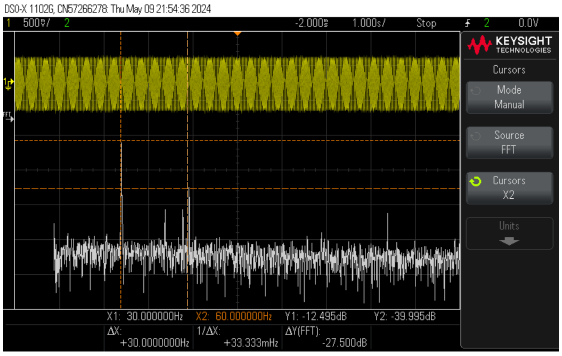


(m) Output amplitude of 3000Hz input frequency difference. The frequency is 3000Hz, the screenshot was taken at a inconvenient moment.

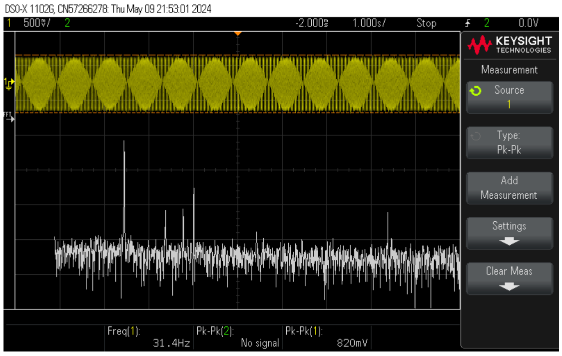
Figure A.59: Images of scope for each tested frequency, both amplitude and FFT.

A.12 Integration Test Results

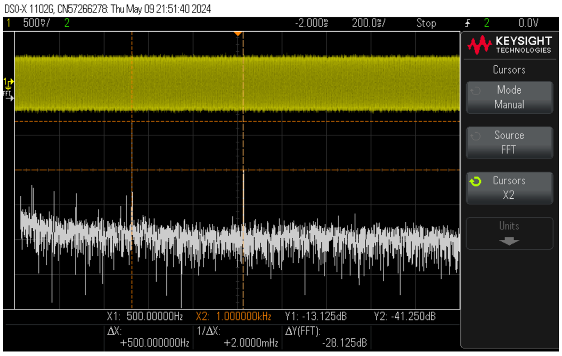
A.12.1 Scope images from mixer preamp test



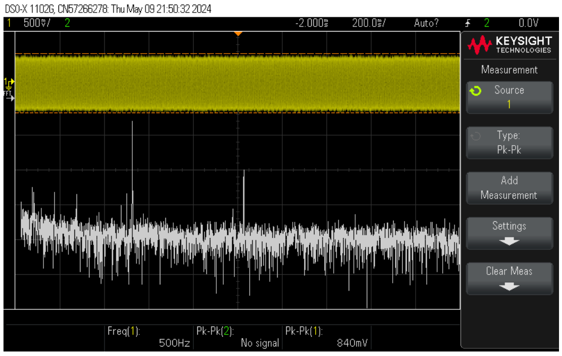
(a) Output FFT of 30Hz input frequency difference.



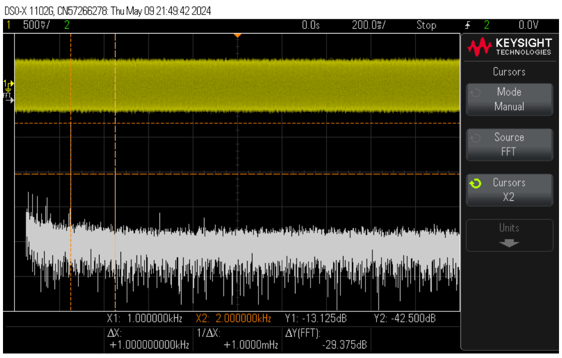
(b) Output amplitude of 30Hz input frequency difference.



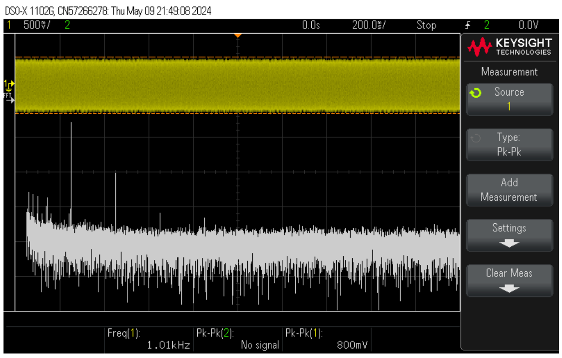
(c) Output FFT of 500Hz input frequency difference.



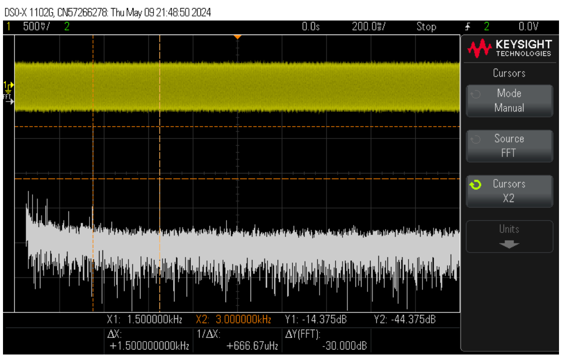
(d) Output amplitude of 500Hz input frequency difference.



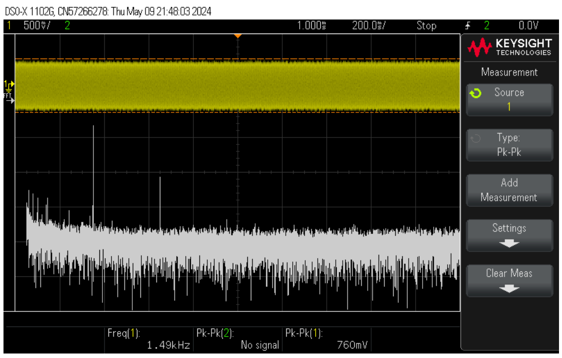
(e) Output FFT of 1000Hz input frequency difference.



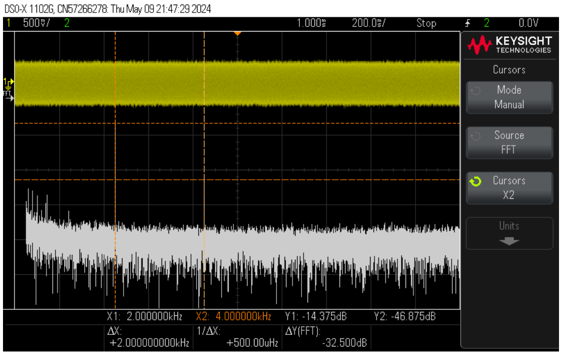
(f) Output amplitude of 1000Hz input frequency difference.



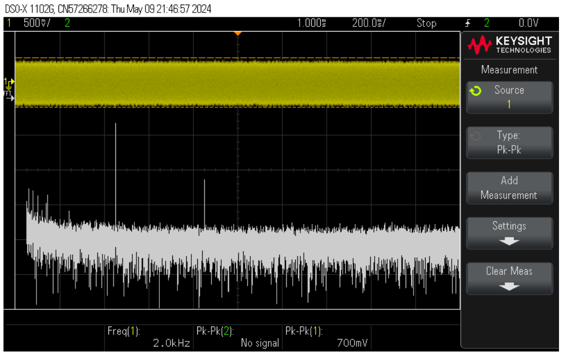
(g) Output FFT of 1500Hz input frequency difference.



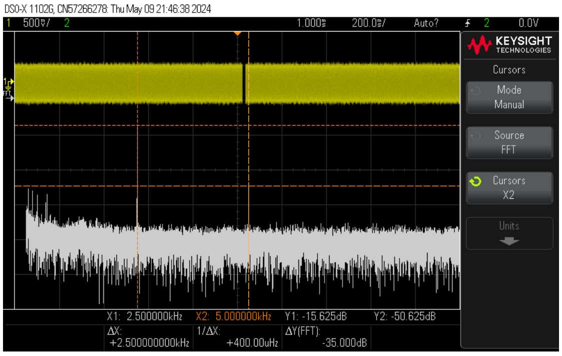
(h) Output amplitude of 1500Hz input frequency difference.



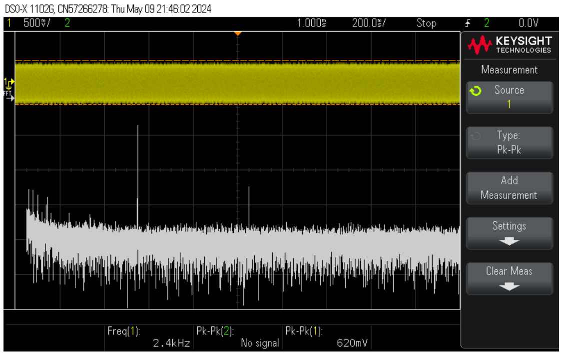
(i) Output FFT of 2000Hz input frequency difference.



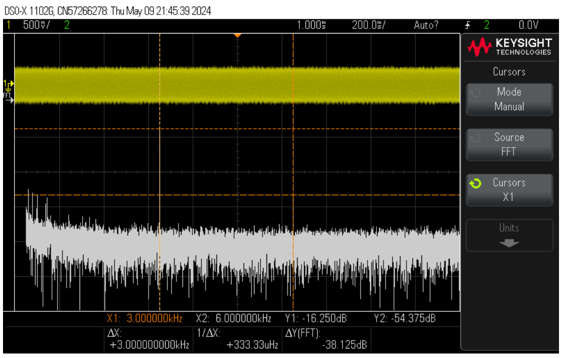
(j) Output amplitude of 2000Hz input frequency difference.



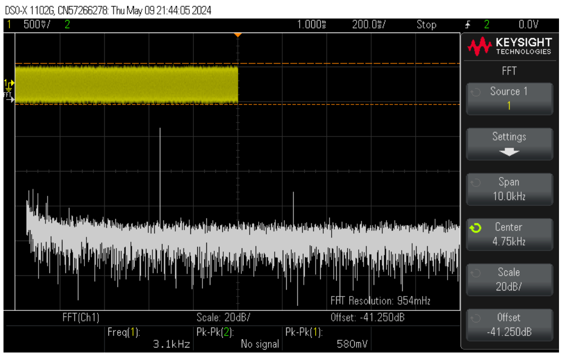
(k) Output FFT of 2500Hz input frequency difference.



(l) Output amplitude of 2500Hz input frequency difference.



(m) Output FFT of 3000Hz input frequency difference.



(n) Output amplitude of 3000Hz input frequency difference.

Figure A.60: Images of scope for each tested frequency, both amplitude and FFT.

A.13 Accept test results

Test no 1	Hz	mV	Test no 2	Hz	mV	Test no 3	Hz	mV	Test no 4			Test no 5			AVG	
Length	Frequency	Amp	Length	Frequency	Amp	Length	Frequency	Amp	Length	Frequency	Amp	Length	Frequency	Amp	Length	Freq
1	2400	300	1	2300	280	1	2200	280	1	2100	273	1	2200	260	1	2240
2	1300	322	2	1450	305	2	1400	318	2	1500	305	2	1500	305	2	1430
3	970	340	3	1200	320	3	1100	334	3	1100	325	3	1200	325	3	1114
4	750	350	4	900	340	4	860	342	4	870	340	4	860	345	4	848
5	630	355	5	650	350	5	650	350	5	670	350	5	700	350	5	660
7,5	400	360	7,5	425	360	7,5	420	360	7,5	420	360	7,5	420	360	7,5	417
10	280	370	10	280	360	10	260	366	10	265	365	10	270	365	10	271
12,5	200	370	12,5	190	370	12,5	180	370	12,5	175	375	12,5	180	370	12,5	185
15	150	378	15	135	380	15	128	382	15	122	386	15	130	382	15	133
17,5	115	385	17,5	100	390	17,5	97	390	17,5	81	394	17,5	87	390	17,5	96
20	87	390	20	70	395	20	67	394	20	55	382	20	60	390	20	67,8
22,5	65	390	22,5	50	382	22,5	40	370	22,5	33	358	22,5	39	365	22,5	45,4
25	50	382	25	33	362	25	37	350	25	13	330	25	20	340	25	30,6
27,5	33	362	27,5	15	330	27,5	10	326	27,5	0	0	27,5	0	0	27,5	11,6
30	23	346	30	0	0	30	0	0	30	0	0	30	0	0	30	4,6
32,5	0	0	32,5	0	0	32,5	0	0	32,5	0	0	32,5	0	0	32,5	0
35	0	0	35	0	0	35	0	0	35	0	0	35	0	0	35	0
37,5	0	0	37,5	0	0	37,5	0	0	37,5	0	0	37,5	0	0	37,5	0
40	0	0	40	0	0	40	0	0	40	0	0	40	0	0	40	0
42,5	0	0	42,5	0	0	42,5	0	0	42,5	0	0	42,5	0	0	42,5	0
45	0	0	45	0	0	45	0	0	45	0	0	45	0	0	45	0
47,5	0	0	47,5	0	0	47,5	0	0	47,5	0	0	47,5	0	0	47,5	0
50	0	0	50	0	0	50	0	0	50	0	0	50	0	0	50	0
No interference	0	0	No interference	0	0	No interference	0	0	No interference	0	0	No interference	0	0		
	Frequency	Varience		Frequency	Varience		Frequency	Varience		Frequency	Varience		Frequency	Varience		

Figure A.61: The full table of measured results of the range test of the entire system.