Capacitive Sensing Unit

Analogue Project

Aigner Christoph
Meadowcroft Chad

March 10, 2016

Contents

1. Initial Idea **3**

2. Development Schedule **3**

3. Components **5**

3.1. Relaxation Oscillator Circuit . . . 5

3.1.1. Oscillator Properties . . . 6

3.1.2. Can Capacitors . . . 7

3.2. FM-Demodulation Circuit . . . 7

3.2.1. Calculation of Low-Pass Filter . . . 8

3.2.2. Calculation of Signal Amplification . . . 8

4. Tests and Measurements **9**

4.1. Frequency Deviation from Calculations . . . 9

4.2. Frequency Change of Two Sensing Circuits . . . 9

4.3. Transfer Function of the Active Low-Pass Filter . . . 10

5. Discussion and Issues **11**

Appendices **13**

A. Breadboard Images **13**

A.1. Relaxation Oscillator . . . 13

A.2. Active Low-Pass Filter . . . 13

A.3. Overall Circuit . . . 14

B. Can Capacitors **14**

C. Equipment and Key Components **15**

1. Initial Idea

Capacitive sensing is used in many technological areas from control units for elevators to smart phone touch screens. The sensitivities in each case will vary between where (almost) touching will trigger a reaction to near field applications, where the proximity of an approaching body (up to 10cm) can be detected. In order to find out about the functionality and principles of such sensing units, we want to create a device that is similar to a simple near-field sensing panel.
The idea is that a common metal object will be used as the sensing capacitor. It should be coupled with a relaxation oscillator circuit, which generates an output signal with a frequency that is related to the capacitance of the metal object. If we approach the sensing capacitor or touch it, the capacitance of that circuit is manipulated, resulting in a change of frequency at the output. Variable base capacitances will be tested in order to find the optimum circuit construction that is suited for touch recognition or proximity detection.
Several copies of this device can then be coupled with a simple FM-demodulator and the resulting signal could be played through a speaker. The aim is that, when a hand is moved across the field of multiple sensors, the capacitance will change, leading to a change in output frequency which leads to a sound that mimics the hand movement. The observed change of the audio signal is a practical illustration of the change in the near field of the capacitive sensors.

2. Development Schedule

Here, a schedule of deadline and task phases as well as meetings with the supervisors Johan Wernehag and Henrik Sjöland are noted.
red - mandatory attendance
blue - regular attendance
black - milestone target date
green - milestone credit date

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Jan 18th **1** 10.00 Course Introduction	19th **2**	20th **3** 13.45 Initial Team Meeting 14.15 Meeting w. Supervisors	21st **4**	22nd **5**	23rd **6**

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
25th **7** 15.00 Supervisor Meeting	26th **8**	27th **9**	28th **10**	29th **11**	30th **12**
Feb 1st **13** Finished Concept	2nd **14**	3rd **15** Finished Concept 15.00 Supervisor Meeting	4th **16**	5th **17**	6th **18** Sensing Circuit Finished
8th **19**	9th **20**	10th **21** Sensing Circuit Finished 15.00 Supervisor Meeting	11th **22**	12th **23**	13th **24** FM-Circuit Finished
15th **25** 15.00 Supervisor Meeting	16th **26** FM-Circuit Finished	17th **27** 11.00 Supervisor Meeting	18th **28**	19th **29** 15.00 Supervisor Meeting	20th **30**
22nd **31**	23rd **32**	24th **33**	25th **34**	26th **35**	27th **36** Fine Tuning and Testing Finished
29th **37**	Mar 1st **38**	2nd **39**	3rd **40** Fine Tuning and Testing Finished	4th **41** Report Finished 13.15 Meeting Supervisor	5th **42** Report Finished
7th **43** 15.00 Report Deadline	8th **44**	9th **45** 10.15 Presentation	10th **46**	11th **47**	12th **48**

3. Components

Here we state the components used, all circuit values and motivations for each choice. Our motivations for each component are based on a mixture of calculation, simulations in LTSpice, advice from our project advisor and practical circuit testing. The resultant breadboard implementation of the circuits can be observed in the appendix A.3.

3.1. Relaxation Oscillator Circuit

A relaxation oscillator as depicted in Figure 1 is the main element of the project. Its functionality is based on a capacitor discharge, so the relaxation of a charge [3]. The choice of this type of circuit was taken because the output frequency is dependent upon the capacitance of C_{prox}, which we can manipulate easily. The relaxation oscillator con-

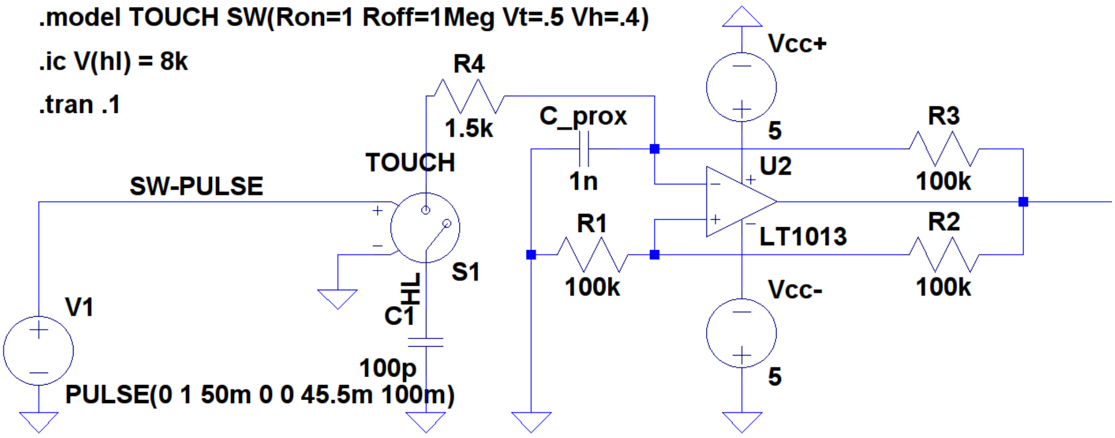


Figure 1: Simulation construction of a relaxation oscillator in LTSpice. The sensing capacitor is C_{prox} and SW-PULSE simulates touch. The touch is regulated by the capacitor C_1 and the resistor R_4 that influence the circuit for about $50ms$, these components are set to ground every $(50 + k \cdot 100)ms$ with $k = 0, 1, 2, \ldots$. The op-amp supply voltage is set to $\pm 5V$ adhering to the optimal operating conditions of the XOR-gate mentioned in Section 3.2.

sists of the resistances R_1, R_2, R_3 and capacitor C_{prox} which are wired to an operational amplifier.

According to the Electronic Discharge Association (`https://www.esda.org/`), a human body can be approximately modelled by the capacitor C_1 and the resistor R_4 and the respective values shown for each [1]. The capacitor C_1 is assumed to be fully loaded and storing a high voltage potential, which we show with the initial condition of the voltage labelled HL being $8kV$.

When this simulation is run, the output frequency is increased as the 'human touch' occurs. Testing the circuit in reality gives a drop in frequency of the oscillation when a touch occurs. Further tests and measurements can be found in Section 4.

3.1.1. Oscillator Properties

Oscillation Progression The voltage V_+ set at the non-inverting input of the op-amp is calculated by the voltage divider:

$$V_+ = \frac{V_{out}}{2} \tag{1}$$

V_- is calculated with Ohm's law and the capacitor differential equation:

$$\frac{V_{out} - V_-}{R_3} = C_{prox}\frac{\mathrm{d}V_-}{\mathrm{d}t} \quad \rightarrow \quad \frac{\mathrm{d}V_-}{\mathrm{d}t} + \frac{V_-}{R_3 C_{prox}} = \frac{V_{out}}{R_3 C_{prox}} \tag{2}$$

Solving this differential equation for the initial conditions $V_{out} = V_{cc+}$ and $V_- = 0$ at time $t = 0$, we get:

$$V_- = A + Be^{\frac{-1}{R_3 C_{prox}}t} \quad \rightarrow \quad V_- = V_{out} + (-V_{cc+})e^{\frac{-1}{R_3 C_{prox}}t} \tag{3}$$

The operation of the oscillator circuit can also be explained descriptively as follows; first, the oscillator circuit generates a square wave. The op-amp starts with its two inputs in an unknown state, we consider the non-inverting input of the op-amp to have a slightly higher voltage than the inverting one. The op-amp amplifies this difference, which appears at the output as the op-amp's positive power supply voltage (PSV). The resistors R_1 and R_2 act as a voltage divider that sets the non-inverting input to half the output voltage. The inverting input is at ground, lower than the non-inverting input, thus the op-amp output stays at the PSV.
Meanwhile, current flows from the op-amp output to ground through the capacitor and charges it. Once the charge is greater than the PSV the inverting input voltage will be higher than the non-inverting input, causing the output to flip to the negative power supply voltage (NSV). The non-inverting input is set to half of the NSV.
Current will then flow in the other direction, discharging the capacitor and reversing its polarity until it reaches the NSV. Once NSV is reached, the cycle repeats from step 1.

Oscillation Frequency We ignore the initial charge of the capacitor, which is irrelevant for frequency calculations. We know that charges and discharges oscillate between $V_{th} = V_{cc+} \cdot k$ and $-V_{th} = V_{cc-} \cdot k$ with $k = \frac{R_1}{R_1+R_2}$ being a voltage divider. In our circuit, V_{cc-} must be less than 0. At half of the period T, V_{out} switches.
Our aim is then to calculate the time period T, in order to find our active oscillation frequency. We examine the time when the oscillation curve switches from the positive to the negative value. Coefficient values like in Eq. (3) can be obtained with the standard formula for a capacitor loading curve in DC applications:

$$V_C = V_{init} + (V_f - V_{init})(1 - e^{-\frac{1}{RC}t}) \,, \tag{4}$$

where the capacitor voltage V_C is the voltage at which the switch takes place (V_{th}). Assuming a stable oscillation, V_{init} is the negative pendant of the threshold voltage,

$-V_{th}$. The value V_f, which the capacitor tries to reach, is V_{cc+} as this is the current op-amp output. R and C of the time constant are the same as in Eq. (3). Setting these values and solving gives $\frac{T}{2}$:

$$V_{th} = -V_{th} + (V_{cc+} - (-V_{th}))\big(1 - e^{-\frac{1}{R_3 C_{prox}}\frac{T}{2}}\big) \tag{5}$$

$$V_{cc+} \cdot k = kV_{cc-} + (V_{cc+} - kV_{cc-})\big(1 - e^{-\frac{1}{R_3 C_{prox}}\frac{T}{2}}\big) \tag{6}$$

$$V_{cc+} \cdot k = -kV_{cc+} + (V_{cc+} + kV_{cc+})\big(1 - e^{-\frac{1}{R_3 C_{prox}}\frac{T}{2}}\big) \tag{7}$$

$$\frac{V_{cc+}(2k)}{V_{cc+}(1+k)} - 1 = -e^{-\frac{1}{R_3 C_{prox}}\frac{T}{2}} \tag{8}$$

$$\ln\left(\frac{1-k}{1+k}\right) = -\frac{1}{R_3 C_{prox}}\frac{T}{2} \tag{9}$$

$$T = 2\ln\Big(\frac{1+k}{1-k}\Big) R_3 C_{prox} \;\; ([4] \text{ for } R_1 = R_2) \tag{10}$$

For the parameters of the presented circuit the period T is

$$T = 2\ln\Big(\frac{1+\frac{1}{2}}{1-\frac{1}{2}}\Big) \cdot 100k\Omega \cdot 1nF = 219.7\mu s \tag{11}$$

which is equivalent to the oscillation frequency $f = 4551.2Hz$ while our simulation results in $f = 3906.3Hz$. We already see that we will have to deal with some degree of error due to real components that are not ideal.

3.1.2. Can Capacitors

Regarding the sensing capacitors, we wanted something simple to build, variable in capacitance and ideally made from a household object. This would give good variability of testing as well as adding D.I.Y aspect to the design. We had the idea to construct the sensors from aluminium drinks cans (see Appendix B). The shape is cylindrical so our capacitor calculations follow that of a wide coaxial cable.

3.2. FM-Demodulation Circuit

For demonstrative reasons, we agreed the effect of the circuit is best illustrated via sound through a speaker. The idea is that a change in frequency of the sensing circuit can be audible. To achieve this goal, we created the circuit shown in Figure 2 in order to generate a signal of the right qualities to be played back through a speaker. This circuit takes two frequency signals from two sensing circuits respectively and performs an XOR operation on them. This operation may be seen as a very rudimentary measure of correlation between the compared signals. If both signals at sample time have values below or above a certain threshold, the XOR-output is $0V$. In any other case, the output is $5V$ (in accordance with a supply voltage of $5V$). The short term frequency

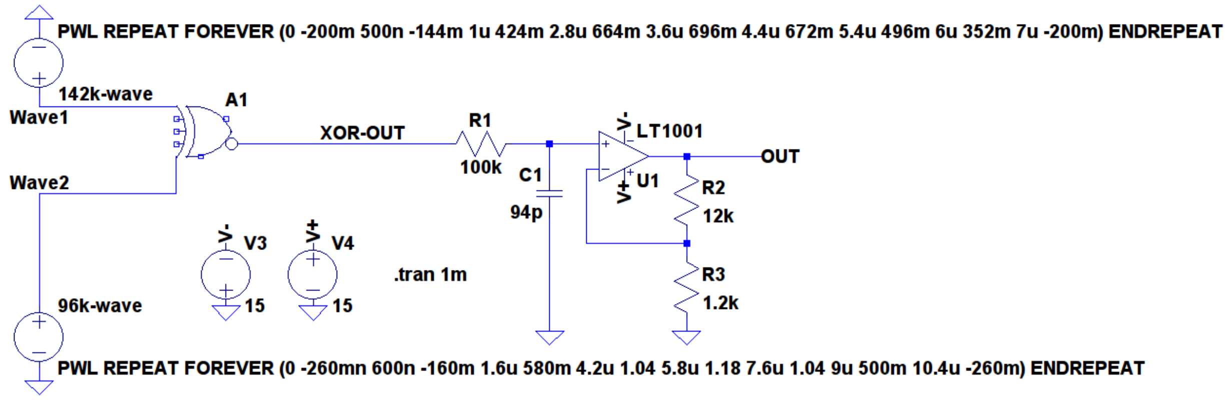


Figure 2: The frequency demodulating component is an XOR-gate which has its output coupled to an active low-pass filter. The low-pass filter is implemented to reduce noise in high frequency parts of the signal. The XOR-gate is driven with a supply voltage of $5V$, the amplifier with $\pm 15V$.

fluctuations may add noise to our output signal so a low-pass filter (LPF) is connected in series after the XOR-gate to smooth out the waveform. Note that the speaker also has a filter included, but adding a second here can smooth out the signal even further. Finally, as the circuits are driven with a relatively low voltage, a non-inverting amplifier is inserted before the signal reaches the speaker in order to obtain an amplitude of an audible level.

3.2.1. Calculation of Low-Pass Filter

We designed the LPF to have a cut off frequency just below that of the human ear, this is to ensure that only audible frequencies are amplified [2].Humans can hear roughly from $20Hz$ to $20KHz$ so we decided on a cut off of $17kHz$. The cut off frequency f_c for components as they are shown in Figure 2 and as used in our circuit is found simply by:

$$f_c = \frac{1}{2\pi C_1 R_1} = \frac{1}{2\pi \cdot 94pF \cdot 100k\Omega} = 16931.4Hz \tag{12}$$

3.2.2. Calculation of Signal Amplification

The gain function of the non-inverting amplifier is:

$$A = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_3} = 1 + \frac{12k\Omega}{1.2k\Omega} = 11 \tag{13}$$

where V_{out} is the output voltage and V_{in} is the input voltage at the amplifier. This value is equivalent to $|A|_{dB} = 20.83dB$.

4. Tests and Measurements

The following section presents tests and respective results related to the performance of the circuit as well as independent measures of the capacitive sensors and other components of the audio system as a whole.

4.1. Frequency Deviation from Calculations

The relaxation oscillator's component values can be calculated by considering ideal functionality. Achieving a real behaviour close to ideal is difficult to achieve. In order to be able to select different configurations for the relaxation oscillator circuit, measurements were performed to obtain knowledge about the deviation factors that have to be taken into account at the configuration stage of the circuit.
For the first test, we chose the component values $R_1 = R_2 = 100k\Omega$ and $R_3 = 470k\Omega$ and varied the capacity C_{prox} using different ceramic capacitors. A second test changes R_3 to $100k\Omega$.
The measured and calculated frequency values can be found in Table 1. From these val-

	$R_3 = 470k\Omega$		$R_3 = 100k\Omega$	
$C_{prox}[pF]$	$f_{calculated}[kHz]$	$f_{true}[kHz]$	$f_{calculated}[kHz]$	$f_{true}[kHz]$
1	968.34	11.30	4551.20	46.58
2.2	440.20	10.02	2068.73	45.91
4.7	206.00	6.71	968.34	44.68
10	96.83	10.00	455.12	42.32
22	44.00	8.86	206.87	37.49
47	20.60	6.76	96.83	30.85
220	4.40	2.02	20.69	13.56
470	2.06	1.69	9.68	7.74

Table 1: Calculated and measure frequencies of an oscillation circuit.

ues, a correction factor ϑ can be computed to compensate for our circuit misbehaviour, so that $f_{true} = \vartheta \cdot f_{calculated}$. The respective values can be found in Figure 3. We see that for lower capacitances C_{prox}, the calculation's offset is significant. The frequency deviation shows a nonlinear behaviour. We are not sure about the cause, but can suggest some factors that could be the case: capacitive properties of the breadboard, connection resistances, capacitances and resistances due to long cablings.

4.2. Frequency Change of Two Sensing Circuits

Two identical relaxation oscillators were installed as sensing circuits. Their component values have been determined by estimation through calculation and empirical testing. R_1 and R_2 keep the value $100k\Omega$, but R_3 is installed with $470k\Omega$. The can capacitors are adjusted such that one oscillation circuit has an output frequency of $5kHz$ and the other $7.5kHz$. These settings were chosen as they provide a signal with the greatest

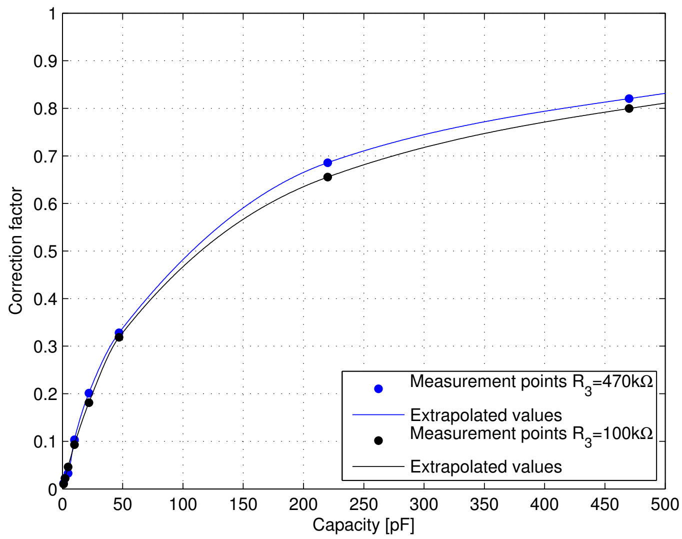


Figure 3: Calculation correction factors ϑ for $R_3 = 470k\Omega$ and $R_3 = 100k\Omega$.

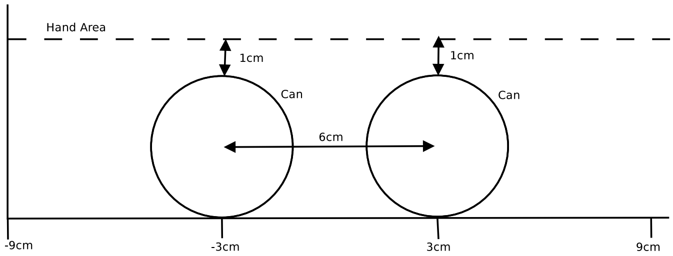
perceived change in frequency (pitch) for an idle listener [1].
The experiment works with the two can capacitors lying next to each other on their long sides. Their centres are $6cm$ apart from each other. A test person waves their hand over the capacitors, triggering the oscillation frequencies and thus the output of the XOR-gate to both change. The hand's vertical distance to the capacitors thereby was about $1cm - 2cm$. The second dimension in which the hand waves is alongside the short and round sides of the can going from $6cm$ left of the first can to $6cm$ right of the second can [2]. The measuring setup is depicted in Figure 4a. Figure 4b shows the results of the approach. We spot slightly decreased frequencies at the capacitors where the middle of the hand is located close or directly above them. The frequency change of the second (right) capacitor is stronger as the capacity is adjusted to be lower than that of the left hand one. We can see in Figure 1 that the circuits external capacity is set parallelly . Sensitivity is greater for a lower capacitance as the approaching body part will make a larger relative difference in value.

4.3. Transfer Function of the Active Low-Pass Filter

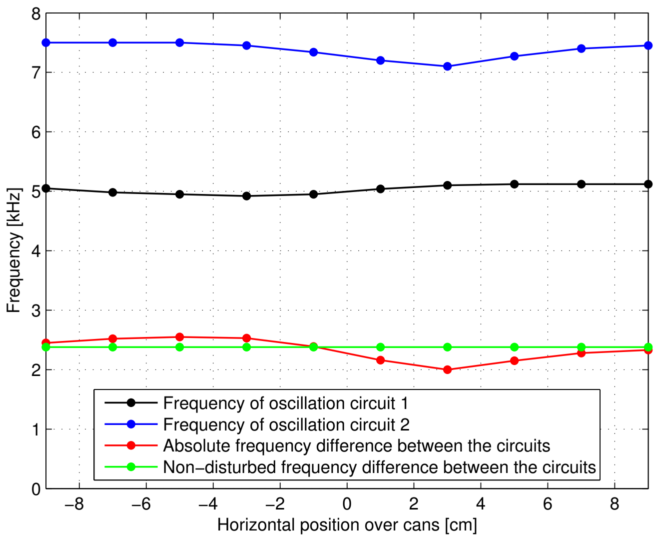
The measured operating range of the whole active LPF (LPF and non-inverting amplifier) is depicted by the Bode diagram in Figure 5.

[1] Almost equal frequencies lead to nearly no change of the discrete XOR-gate output. Thus there is no oscillation to be processed by the speaker. Only for very close field alterations at the oscillators, audible signals were produced

[2] No framework was built to keep an even distance to the setup, so distance measurements sometimes depended on an educated guess.



(a) Can setup for the sensitivity test.



(b) Change in oscillation frequency induced by waving a hand 1cm above the can capacitor setup.

Figure 4: Measurement of the can capacitor frequency response.

5. Discussion and Issues

During the testing sessions, we were experiencing frequency offsets between the circuits the two handmade can capacitors are connected to. Their adjustment proved to be problematic at several occasions, especially when we wanted to measure the sensitivity progression over two cans in Section 4.2. At that point we came up with the idea that this difference may not necessarily be a disadvantage. The difference in properties between the cans could let us differentiate an audible signal even better.
For completeness, we must state that the sensor cans are not just influenced by our hands but also by the environment around and amongst each other. As their positions are fixed, the latter influence should be stable and not disturb measurements.
Decoupling is not found in the pictures added in the appendices in terms of better visibility of components. Capacitors must be added to the power supplies of the op-amps

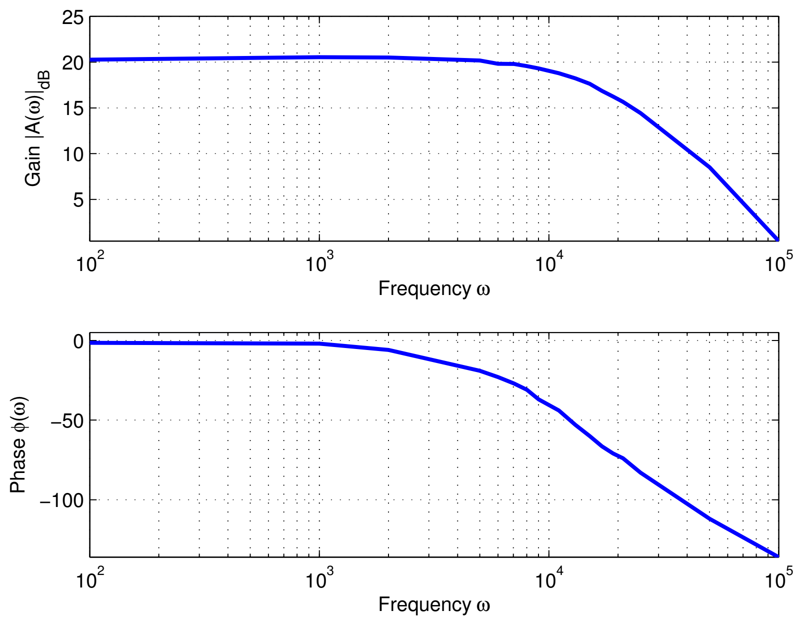


Figure 5: Bode diagram of the active low-pass filter. The op-amp is driven by a supply voltage of $\pm 15V$ with a regular sinusoid input signal.

and the XOR-gate to compensate for noise, we added these at the end and noticed some improvement in noise and self inductance reduction.

References

[1] Fundamentals of Electrostatic Discharge, Part Five - Device Sensitivity and Testing. ESD Association, Rome, NY. 2010.

[2] A. P. Godse, U. A. Bakshi. Semiconductor Devices and Circuits. Technical Publications Pune. ed. 6, p. 668, 2008.

[3] J. Fraden. Handbook of Modern Sensors: Physics, Designs, and Applications. Springer. 2015.

[4] R. J. Herrick. DC/AC Circuits and Electronics: Principles & Applications. Cengage Learning. pp.1146, 2003.

Appendices

A. Breadboard Images

A.1. Relaxation Oscillator

Figure 6 shows how the relaxation oscillator translated to a breadboard. The black banana connector indicates ground, the red one a positive voltage and the yellow one a negative voltage.

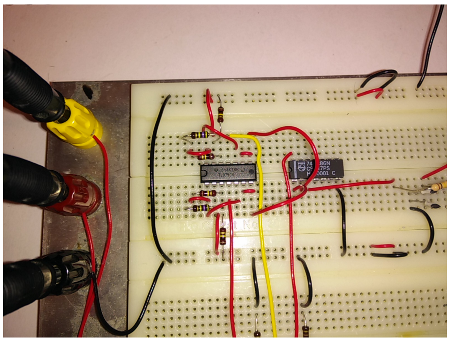


Figure 6: Two relaxation oscillators (left) on a breadboard that are coupled to an XOR-gate (right).

A.2. Active Low-Pass Filter

Figure 7 shows how the active LPF translated to a breadboard.

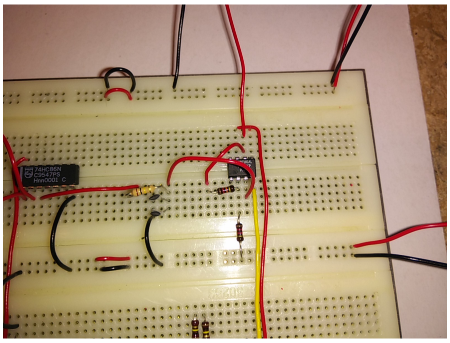


Figure 7: An active LPF (right) receiving the output signal of the XOR-gate.

A.3. Overall Circuit

Figure 8 shows our whole circuit all integrated on a breadboard. The black banana connector indicates ground, the red one a positive voltage and the yellow one a negative voltage.

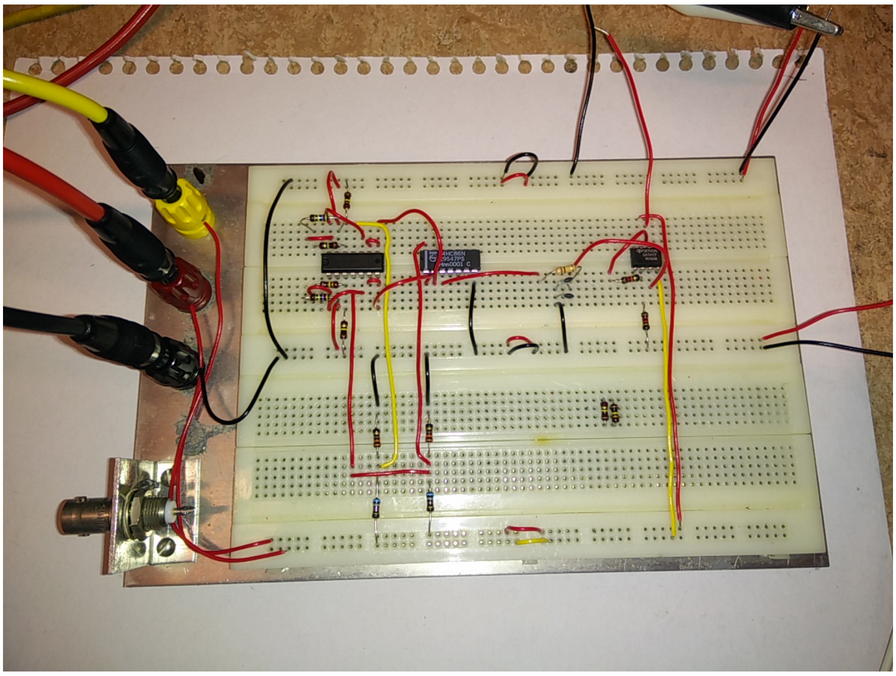


Figure 8: From left to right: sensing circuit, XOR-gate and active low-pass filter. The can capacitors are connected via the wirings at the far right of the picture. The test rod of the oscilloscope is connected to the output of the circuit. For clarity reasons, no decoupling elements are connected at the power supply terminals of the components in this picture.

B. Can Capacitors

The can capacitors were built by taking two metal cans, an outer and an inner, cutting open the outer and sliding the inner inside. A medium of cardboard was added in between to help achieve a uniform distance between and eliminate the possibility of a short circuit between the two.
Each can then was sanded at a point where wires were then soldered on to, here we are hoping to achieve minimum connection resistance. Because of the design of our capacitors, it is possible to change the capacitance by sliding the inner can further into, or out of, the outer can. The lowest capacitance is achieved when the inner can is almost completely removed from the outer, this is because the active surface area

decreases. Check out our fancy design in Figure 9.

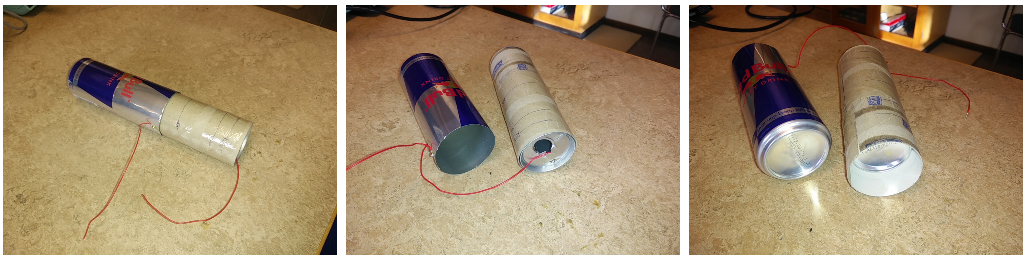


Figure 9: Practical realization of a can capacitor.

C. Equipment and Key Components

For measurements and testing, the following instruments were used:

1. Oscilloscope LeCroy waveAce 202, $60Mhz$, $1GS/s$
2. Power Supply Powerbox $3000B$
3. Signal Generators Leader LFG-1300

The components in the circuit we used were:

1. NXP Semiconductors XOR-gate $74HC86N$
2. Texas Instruments low-noise JFET-input operational amplifier $TL074CN$ for the relaxation oscillator circuit
3. Texas Instruments general-purpose operational amplifier $uA741CP$ for the active low-pass filter