Monitoring of Respiratory and Cardiac Activity based on Piezoelectric Textile Sensors

Master's Thesis in Biomedical Engineering

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Abstract

Monitoring health and health related mechanisms is a growing area of interest. In a laboratory environment it is possible to measure most of these aspects, but in a real situation outside the lab where resources are limited some difficulties may occur. In this study, the focus has been to monitor respiratory and cardiac activity using a recently developed textile sensor which potentially can improve health monitoring and be easier applied in long-term investigations in real/everyday situations. The sensor is made of fibres which have piezoelectric characteristics, and has been proven to stand the forces involved in a weaving process, and can thus be weaved into fabrics. When a force is applied to such fabrics an electrical signal is generated. In an earlier study it was shown that the fabrics can detect stimuli at a few Hertz, but this is not sufficiently low to monitor respiration, which requires a system sensitive to at least tenths of Hertz. The aim of this report was to investigate whether it is possible to extend the low frequency characteristics of the sensor in order to use these fibres/fabrics to monitor respiration and cardiac activity.

A signal conditioning circuit has been created which main circuits are a voltage follower and a charge amplifier. By this configuration the input impedance can be sufficiently high for the conditioning circuit to reproduce the weak electric signal from the piezoelectric sensor. Depending on different aspects such as; the force applied to the textiles, dimensions of the textiles and input impedance of the signal conditioning circuit, different amplification levels may be needed, but is in the order of 100 times. A trade-off of extending the low frequency range to be able to monitor respiration is a slow system response with time lag. These two aspects needs to be considered and balanced in relation to the intended application.

In order to evaluate the entire sensory system, i.e. the textile sensor and the signal conditioning circuit, a test setup was created where repeatable and controllable measurements could be performed. The test setup enabled three different signals: 1) a sinusoid generated by an ex-centric point at DC motor shaft, 2) a step generated by a dropped weight at steady state and 3) a motor-driven ramp followed by a step. Using this setup, the sensors and signal conditioning circuit proved to have its low end sensitivity lower than 17 mHz, which is well below requirements of monitoring respiration. Due to the fact that varied circuit characteristics may be required for different textile samples and applications, the signal conditioning circuit can be adjusted in gain and offset to match the analogue to digital converter of the transferring unit, in terms of maximum output and resolution. The transferring unit could be a bluetooth unit (in this case an Arduino board) which transfers the signal to a computer for real time presentation of the signal.

Finally, the sensor system was compared to a previously suggested textile solution to monitor respiration, based on piezoresistive textiles in a Wheatstone bridge. By comparing both textile solutions it was found that the piezoelectric system is limited to dynamic forces and needs less manual adjustments/calibration prior to measurements while the feeding of a comparative bridge can exchanged to an amplifier. The suggested system was proven to be useful, but needs further development for practical use. Nevertheless it was found that piezoelectric fibres can be used to measure low frequency forces, close to static levels.

Keywords: Smart Textiles, Piezoelectric, Charge Amplifier, Respiratory monitoring, Heart Beat, Signal Conditioning, Cut-off Frequency

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David Wristel, Gothenburg October 24, 2014

Contents

List of abbreviations

PVDF = poly(vinylidene fluoride)
THS = Swedish School of Textiles (Textilhögskolan)
ADC = Analogue to Digital converter
ECG = Electrocardiogram
SNR = Signal to Noise ratio
FFT = Fast Fourier transform

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1 Background

In the hospitals today there are several methods to measure and monitor human body activities which can be vital for health. These techniques are often well known and reliable, but this does not make them optimal in every situation. With new developments and new equipment introduced there are new building blocks that the measurement systems can use, making it possible to develop them even further. One such interesting possibility is *smart textiles*, a term which has several descriptions but, the ability to sense or alter their characteristics depending on the surroundings is common to all of them [1].

In many situations today it is possible to measure most things that can be of interest when it comes to humans, but are limited to a lab environment. Inside labs it is possible to connect large systems with lots of possibilities when it comes to computational power, power consumption and sensitivity, but in a lab it is hard to mimic a normal situation. To be able to use a system in reality to measure realistic situations and perform long term investigations it is in most cases not possible to be inside a lab, and adding availability for many users it is definitely not realistic in a lab. For this reasons it is necessary to use systems which are compact and with high usability (with all that is included, such as small size, low power consumption, easy to interpret results and so on). This is one area where smart textiles might be useful.

In the area of smart textiles there are many different possibilities, ranging from relatively simple solutions where e.g. conductive textile is used as cables that can be incorporated into fabrics, to more advanced situations of large sensor system detecting signals and altering its characteristics, or even energy harvesting from sensors which generates an electrical signal [2]. Depending on the situation and the complexity of the system the fabrics can be used in various objects e.g. clothes, mattresses or furniture. The flexibility of this technology makes it possible to build advanced systems and preserve the softness and comfort of the textiles. Regarding the area of smart textiles as sensors, these could possibly be incorporated into fabrics which might simplify application and increase comfort when needed, for example when measuring signals from human bodies. This could be relevant in many situations, especially if the measured object is sensitive or are to use the sensors for a long period of time. By different sensors it is possible to measure both external signals, but also inject signals into the body, by for example textile antennas.

When it comes to smart textiles there are several different kinds, and two examples are piezoelectricity and piezoresistivity. Regarding piezoresistivity in a ”normal” application, it is possible to create materials which alter its resistance as the material is stretched due to an applied force. This property can be added to textiles making it useful in different areas as sensors. One application where this can be used is in human monitoring, e.g. monitoring respiration [3]. In the case of piezoelectricity it has been found that a fibre made of PVDF is generating a signal when a force is applied [11]. For a fibre with integrated piezoelectric properties, the resulting output signal is dependent on both the amplitude and direction of the force (pressure and/or stretching) and can thus be used to detect movements.

1.1 Applications

Several interesting applications exist, and especially in situations where it is required to monitor signals over longer periods of time. An example of an area which often has this requirement and is hard to measure in an out of laboratory situation is respiration. Since respiration is under the autonomic nervous system where it in a normal situation is automatic but voluntarily controllable, it is hard to measure the truly normal activity [4]. When a person under test is aware of the test, he/she might influence the result, which is undesired. In a laboratory situation it is relatively easy to measure and has many solutions, given that the person under test will be aware of it and possible influence it. In a perfect situation it should be possible to measure without the person noticing it, then the natural respiration can be measured. But it is a problem that the solutions often require connections and sensors that the person is not used to. In a critical situation where hospitalization is needed and respiration needs to be monitored for safety reason in a controlled and limited area this is not a problem. However, when it comes to measure in everyday life where dimensions, freedom of movements, comfort, simplicity and costs are important and limiting factors something different is needed.

Nowadays it exist systems to monitor breathing and heart rate, and monitor this remotely on other device, for example Zephyr[1] [5]. This system uses conductive leads to detect the heart rate and a fixed strap around the chest together with a pressure sensor to detect respiration. The system uses the chest expansion when breathing and the pressure sensor placed towards the body. When the chest expands the increased pressure from the fixed band is measured [6]. Other systems where pressure sensors are used exist on the market, but none of these solutions can in the same manner be included in the fabric and clothes as piezoelectric/piezoresistive fibres. The fibres that are used in smart textiles are typically flexible and somewhat elastic which can maintain most of the textile characteristics when it comes to comfort, and are likely to have higher comfort than tight, more or less static strap around the chest. Since it is possible to incorporate these fibres into clothes it should be possible to increase the comfort of the person under test. By increased comfort it is possible to wear the monitoring system for a long time, and with little disturbances due to low comfort. Other problems related to long term investigations is the mobility, where the monitoring unit needs to be without limiting cables, low powered and small. To be able to reach many users, which often is the goal, the unit also needs to be easy to understand and operate, which adds to the list of demands.

1.1.1 Previous work

In a previous work, performed by S. Ratnarathorn, a solution to measure respiration using piezoresistive textiles was created [3]. In the work a shirt consisting of two elastic piezoresistive textile sensors, manufactured by L. Guo, was used [7]. The shirt was designed relatively tight in order to let the shirt follow the chest movements. During inhaling the chest/abdomen extends which alters the resistance of the piezoresistive sensors in the shirt. The sensors were made of conductive coating, more specifically *ELASTOSIL*®LR 3162 from Wacker[2] and the textile substrate was based on PA/Lycra woven fabric [7]. For visualization, an Arduino board, see appendix A, was used to digitize and transfer the signal to a computer with a software interface created in LabVIEW,

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[1] www.zephyranywhere.com

[2] http://www.wacker.com/cms/en/products-markets/brands/elastosil/elastosil.jsp

see appendix B [3, 7].

In another recent study performed by K. Rundqvist, based on previous development by A. Lund [8–10], it was found that it is possible to incorporate piezoelectric fibres in a weaving process and create fabrics with piezoelectric characteristics [11]. By including the fibre in the weaving process it can be included in the fabric and after “poling”, a process where the piezoelectric properties are created, an applied force generates a signal. It was also found by Rundqvist that depending on the construction of the fabrics a given force can result in different signal amplitude. From the measurements performed it was found that the output of such fabrics depends on the weaving structure, the size of the polarized area and the poling process, but is in the range of a few volts and a few nanoamperes[3] [11]. Due to the weak signal it needs to be amplified to be useful. The demands on such amplification circuit is high due to the low current, requiring some kind of impedance transformation to be able to handle the signal.

1.2 Aim

The aim of this study was to investigate the possibilities of monitoring respiratory and cardiac activity by using smart textiles. The work was built on previous research performed by Ratnarathorn, Gou and Rundqvist [3, 7, 11]. In these studies it was shown that it is possible to measure and transfer respiratory signals by the use of a piezoresistive system and that piezoelectric fabrics can be used to detect movements. In the work of Rundqvist it was found that a few hertz could be detected using the textile sensors, but this is not sufficiently low to monitor respiration.

In this study it was investigated whether it is possible to extend and enhance low frequency characteristics of the textile fibres, and by this detect:

- respiration using piezoelectric textile? Under what conditions is this possible?
- cardiac activity using piezoelectric textile? Under what conditions is this possible?

The main part of the investigation is to construct a system which can make a signal from piezoelectric sensors available for evaluation and visualize it on a computer. All parts of the system, from the feeding signal of the textiles to visualization will be created. The suggested unit should have the goal of being portable which requires that:

- signals generated matches the requirements for transmission to a computer
- the signal path from the sensors to the signal conditioning, transmission unit, computer and software needs to be created to be able to present the signal

Further, the following basic design goals should be considered:

- the system should have low power consumption and a monitoring time of a few hours
- the system should be compact enough for portability

By creating such a unit the signals received from piezoelectric and piezoresistive textiles can be compared, since both systems is based on similar solutions. Such comparison will be performed and it will be based on test/evaluation setup as well as tests on person.

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[3] 3V and 14nA for a specific configuration

1.3 Limitations

This study mainly focuses on the hardware that is in between the piezoelectric textile sensors which detects the signals from the body, and the presentation/visualization of the signals. The piezoelectric fibres and the textile design performed at the Swedish School of Textiles (THS) are not in scope of this report. The core of the study is the piezoelectric textile properties, whereas the piezoresistive textile properties are used as reference. The base will be that the fabrics generate signals that can be processed by RC-components[4] and operational amplifiers which can be manually mounted on a circuit board. A design goal is to create a small unit with few components, but it will not be optimized to consist of minimum number of components nor smallest size. In the same manner the signal conditioning circuit will not be optimized for low power consumption as long as it is long enough to for continuously usage, i.e. a couple of hours, in an external environment.

The generated signal will be processed in the conditioning circuit to match the limiting requirements of monitoring respiration and not to be able to adjust for several applications. However, by simple manipulation it should not be a demanding task to alter the circuit for other applications. The criteria of the circuit are limited to handle similar frequencies, but different force and offset requirements to match a transmitter. As a analogue to digital converter and transmitter to send the signal to a computer a commercially available and previously used Arduino board will be implemented. The transferred signal will then be presented in a simple graphic interface, however, optimization regarding visualization will neither be in the scope of this study.

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[4] Resistors and capacitors

2 Theory

As a basis of the work some relevant background theory is presented in the following chapter. The starting point is relevant fundamentals of respiration and cardiac activity. This is then followed by theory regarding piezoresistive and piezoelectric textile. Finally, some basic signal theory and principles for signal conditioning is presented.

2.1 Respiration and cardiac activity

During respiration it is possible to see a movement of the chest and/or the abdomen. Depending on person and situation different types of breathing patterns can be found. By analysing breathing patterns and compare usage of chest and abdomen it can be investigated whether a person is stressed or relaxed [12]. A person that is stressed is breathing faster and higher, i.e. more with the chest than abdomen, whereas a relaxed person does the opposite. When it comes to measure breathing with wearable fabrics it is important that the textiles are tight enough to be stretched during inhalation, but should not limit the movement.

Not only respiration is affecting chest movements, shoulder and major body movements affect the circumference to some extent as well. A smaller change of the circumference is also occurring when the heart beats. As a logic result, higher sensitivity is required if the sensory system should detect heart beats.

Normally the frequency range of respiration is in between 0.1 to $10Hz$ and frequencies relevant for ECG are up to $250Hz$ [13]. However, a full ECG measurement is not required to be able to measure the heart beats, which normally is in the range of $70bpm$ but can be increased due to arrhythmia a few times, up to $300bpm$ [14]. This results in a frequency range of some Hertz, basically the same as respiration. It is also understood that when performing other movements of the body, such motions often falls within the same frequency range which would disturb the measurement. This type of disturbance will be described as *motion artefacts*.

2.2 Piezoresistivity

A piezoresistive object has the ability to alter its resistance in relation to an applied force/stretching. This property can be used in many different applications, but are applied in e.g. pressure sensor for measuring sea depth [15], shear stress measurements [16] and also human monitoring e.g. respiratory rate [3]. Since the resistance changes due forces, it is possible to use a setup to measure the resistance and relate this to the applied force. The fundamental principle is based on the textile structure where one configuration results in a constant resistance, meanwhile another structure has another. Since the resistance is altered depending on the structure of the material a constant applied force should result in a constant molecular structure and therefore a constant resistance. From this a short conclusion can be drawn; it should be possible to use a piezoresistive material to measure static forces. The material can be compared to other types of sensors, i.e. strain gauges [17]. Due to similar appearance the characteristics is also similar, even if strain gauges itself are a wide area [17].

2.2.1 Frequency range

From the theoretical background above, the frequency range for a piezoresistive material is DC, at the low end. At the high end it is instead limited by the time it takes for the material to return to its initial structure. If the time it takes to reconstruct is longer or in comparison to the period of the stimulus it is not possible to use it in the intended application, instead a faster material is needed. This parameter is dependent on material, wearing, among others.

Other limitations which are of importance when it comes to measure the signal are related to the measurement system that is used. In this context the sampling frequency of the measurement system can be a limiting factor which is stated in the Nyqvist theorem, see section 2.6.3. This limitation is however possible to alter by improved measurement system, resulting in a high frequency limit of the reconstruction time.

2.2.2 Output signal

The signal that is derived from piezoresistive measurements is derived using a resistive measurement system to find the resistance of the textile to be able to relate the signal to the applied force. Several such solutions exist with different limitations. By limiting it to usage of a voltage source, fewer but still some ways to measure the resistance of a component exists. One of the easiest is a voltage divider, see figure 2.1. By applying a known voltage over two resistances where one is unknown, i.e. the piezoresistive component, it is possible to derive the resistance according to Ohm's law. This method is relatively easy, but it has low sensitivity.

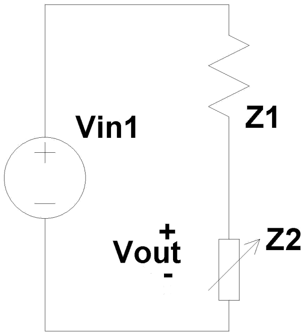


Figure 2.1: Schematics of a voltage divider. The variable resistance is the piezoresistive fabric.

A way to increase the sensitivity is to use a Wheatstone bridge, see figure 2.2 [18]. A description of a special case of the bridge is two parallel voltage dividers where three resistances are known and the fourth are the piezoresistive part. The output signal is the voltage between the two middle points of the dividers [19]. From the configuration a zero output is achieved when the unknown resistance is the same as the others. A benefit of this configuration is that it is possible to calibrate the system to have a zero output when the material is in its normal state/average force. As a result it is possible to alter the normal state which gives the opportunity to control the maximum and minimum output to be in a desired range.

The output signal is therefore not only dependent on the force, material, structure and dimensions, but also on the measurement system that are used. By selecting a

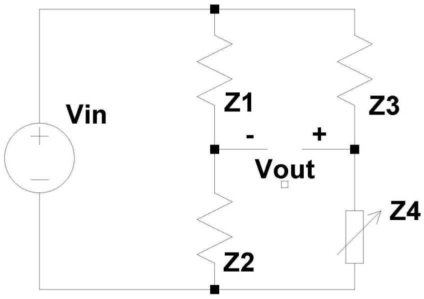


Figure 2.2: Schematics of a Wheatstone bridge. The variable resistance is the piezoresistive fabric.

suitable feeding voltage to the measurement system it is possible to achieve an output signal which is matching the requirements/criteria of the following connected unit.

2.3 Piezoelectricity

In recent research performed by SWEREA it was found that it is possible to create so called functional fibres in different layers, where an outer shell is a ”normal” textile and the inner part of the fibre can have different characteristics [2]. By this formation the fibres preserve the textile functions defined by the properties of the “shell”, such as wash-ability, while the inner part can be used to create e.g. conductive, piezoresistive, piezoelectric or antibacterial layers which makes the material *smart* [2].

In other research it has been found that PVDF and its copolymers can be used to achieve piezoelectric characteristics [20]. A specifically interesting area for piezoelectric textiles is in force measurements where comfort is needed. By applying a force that changes the dimension of the piezoelectric material, i.e. pressure and/or stretching, an electrical signal is generated, making it possible to be used as a force or stretch sensor.

2.3.1 Basic understanding regarding piezoelectric fibres

The fundamental principle of piezoelectric materials is that they are built on differently charged molecules, but in a poling process these have been polarized in a specific order, which is then considered as a ground state for the structure [21]. By applying a force to the material the molecules are forced to move, resulting in an altered structure. To neutralize this new orientation/order of the molecules a voltage is induced over the material [22]. The induced voltage is therefore a measure of the applied force since a larger force results in a heavier rearrangement and therefore higher voltage, see equation 2.1 [22].

$$q = kF \tag{2.1}$$

where q is the charge, k is a material dependent piezoelectric constant with unit C/N and F is the applied force.

By a rough simplification, seeing the piezoelectric material as a parallel-plate capacitor an equation for the output voltage can be found [22]. The voltage for a parallel-plate capacitor with the charge q is seen in equation 2.2 [22].

$$v = \frac{q}{C} \tag{2.2}$$

where C is the capacitance of the capacitor, which can be related to physical properties as equation 2.3 [22].

$$C = \epsilon_0 \epsilon_r * \frac{A}{x} \tag{2.3}$$

In equation 2.3 ϵ_0 is the dielectric constant of free space, ϵ_r is the relative dielectric constant of the insulator between the plates, A is the area of the parallel plates and x is the distance between the plates. By the equation it is found that several parameters can be altered to increase the signal achieved from the sensors. However, the equations are describing a material consistent of pieces of piezoelectric material, and not fibres. Instead, fibres are basically arranged in one specific direction giving a higher signal at increased length. Because of this the length of the active fibres should be maximized for maximized signal.

From earlier equations it is possible to find the theoretically maximum value of a piezoelectric material. By substitute equation 2.1 into equation 2.2 and as well use that the capacitance C is related to the physical properties of equation 2.3, the total voltage output of the piezoelectric material is concluded in equation 2.4 [22].

$$v = \frac{kFx}{\epsilon_0 \epsilon_r A} \tag{2.4}$$

The conclusion from the above equation is that depending of the parameters and material chosen different output signal can be achieved. Depending on the application it is possible to use different materials, dimensions, poling techniques and more, to match the force to optimize the resulting signal.

Another aspect that is relevant to consider is the frequency of the applied force. As nonperfect capacitors are leaking and losing their voltage over time, so does piezoelectric sensors. Because of the leakage and that a signal is generated at applied force, piezoelectric sensors is not suitable for static measurements [23]. However, as long as there is any alteration of the molecular structure, piezoelectricity can be considered as generating a signal that can be measured.

2.3.2 Frequency range

From the presented theory it is understood that it is not possible to measure a static force using piezoelectric materials [23]. In the limit towards static the signal will be weak but as long as there is a change there is also a signal. Theoretically, it will be possible to measure even the smallest of movements, but the processing of the signal will have higher demands. In reality, at the limit of detection, the signal is drowning in noise which is resulting in a lowest possible match between force/movements and textile sensitivity.

On the other side of the spectrum is the high frequency limit. As in piezoresistive measurements sampling is crucial. However, the need of matching the lower cut off frequency to the intended application, the higher cut off frequency is limited by the circuit (current leakage) and molecular rearrangement. In section 2.6.2 it will be seen that lower cut off frequency results in slower system, which limits the high frequency possibilities. Therefore the need of matching the system to the application is again of vital importance.

2.3.3 Output signal

The signal which is generated in piezoelectric textiles is dependent on several factors, such as dimension of active area, applied force, structure and poling technique. The signal which is generated is required to be dynamic, whereas a movement which is close to static should still be measurable. A slower system would result in a lower signal.

To be able to notice the generated signal a circuit to detect the signal needs to be attached to the sensors, and such circuit is affecting the generated signal. By increasing the impedance of the detecting circuit it is possible to increase the voltage which is generated, resulting in a higher output (in voltage mode measurements).

2.3.4 Sensitivity

The sensitivity of the piezoelectric fibres that have been used is dependent on the molecular structure, force and the characteristics of the system. This makes the systems sensitivity dependent on the material used but also poling and weaving structure, which affects the resulting signal [11]. If the textile is exposed for a high force at the initialization of a measurement, a higher force is required to extend it further, which according to equation 2.4 will result in an increased sensitivity (given that the total length of movement is unchanged).

Since the signal that is achieved from the fabrics is low, with respect to current, it is required to have high impedance at the measurement system to get a clear signal. Since the fibres used are based on PVDF, which can be considered to have high impedance [24], it is possible to increase the impedance of the connected circuit for suitable amplification without risking the impedance of the fibres is affecting the total input impedance. From the choice of circuit it is possible to find one which has sufficiently high impedance to extract the signal, which is a limiting factor [25].

2.4 Signal conditioner circuit

As seen in the section about signal generation a signal conditioning circuit which are matched to the generated signal and the intended application is needed. Depending on these factors it could be desired to have different amplification, signal to noise ratio (SNR), cut off frequencies and so on. By increasing the SNR of the measurement lower demands are put on the conditioner circuit due to more obvious signal. By using the criteria of a specific application it is possible to perform some signal processing to enhance the signal to match the specific application. Such processing can be for example low pass filtering when the signal is known to be of low frequencies. By the use of such filters and knowledge it could be possible to lower the amount of noise in the signal and increase the SNR.

The signal that is created is maximized, regarding voltage, when current is minimized, which is achieved by high impedance. This is achieved by having operational amplifiers in some configuration, which will be described further on. It is also required to have some gain in the system to match the requirements. By some research it is found that for example a voltage mode amplifier or a charge amplifier can be used.

2.4.1 Voltage follower

The most basic active circuit that can be used is a voltage follower, see figure 2.3. It is used as a buffer to avoid negative interference between different sections of the conditioning circuit, therefore it is also called buffer amplifier [26]. As long as the operational amplifier is in its linear range, the output of a voltage follower will be the same as the input [27]. Due to the properties of the operational amplifier it is possible to extend the system without affecting the previous step. One property of an ideal operational amplifier is that the input impedance at the ports are optimally infinite. In reality it does not reach infinity, but is of a high value.

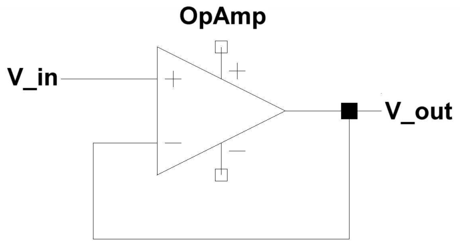
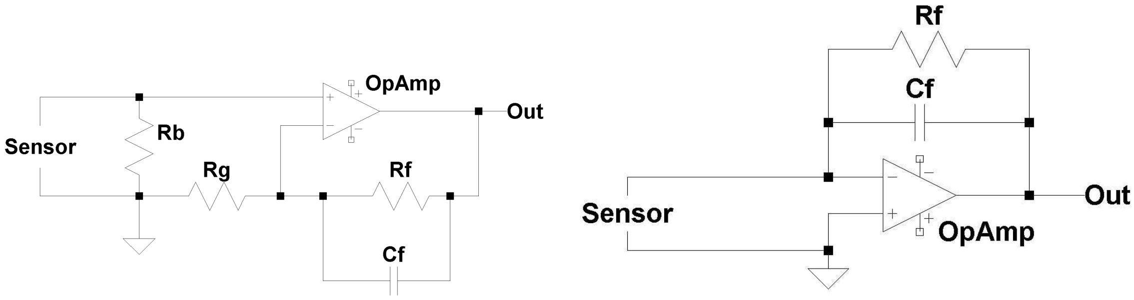


Figure 2.3: Voltage follower. No other components than an operational amplifier in negative feedback.

2.4.2 Amplifier circuit

It exist several types of circuit solutions which amplifies the signal. There are mainly two types of circuits used for piezoelectric materials; voltage mode amplifier and charge mode amplifier, see figure 2.4 [25]. Both circuits can be used for signal amplification whereas there are some different properties that will be described.



(a) Voltage mode amplifier

(b) Charge mode amplifier

Figure 2.4: Different amplification circuits.

One similarity is that both circuits are based on a negative feedback loop with resistor and capacitor in parallel. The capacitor is affecting the flow in the circuit since it charges at incoming current, which affects the related cut off frequencies. In theory the charge is then stored in the capacitor until it is uncharged by an outgoing current. Without both phases the voltage across saturates the amplifier. However, in reality there is some leaking over the capacitor which discharges it. By attaching a resistor the leakage of the capacitor can be somewhat controlled [28]. Because of this charging/discharging phase a signal that are symmetric[1] around zero voltage and evenly will have the same period, resulting in a signal that are periodic over time. If the signal instead is biased with a DC voltage or not symmetric around zero, the output is also biased. Note that the capacitor and amplifier has maximum capacities which limit the voltage across the capacitor. For resulting figures of the characteristics chosen see chapter 4.

In figure 2.4(a) a voltage mode amplifier is illustrated. The characteristics of the amplifier are based on the components used in the circuit as equation 2.5 and 2.6 [20, 25].

$$g = 1 + \frac{R_f}{R_g} \tag{2.5}$$

$$f_{high} = \frac{1}{2\pi R_f C_f} \tag{2.6}$$

At the lower end there are limitations of the parasitic capacitances over the sensor and between the attached cables. This result in a lower cut off frequency dependent on parasitics, see equation 2.7 [25]. By increased parameters the high cut off can be lowered giving a slower system, but since parasitics are affecting the lower end, this value is not arbitrary in the same manner.

$$f_{low} = \frac{1}{2\pi (R_p||R_b)(C_p||C_c)} \tag{2.7}$$

In equatiopn 2.7, R_p and C_p are parasitic resistance respective capacitance in the sensor, whereas the C_c are parasitic capacitance parallel to R_b.

Even though it is possible to use a voltage mode amplifier there are some drawbacks that limits the characteristics. According to Webster [21] there are specifically some reasons why not to use a voltage mode amplifier in piezoelectric measurement system. The main reason is seen in the equations, where the voltage amplifier has a higher cut off frequency that is related to the component chosen, but the lower cut off is dependent on undesired parasitics. Since the lower cut off frequency is the limiting factor of the intended application this is a large drawback. This makes the system dependent on the connections of the sensors, which of course are undesired [21].

To avoid the limitations from a voltage mode amplifier a charge mode amplifier can be used instead, see figure 2.4(b). This kind of amplifier is suitable since the parasitics from connecting cables between sensors and amplifier can be neglected [21, 25]. Similar to the voltage mode amplifier, a charge mode amplifier uses the ability to charge the capacitor with some charge and build up the voltage across the loop [21]. For this circuit the lower cut off frequency is dependent of the resistor and the capacitor, see equation 2.8, 2.9 and 2.10 [20, 25]. A reason for including the resistor is again to not saturate the operational amplifier and control the parameters.

$$g = -\frac{q}{C_f} \tag{2.8}$$

$$f_{low} = \frac{1}{2\pi R_f C_f} \tag{2.9}$$

$$f_{high} = \frac{1}{2\pi R (C_p + C_c)} \tag{2.10}$$

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[1] same total content of signal positive as negative

In equation 2.8, q is the charges that build the current, R is a resistance at the input of the amplifier, modifying high frequency cut off and C_p and C_c are parasitic capacitances as previously. By include a resistor at the input of the charge amplifier it is possible to alter the amplification.

Note the differences between the voltage and the charge mode amplifiers. In the voltage mode the input is at the positive port of the operational amplifier whereas it is on the negative on the charge mode, but both uses negative feedback for amplification of the signal. The different configurations alter the characteristics in such a way that the cut off frequencies and dependency of parasitic currents are altered. In the charge mode amplifier it is possible to alter the lower cut off frequency by choice of components, and the lower cut off is the interesting to minimize for the use of low frequent signals.

Due to the limitations in the settings it is preferred to use a charge mode amplifier. Since the signal from the fibres are in the range of some voltages, but low current it is needed to have an operational amplifier with high input impedance to measure the signal [24]. It is also important that it is sensitive enough to react at low current, i.e. has low bias current.

2.4.3 Matching the output signal to ADC

To be able to match the output signal of the signal conditioning circuit to the requirements of the analogue to digital converter (ADC) a variable gain and biasing is needed. The amplification can be altered by potentiometers instead of constant resistors in the created system. Since the offset of the circuit also needs to be altered a circuit for this is as well needed. One solution to achieve an offset shift is to add a DC using a summing amplifier [29]. This amplifier can also be used to amplify the signals if desired. In figure 2.5 the schematics of a summation amplifier with three inputs are seen, but the numbers of inputs are arbitrary.

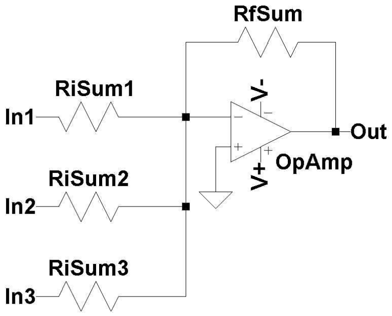

Figure 2.5: Schematics of a sum amplifier. The number of inputs are arbitrary, but sum needs to be in range of the operational amplifier.

Equation 2.11 is the theoretical equation for a summing amplifier, with special case of three input signals [29]. By adding a constant voltage to one of the inputs an offset signal can be generated.

$$V_{out} = -(\frac{R_{fSum}}{R_{iSum1}} * V_{In1} + \frac{R_{fSum}}{R_{iSum2}} * V_{In2} + \frac{R_{fSum}}{R_{iSum3}} * V_{In3}) \tag{2.11}$$

2.4.4 Transmitting unit

In order to use a digital transmission link to visualize the signal on a computer the analogue signal generated by fabrics needs to be digitalized. In the intended usage the transmitting is based on an Arduino board which having an ADC with a voltage range from zero up to 5V and a resolution of 10 bits [30]. For optimal performance of the ADC the analogue signal should match the requirements of the ADC. In an optimal situation the maximum and minimum signal after amplification is maximum respectively minimum of the ADC, and for positive/negative measurements the normal level should be at the middle. By centring the signal it is possible to see both stretching and relaxing stress of the textile. The analogue signal processing unit therefore needs to optimize the amplitude and offset to the ADC for optimal presentation. Improper matching is resulting in low resolution, either at peaks where ADC/amplifier is saturated or at the low end at quantization level. The quantization level can be derived from the range and resolution, see equation 2.12. From the equation it is derived that the Arduino board has a quantification level of $1.95mV$.

$$V_{quant} = \frac{Range}{Resolution} \tag{2.12}$$

2.5 Transfer function

To be able to characterize a system different models can be used, which can be related to either time or frequency domain. By mathematical transformations it is possible to alter between the domains, but both fully characterize the system. In the frequency domain the model is called the transfer function of the system. This function is describing how the output is related to the input through the system, depending on frequency [31]. By knowing this the full frequency characterisation of the system is known. This is mainly related to a linear system, but can be expanded to a non-linear system as well.

2.6 Characteristics of signals

Signals of different kinds are characterized by different amount of constituent frequencies. The simplest continuous signal, apart from constant level, is a signal of one frequency, i.e. a sinusoid. Since a sinusoid can be of various frequencies a sum off different such can build up different signals. It can be shown that any periodic signal with finite power[2] can be presented as a sum of sinus and cosinus waves [32]. This reveals that by summing different amount of phase shifted sinusoids, basically any periodic signal can be created. From this it is also understood that the frequency content of any such signal can be found if the signal is divided into each sinusoid. Since different signals is affected differently by the circuit a signal with all frequencies or several signals needs to be applied to derive the full characterisation of the circuit. A tool to derive the different frequencies included in a signal is called FFT. The theory of FFT is beyond the scope of this report, enough is to accept that it is possible to distinguish the different frequencies in the signal [32].

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[2] See source for more information

2.6.1 Square wave

A square wave is a signal with the characteristics that it has, in theory, all frequencies included in the signal. A perfect square wave is built up by a DC level and infinite number of sinusoids signals. It is not possible to realize a perfect square wave in practice, but a good signal generator can be close enough, including frequencies to the extent that other parts of the system are the limit. A perfect square wave without DC level can be seen in figure 2.6, where also a high and low pass filtered version are included as reference. If a DC level is included the average level is increased by the same amount. A square wave that is filtered through a high pass filter will have lower amount of DC characteristics, indicated by losing amplitude at the top of the wave over time. A low pass filtered version is instead having lower high frequencies, which is illustrated by longer transition and settling time in the turnovers.

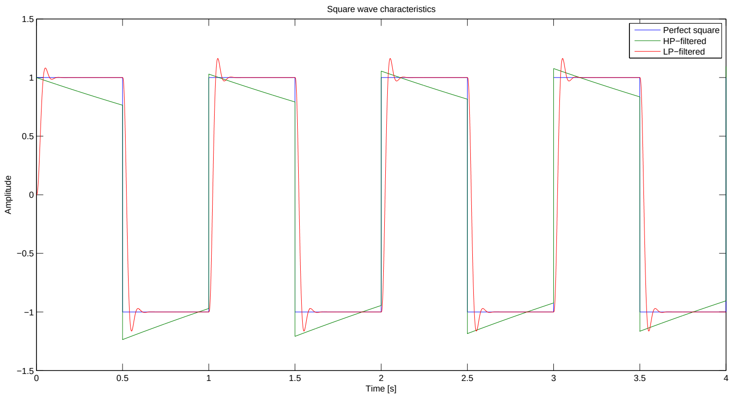

Figure 2.6: Square wave and its filtered versions. Note how the high pass filtered version looses hight and how the low pass filtered are having long transition time.

2.6.2 Time constants

The *time constant* of a RC-circuit[3] can be estimated from the response of a step. According to Witte [33] the step response of a RC-circuit is described by equation 2.13. In a RC-circuit the time constant is the time it takes to reach 63.2% of its final value from steady state when a step is applied. The reason of having 63.2% is described in equation 2.14 where the 1 in the exponent is referring to a single time constant, according to the definition [33].

$$v_o(t) = V_s(1 - e^{-t/\tau}) \quad for \quad t \geq 0 \tag{2.13}$$

$$v_o(\tau) = V_s(1 - e^{-1}) \approx 0.632 * V_s \tag{2.14}$$

Note that the time constant τ is related to the components included in the circuit as equation 2.15 [33].

$$\tau = R * C \tag{2.15}$$

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[3] circuits of resistances and capacitances

This can, according to Witte [33], also be related to the frequency response of the circuit as:

$$f_{3dB} = \frac{1}{2\pi\tau} \tag{2.16}$$

where f_{3dB} is referring to the point where the signal has lost half of its power.

Another time aspect is the *rise time* of a circuit. The rise time is defined as the time the output signal takes to rise from 10% to 90% of its final value, when a step is given as an input signal to the circuit [34]. The definition is limited to 90% since the time to reach the full voltage in theory is infinite [33]. In the report the rise time will be used. The rise time is related to the circuit's time constant τ as in equation 2.17 [35].

$$\begin{aligned} 0.1 &= 1 - e^{-t_1/\tau} \\ 0.9 &= 1 - e^{-t_2/\tau} \\ t_r &= t_2 - t_1 \\ t_r &= -\tau(ln(0.9) - ln(0.1)) \\ \Rightarrow t_r &= t_2 - t_1 = -\tau(ln0.1 - ln0.9) \approx 2.197\tau \end{aligned} \tag{2.17}$$

where t_1 and t_2 is notation for time index when curve passes 10% and 90%, and τ is the step time constant from above. From the fact that it is a constant conversion factor between the rise time and step response any way of determine one of the time aspects is as good as the other.

The equations above originates from a first order RC-circuit, see figure 2.7, but the concept can be and is often used to describe higher order circuits as well [34].

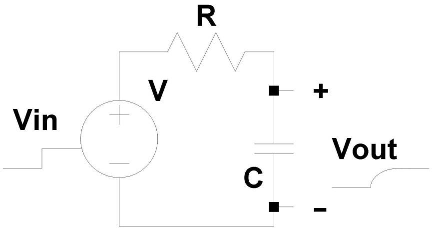

Figure 2.7: First order RC circuit.

2.6.3 Sampling

Depending on the signal that is about to be measured it is important to use the correct sampling frequency to be able to correctly interpret the result. According to the Nyqvist theorem it is required to sample at twice the highest frequency in the signal for correct interpretation of the result [36]. At lower sampling frequency undesired effects as aliasing occurs. The highest frequency related to body measurements is, according to table 1 in Webster, the nerve potentials and electromyography up to $10kHz$, phonocardiography at up to $2kHz$, electrocardiography at $250Hz$ and $150Hz$ for electroencephalography [13]. The mentioned frequencies are to correctly interpret a full continuous signal of the measurement where no information is missed. This reveals that: fully interpretation of any signal in the body requires a sampling frequency of $20kHz$. However, if full interpretation is not required it is possible to have a lower sampling frequency. In the intended application frequencies of ECG is the highest, but a full ECG is not required to detect heartbeats whereas an even lower sampling frequency is required. Sufficiently high frequency of the application should be at about $20Hz$ due to the respiration frequency. Note however that respiration and cardiac activity is not basic sinusoids since these are zero in large extent over one cycle, but it can be considered to be sufficiently high using a sampling frequency of $20Hz$.

2.6.4 Noise and filtering

The signal that is measured in the respiration is in the range of a few Hertz, and higher frequencies could be regarded as noise. In all real measurements different amount of noise is introduced in the measured signal due to inaccuracies and limitations. Noise can originate from e.g. circuit inaccuracies and converting errors. Since these kinds of noise sources are of higher frequencies than the intended application it is possible to extract the interesting signal by low pass filtering [27]. As seen in figure 2.6 low pass filtering induces an increased rise time in the system, and such response to an input step signal is indicating a limited frequency response of the system. In figure 2.8 a first order active low pass filter is seen. Note that at DC the filter turns into a normal inverting amplifier. At high frequencies the capacitor turns into a short circuit, hence no gain at these frequencies.

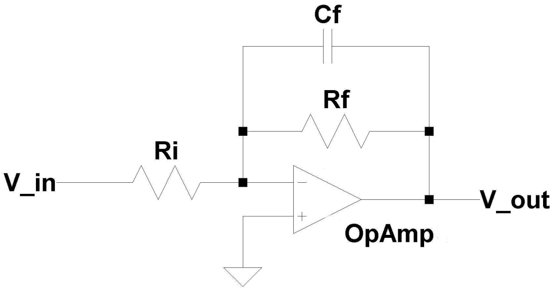

Figure 2.8: A low pass filter and related alterations due to frequency dependency. Note that the capacitor can be regarded as short at infinitely high frequency and open at DC.

However, other disturbances than high frequency noise can be present in the detected signal. Examples of such are motion artefacts which are considered as undesired motions during the measurements. Other disturbances are the interference to the $50Hz$ power grid and also disturbances due to skin/sensor interface, which also is to consider as artefacts. These disturbances are of lower frequencies and especially motion artefacts can be in the same frequency range as the intended application making it hard to filter these. To be able to detect the correct signal for increased sensitivity and processing possibilities it is desired to minimize all noise and disturbances in the system when measuring.

3 Methods

The method of performance was based on different parts, where the basics are derived from literature research. During the study some literature study has been performed simultaneously as the laboratory investigation. The laboratory work has included creation of signal conditioning circuit which has been tested by various feeding signals generated by either signal generator or by mechanical system which was stimulating the textiles.

To be able to separate the systems and the different signals some terminology have been used throughout the study. In figure 3.1 a schematic of the full setup and terminology is presented.

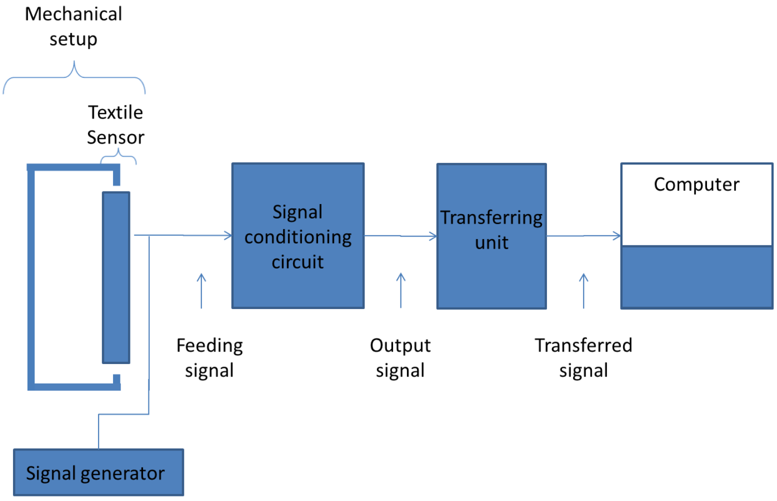

Figure 3.1: A schematic over the full system that been used. To generate signals either signal generator or the mechanical setups have been used to create the "feeding signal". The signal conditioning circuit is the unit which is to be designed to match the requirements of the transmission unit. Transmission unit is commercially available and the visualisation was performed on computer using LabVIEW.

3.1 Literature research

As a first part of the study a literature search was performed. The goal of the literature search was to understand both the piezoresistive as well as the piezoelectric textiles. Due to prior knowledge some books was chosen to search through, and also Internet searching for piezoelectricity and piezoresistivity. For the piezoresistive textile some searching of how to measure resistance was involved. Previous work was also investigated, regarding both textiles and the measurement system. To understand the piezoelectric properties some research was performed in books and articles where piezoelectricity is described. To broaden and achieve updated information research on the Internet was performed. Due to prior knowledge it was searched for deeper understanding of the piezoelectric properties by vague research words as *"piezoelectric properties"*, *"voltage piezoelectricity"*, *current piezoelectricity*, *"amplify piezoelectric signal"*, *"piezoelectric measurements"* and similar. This results in many hits, whereas most relevant is appearing high in the list of hits, and hits after a few pages can be discarded. It has also been searched for different solutions of interfacing the piezoelectric textile with the electronics, as well as for *"wearable electronics"*. As an outcome of the research different amplification possibilities was found, which was compared, and pros and cons was considered.

3.2 Previously solution

Simultaneously as the literature study, it was investigated whether the previous solution using piezoresistive textiles of S. Ratnarathorn [3] could be used. To get this up and running some software installations and program environment setups was required. The software installation of the Arduino board is presented in appendix D. The LabVIEW interface of appendix B was also created which is the basis of visualization.

3.3 Design goals

Through the literature search some basic understanding was received. It was also derived that some system requirements of the unit were needed to be able to create a system that could handle the signals, but has suitable constraints for the purpose of the report. It was desired to create a system that was not dependent on the sample that is generating the signal. Since different textile samples generates different amount of signal, a sample specific system would be too limited. However, the system should still be created in an application specific purpose to limit the complexity of the system. A tuneable system is more useful in a large amount of research areas, but is also more complicated than a specific implementation. Due to this a system with an application specific frequency range, with ability to be altered to match output requirements was to be created. Therefore it should be possible to switch textile sample and be able to have a suitable output by simple calibration. The application that was in focus in the study was mainly respiration, and should therefore be able to handle frequencies up to $10Hz$.This range should also be sufficient to detect heartbeats. However, if another application is of interest it should not be a demanding task altering the signal conditioning unit to match the new criteria.

Other design criteria are that the unit that is measuring should be of small size, low weight and have low power consumption to enhance the portability of the system. Nevertheless, it is not of focus to optimize the unit in any extent. A solution which can handle respiration, match different textile samples and ADC's, be sufficiently small size for portability and be able to visualize the signal is good enough.

For these goals to be fulfilled, relevant conditioning circuit and components was needed. When choosing the components to use, main focus has been to find components in a suitable bias current range. The secondly rated level is size and costs. The system should not be very expensive nor large, but it is essential that the system is working whereas the laboratory part has not been to minimize cost. The latest thoughts have been power consumption, where components with low supply current and higher efficiency have been chosen. However, extra components were considered for comparison since true range was not known.

3.4 Visualisation of the signal

For visualization purposes it was necessary to create a software interface, where LabVIEW was chosen. This was chosen due to prior knowledge, earlier work, good support and many built-in solutions. One of the built-in functions that exist is bluetooth communication to the commercial platform Arduino. This platform has implemented solution for communication to external devices, both hardware and software. Other techniques exist, but this was used in the previous work and therefore it was chosen for this as well. For simplicity the previous work has been used as a basis for the piezoelectric solution. The Arduino board that has been used is well known where much information and help can be found on-line. Note that the user interface neither is created for optimal performance and effect, as long as the signal can be viewed in real time.

3.5 Materials

The fibres that have been used was manufactured at SWEREA and then used at THS to create fabrics. Two different samples have been provided where the fabric have been used in a wider extent than the single fibre. In figure 3.2 the two samples are seen, marked at interesting areas. The active area is where the samples are coated with black coating, and in one end there is a connection to the inner core which is conductive. In the fabric it is the black conductive plastic seen to the right and for the single fibre it is instead the copper in the top left corner which is the connection. According to A. Lund[1], the textile sample is made in plain weave where the piezoelectric fibres make flotations over six wefts inserts in the band. From the use of one sample of textile the achieved signal should have the same behaviour in all measurements for an identical stimulus. If other weaving was to be used the resulting signal would be different, which can be seen in the work of Rundqvist [11].

3.6 Simulations

By simulations it was possible to derive a basic understanding of how different circuits behave and what component values that is relevant to consider. In the simulations models of active components have been used, so called SPICE-models. The models are developed by manufacturers and are supposed to match the real components. Limitations in the simulations are that it is not possible to create a simulated circuit where all relevant parameters, fluctuations and non-linearities are present as in reality. By using SPICE-models some non-ideal effects are taken into consideration.

Due to the properties of a piezoelectric signal it was not possible to simulate the piezoelectric textiles that been used in the study. According to several sources it is possible to simulate a piezoelectric sensor as a voltage source followed by a capacitor [20, 25, 37, 38]. Based on the sources it was possible to find values of the components that are involved in the simulated piezoelectric material, i.e. the capacitor and voltage, see figure 3.3. However, the true signal is not mimicked by such a solution, but this allows for comparison between the two systems.

Due to the requirements of the signal conditioning circuit to handle the feeding signal and also match the transmitting unit, some understanding of the circuit is relevant. By simulations it was found how the conditioning circuit should be configured, regarding

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[1] Email conversation May 20 2014, anja.lund@hb.se

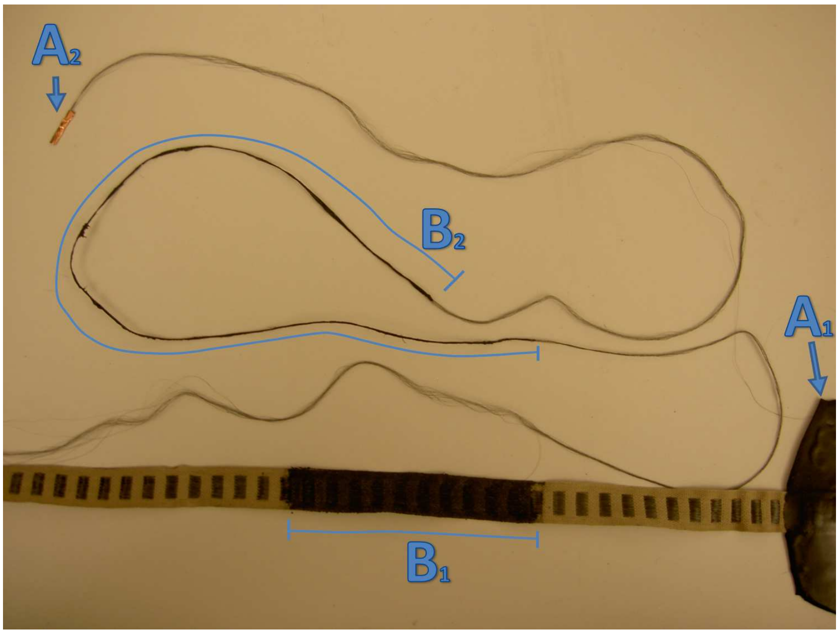

Figure 3.2: The samples that been used. The connections is marked with A and the active area is marked B. The subscription numbers indicates which samples are connected to which, 1 is for the textile and 2 is for fibre. In the following text when discussed about a specific piezoelectric fibre in text it is referring to this sample and the same for textiles.

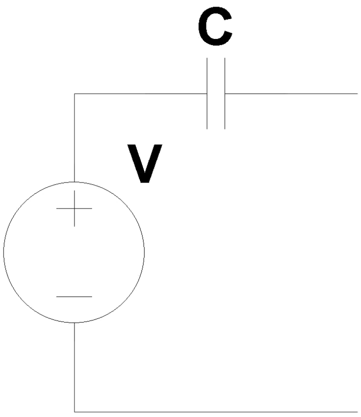

Figure 3.3: Possible simulation solution for a piezoelectric sensor.

values, for suitable amplification, and specially how to alter the circuit for increased performance when a true feeding signal is handled. With this as ground it was important to perform simulations for relevant understanding, but the final realization could not be based solely on simulations.

3.7 Evaluation

For characterisation of the fibres and the conditioning circuit it is desired to test the limitations of one separately from the other. Even though any measurement alters the characteristics of the system under test, a minimum system change is desired when attaching the measurement system. By using different electrically generated feeding signals and mechanical setups to generate piezoelectric signals it has been possible to see and compare differences between signal conditioning circuits and the fibres directly.

3.7.1 Recording of data

For comparing reasons the data is recorded from a triggering point where the input is reaching above a certain limit. Due to this there can be small timing errors when the signal is registered, but this is seen as a minor error. Other circumstances that both affect triggering and signal collection is present noise which influences the signal. When registering the signals a digital oscilloscope[2] have been used, connected to measure either single output or both the output and the feeding signal.

Since the piezoelectric feeding signal is dependent on the input impedance of the signal conditioning circuit and the oscilloscope when it is connected, the attached measurement system needs to be considered. Due to this it is stated when oscilloscope are used and when it is not. Since most measurements are comparing different setups where the configurations are the same accept from a specific part it is possible to compare the results even if the oscilloscope affects the total result. In measurements where registration of feeding signal is not of vital importance the oscilloscope has been excluded to mimic a real situation.

3.7.2 Testing signal conditioning circuit

To evaluate the limits of the signal conditioning circuit a system set up was created where it is possible to apply a known signal from a signal generator. The test signal was limited by the possibilities of the signal generator that was used. To test the characteristics of the conditioning circuit a square signal provides essential information, according to section 2.6.1. From such an evaluation important aspects of the system can be derived, such as time constants and high/low frequency characteristics. In the investigation a signal generator[3] with ability to specify DC offset, positive or negative on/off time and time intervals has been used.

The piezoelectric signal generated by textiles cannot, however, be mimicked by a generator, making it important to test the conditioning circuit with not only signals from generator but also from the piezoelectric textiles sample. To perform repetitive stimuli some mechanical systems was developed, see section 3.7.4.

3.7.3 Testing fibres

To be able to characterize the fibres, different stimulus is applied directly to the fibres, and the output is evaluated. Note however that the resulting feeding signal is dependent on the quality of signal that can be generated from the fibres using the mechanical setup. The stimulus applied to the sensor needs to have a mechanical stretching of the textile, where the applied force is the crucial parameter. For this it is highly interesting to measure different frequencies, more facts about this in section 2.3.

3.7.4 Mechanical setups

To be able to find components suitable for the final realization a feeding signal generated from the fibres are required. Due to trouble of substituting the sensory signal by a signal

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[2] Tektronix TDS 3012B

[3] TT*i* TG320 Function generator

from generator, some mechanical setup has been created which enables repetitive and controllable feeding signals. For details of the measurement system see the following sections.

3.7.4.1 Sinusoidal

To be able to test how the actual fabrics respond to a continuous sinusoidal signal such a mechanical stimulation setup was developed. The setup is based on a DC motor which speed can be controlled by altering the applied voltage, see figure 3.4. Since the output of the motor is a rotating movement this is converted to a linear movement by a wheel of low friction. By this performance a longitudinal sinusoidal force alteration can be applied to the tested textile sample. After the wheel a rubber band is attached acting as spring to the fabric and static point. The rubber band is increasing the extension possibilities and is needed since the elasticity of the fibres is limited whereas the pulling force and distance of the motor is limited to a specified distance. A stiffer band results in higher force across the fabric, but due to limitations of torque and diameter of the motor axis the band is required.

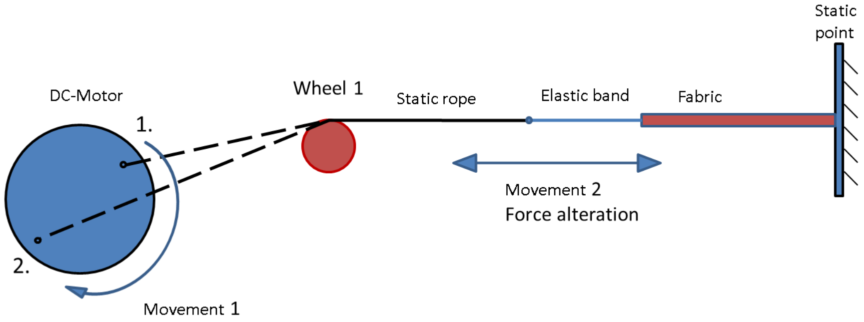


Figure 3.4: The schematic picture of the system for measuring continuous sinusoids. At point 1 the system is short indicating low force across the fabric. When motor is turning towards 2 the distance to static point increases and so does the force across the fabric.

The setup makes it possible to alter the applied force, the frequency and to repeat any conditions/settings. The setup is limited to the specific sample that is used, and depending on the settings and sample that is tested different feeding signal can be generated. All parameters necessary for recreation of the setup is not known, but as long as the stimulus can be repeated over many cycles generating similar and comparable feeding signals, it does not need to be a specific input. Another limitation is the elastic band which acts as a low pass filter of the mechanical system. The cut off frequency of this filter is regarded as high enough to not limit the signal which is of low frequencies.

In figure 3.5 the system of measuring a sinusoid is seen in the reality. The system is built with Meccano and rubber band which makes it easy to alter the force applied to the fabric and also the length if other textile samples are to be used. The power supply is feeding the Arduino board to minimize troubles when converting to portable system. It is also desired to have as small movements of the fabric as possible, except in the direction of elongation to minimize noise. The wheel is "hidden" in the "house", which is there to increase stability. Note that the Meccano pieces are not perfectly stable due to low thickness, whereas stability can be increased by extended construction.

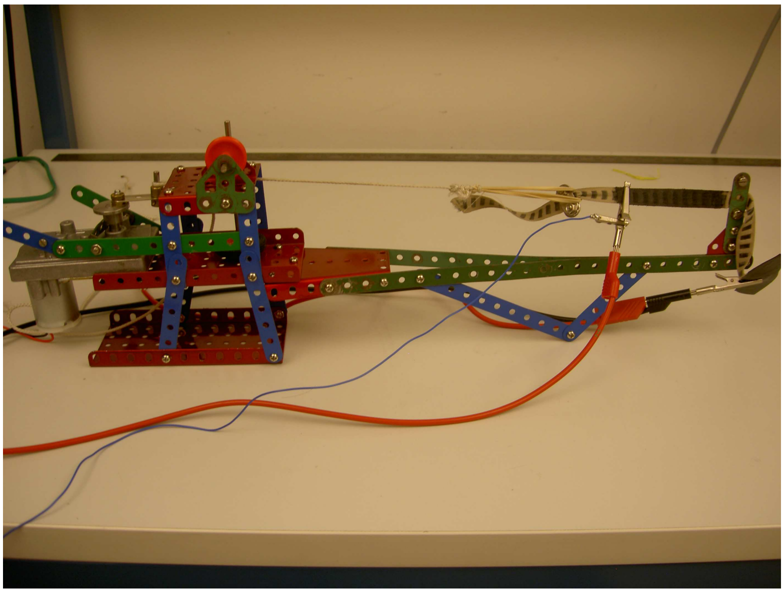


Figure 3.5: The system that is used to measure a sinusoid signal.

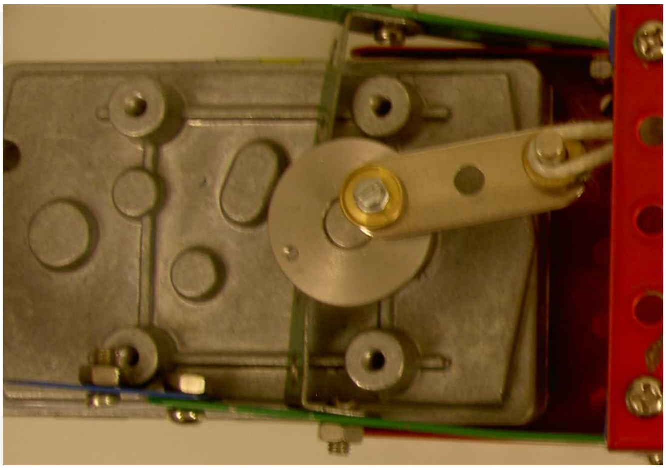


Figure 3.6: A closer image of the configuration at the motor when performing sinusoid measurements. The bar is freely turning around the ex-centric point.

3.7.4.2 Step

To be able to measure high frequency aspects, a mechanical setup which generates a step function was also created. In this system the limitations regarding DC have been used to have a constant extension distance where the output can stabilize. The setup uses gravity to create an inverse step, i.e. the tested sample is exposed to a step where the change is from a released force, see figure 3.7. Since the fibres are sensitive to a change in force, rather than static, the idea is of this setup is to expose the sample to an instant release of force. This is achieved by hanging a mass in one end of the sample, fixing the other, wait until the feeding signal is stable and then release the mass. During the preparations of the setup some unrepeatable forces are affecting the signal. By waiting for settling time the starting signal is constant prior to all measurements. Since the mass is constant, the contraction due to the release of the mass will as well be constant. The theory of this is based on static gravitational field and Newton's laws of motion. A drawback of the system is that the release of the mass needs to be instant, no small jumps should occur during releasing which can influence the signal, and for data acquisition purposes the triggering timing is as well a limiting factor as release is not fully controllable. Added to this, there is also manual work needed to arrange the setup and release in between each measurement.

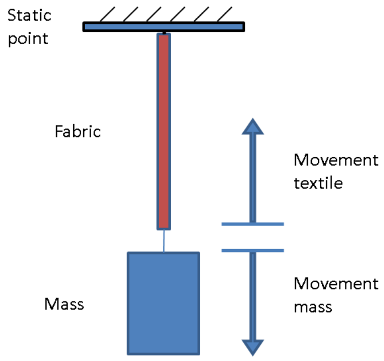


Figure 3.7: The system to generate an inverted step.

Next tricky part of the measurement setup is the releasing of the weight, any swing in the system may alter the result. Due to this it is desired to release the mass without interference with the setup. There are several possible solutions, but there are also limitations in this since the mass should be of minimum weight to increase the contraction and to minimize oscillations after releasing. In the system used this was solved by attach a needle by a crocodile clip to the fibre and a rubber at the mass. The needle is inserted into the rubber, which slowly slides down the needle by the new total weight. In this setup the mass was chosen to be $200g$. At some point the friction of the needle/rubber interface is smaller than the force the mass is pulled by which releases the mass. Due to the smooth movement of the rubber against the needle, disturbing steps are avoided, and at one instant the mass falls, resulting in a step.

3.7.4.3 Ramp and step

To create a stimulus of a step, which does not require manual work, the DC motor was used to generate a continuous signal of a ramp followed by a step. Instead of having the rope attached to a point on the wheel, as in the sinusoidal, a static bar is attached. When the wheel spins the bar catches a flipping arm that follows the turning, at 1 in figure 3.8. At 2 the flipping arm is released and flips back due to the force of the rubber band.

This test setup was used to create a stimulus which does not require manual work, but include a large amount of frequencies. Note that it basically is the same setup as for the motor-driven sinusoid, but with a different connection to the motor. By having the same DC motor it is possible to generate the same frequency of the sinusoid as for the ramp/step signal. However, the shape of the signal is different which enables other circuit information.

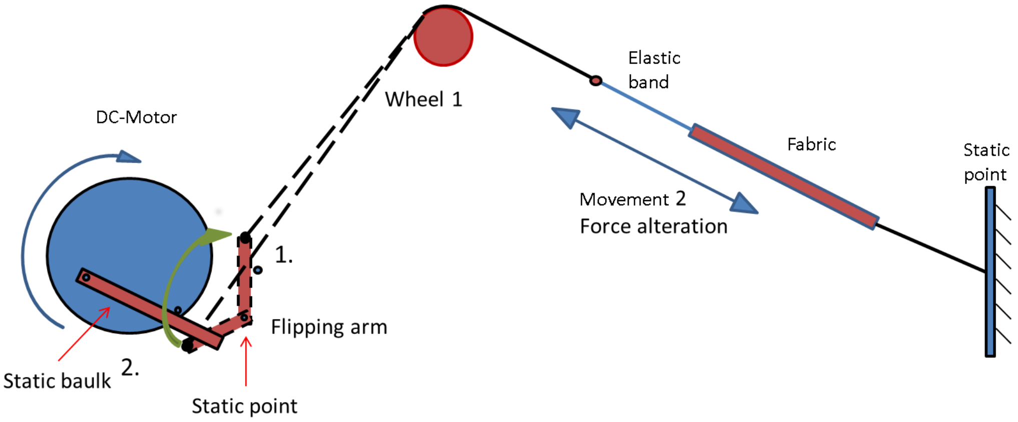


Figure 3.8: A schematic picture of the system for measuring a step, becoming as a triangular wave. At point 1 the system is short indicating low force across the fabric. When motor is turning the bar picks up the flipping arm towards 2, the distance to static point increases and so does the force across the fabric. At a moment the arm slides of the bar and flips back ending in a step over the fabric.

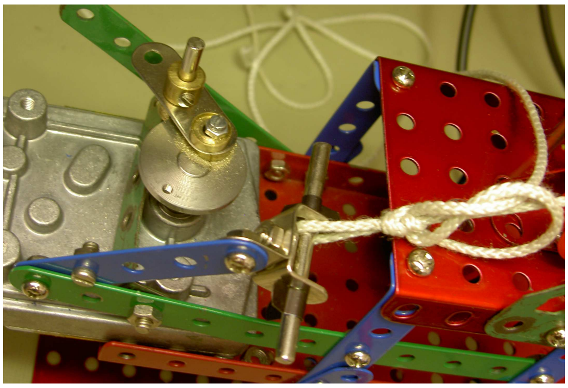


Figure 3.9: The true measurement system for creating a triangular wave, zoomed to relevant area, note that the fabric is out of the image to the right.

The test setup is limited as it is not possible to wait for settling time to be reached since the motor constantly turns. The system is nevertheless useful to give another type of signal than the sinusoid in the previous setup. In this ramp setup it is possible to vary the extension and force applied to the fabric as well as the time of the ramp by different rubber band, length of the bar and the speed of the wheel.

3.7.5 Signal conditioning circuit

During the evaluation the feeding signal has been simultaneously registered with the output signal. This is affecting feeding signal, but by using the same measurement system a comparison of the output can still be performed. In some measurements it is of vital importance that both feeding signal and output is registered simultaneously, whereas in others it is not necessary. When the feeding signal is not required it has not been measured.

A photo of the total system can be seen in figure 3.10. In the image it is possible to see the hanging weight that been used to create a step, the pliers hanging from the shelf.

On the desk the motor controlled setups are standing. Depending on the attachment of the left end of the static rope different signals are created. The motor and Arduino is controlled by the DC power supply to the left and the motor also has a switch to be individually controlled.

To be able to switch components in a simple manner a bread board was used. Such a platform could possibly influence the characteristics of the signal conditioning circuit but such or similar is basically required for testing. To test whether the board are affecting the signal some tests was performed where the layout, cable placement, sockets of operational amplifiers and operational amplifier samples were altered.

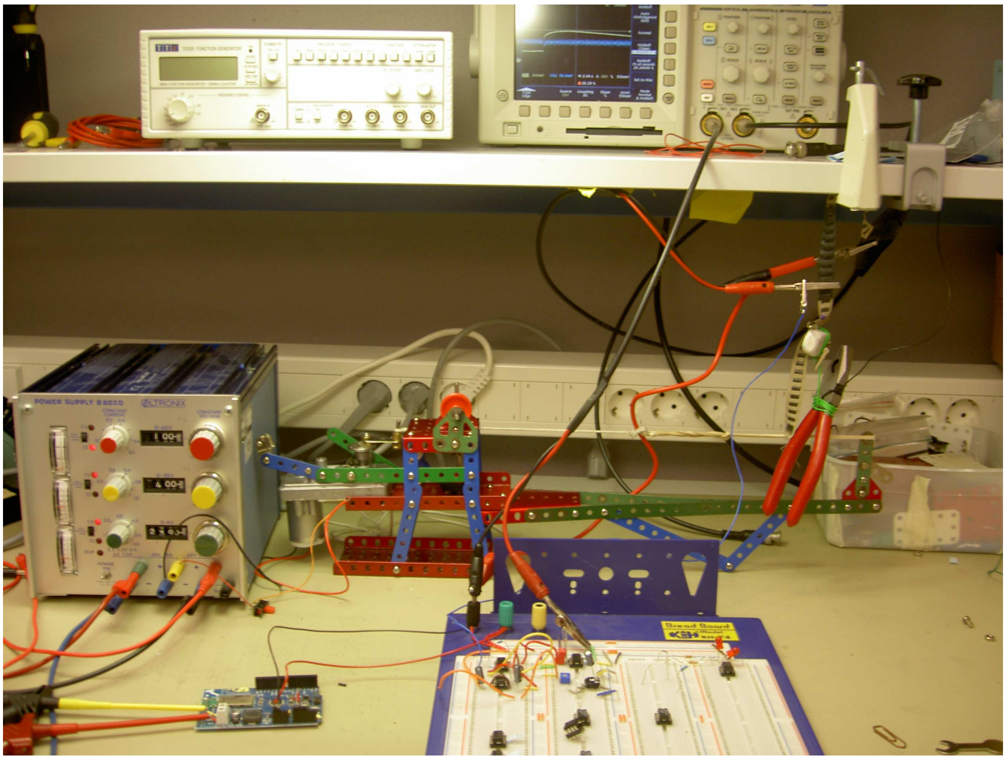


Figure 3.10: The over all system that been used for achieving different signals.

3.7.6 Test total system

To be able to compare feeding signals, output signals and signal conditioning circuit with the unit created for piezoresistive textiles it was relevant to measure both the piezoresistive and the piezoelectric system using the same stimulus. By this performance the output signals should be similar, but due to different sensor types the output could be different, and this is to be evaluated. One such difference is the DC component caused by constant stretching. In the piezoresistive system this needs to be adjusted manually to get a good span and relevant output signal, while for the piezoelectric system such adjustments might be avoided, as long as necessary amplification is received. Measurements regarding need of signal amplification were therefore performed.

For the comparison between the two textile solutions it was desired to use the same system setup. However due to physical limitations of the different textile characteristics the system had to be slightly modified. In the alteration the rubber band is excluded in the piezoresistive measurement.

3.7.7 Test on person

To be able to evaluate true measurements on a test person some solutions to attach the textiles to the chest was created. In the test the person was breathing in different patterns and output was compared to the different respiration patterns. Patterns which are interesting to evaluate is fast/slow respiration, yawning, which is one of the largest expansion of the chest, and no breathing. From such measurements it was possible to determine whether it is possible to detect respiration of different kinds and heart beats. Note that it was possible to visualize the signal in real time during the evaluation. To be able to perform these measurements the piezoresistive solution was built on an almost static band where only the active piezoresistive area is elastic was attached around the chest, and for the piezoelectric system the sample that been used earlier was modified to be able to attached around the chest. The modification consists of two elastic bands where the sample is sewed in between. The modification also enables a locking solution with adjustable band length.

4 Results

In this chapter there will be different sections for the results of each part. In the first section the results of the literature study will be presented. In the second section the performed simulations will be presented and briefly explained. From the simulations some specific circuit solutions and related components were determined which in turn could be realized. Thereafter is the suggested signal conditioning circuit presented with images on the final realization as well as results of respiratory and cardiac activity measurements. With the suggested system presented, measurements which justify the choices are presented. These justifications are presented to justify the presented solution and is started by a presentation of measurements directly on the fibres. After the fibres been presented the signal conditioning circuit is tested by electrically generated signals. After the electric feeding signal the presented mechanical setups was used to generate a piezoelectric feeding signal for realistic measurements of a feeding signal which could potentially be fed to the signal conditioning circuit.

4.1 Literature study

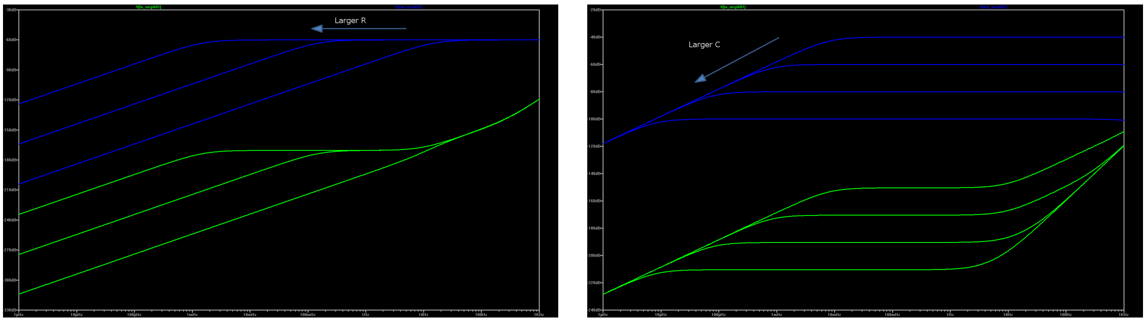
From the literature search in the area regarding piezoelectric signals it is found that it is necessary to use some kind of amplifier with high input impedance. Due to low signal power, and especially low current, it is vital to have high impedance. From the literature search it was found different kinds of sensors where piezoelectric material are used and many forums discussing how to use piezoelectric material in different applications. From the study it was found that there are mainly two possible solutions to amplify the signal: voltage mode amplifier or charge mode amplifier. The result of the literature also indicated that both circuits are having the ability to generate enough gain, and both are having high input impedance which is crucial as the piezoelectric material has very limited current source capacity [25]. Due to this it could be possible to use either of them. Nevertheless, the charge amplifier has some benefits and is therefore preferable [25, 38–40]. The primary benefit is the possibility of manipulate the low cut off frequency of the charge amplifier, equation 2.9, instead of the high cut off in the voltage amplifier, equation 2.6. Another is that the charge amplifier is less sensitive to disturbances between the inputs of the operational amplifier. This is making it possible to have the amplification circuit further away from the sensor [25]. From this it was decided to go for a charge amplifier, with the extra benefit of fewer components involved, which lowers complexity and number of alterable parameters.

From the findings of amplification possibilities it was also searched for commercial solutions. During research for commercial charge amplifiers it is found that these are uncommon other than large laboratory equipment. Since no suitable commercial amplifier was found it was decided to build one of spare components, which also increases matching possibilities.

4.2 Simulations

To be able to choose circuit solution and components which are suitable for realization it is needed to start the comparison from data sheets where relevant parameters are presented. For a piezoelectric system where the current are low it was decided to search for components with a low bias current, high common mode rejection ratio and low noise. An additional important aspect is that the components should be affordable and readily available. The simulations were performed based on the resulting list of components.

In figure 4.1 a frequency sweep of the charge amplifier, seen in figure 4.2, is demonstrated. Which operational amplifier used in the circuit is not of vital importance since the characteristic alterations are basically same for all, but in figure 4.1 the operational amplifier MCP601 was used. Due to simulation limitations regarding the piezoelectric signal it has not been possible to simulate the appearance which occurs in reality with an altered input resistance, i.e. the possibility to alter the gain. In simulations, the value of this resistance made no difference to the circuit characteristics. By varying the components that are related to the amplifier, i.e. the input feedback resistances and the feedback capacitor, different characteristics are achieved. In figure 4.1(a) the feedback resistance is varied and the capacitance is kept constant. It is seen that the low cut off frequency is lowered at higher resistance, while gain is kept constant. In the next figure, figure 4.1(b), the capacitance is instead varied. The result of higher capacitance is lower cut off frequency, but also lower gain of the charge amplifier.



(a) Varied resistance and constant capacitance. At higher resistance the cut off frequency is lower, meanwhile the gain is constant

(b) Varied capacitance and constant resistance. Higher capacitance results in lower cut off frequency, but also lower gain

Figure 4.1: In the figures it is seen how different values of the feedback components alters the circuit characteristics. Note that the input resistance and the operational amplifier are kept the same at both simulations. Green curve is the feeding signal and blue is the output.

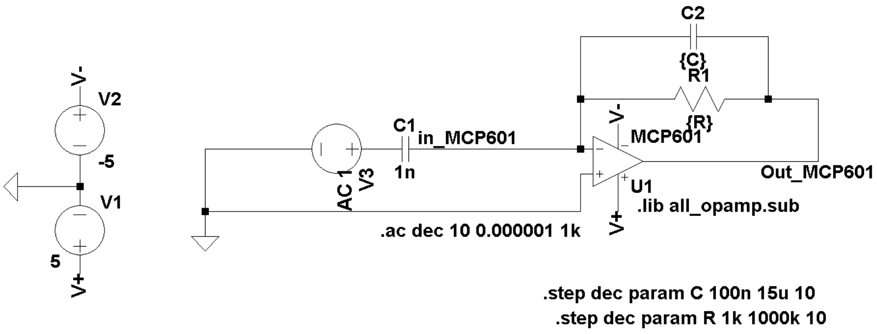
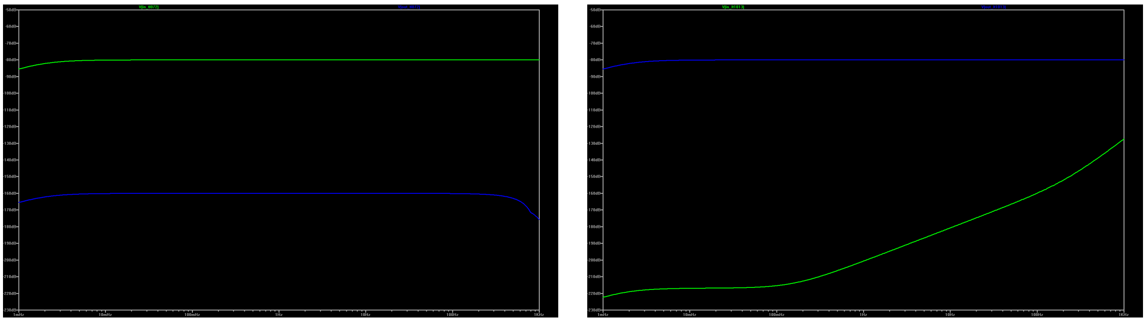


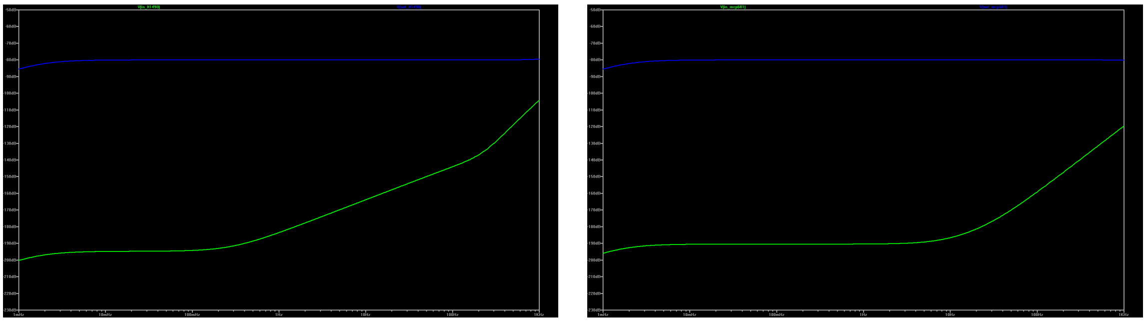
Figure 4.2: Simulated signal conditioning circuit.

The components that were found by searching through the data sheets were simulated by the same parameters to compare the components. To be able to compare the need of different bias current in the realized signal conditioning circuit some components in different bias current segments are chosen for realization.

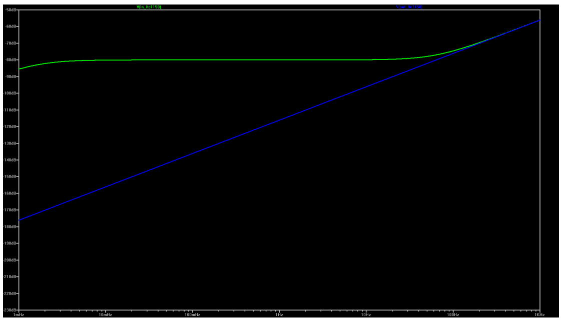
In figure 4.3 the simulated feeding and output signal are seen. From the figures it is seen that depending on the component choice, different characteristics are achieved, regarding both feeding signal and output characteristics. To find a good choice, the components should have an output similar to the feeding signal but increased several times and low feeding signal.



(a) TL072 (b) LT1013



(c) LT1490 (d) MCP601



(e) LTC1150

Figure 4.3: By comparing the figures it is seen that both the input signal and the resulting output signal is dependent on the component. Note that the axis is having the same scale for easy comparison between the figures. Green is feeding signal and blue is the output.

The components in figure 4.3 were found to be the preferred ones with respect to bias current ranges, stated in data sheets. Note that all simulated operational amplifiers are not plotted, but the ones with best characteristics in different bias current ranges. Since generated current is dependent on many factors, this performance is done to make it possible to compare different sensitivity areas. In some ranges the number of possible components to choose from is fewer than others allowing for better signal characteristics.

4.3 The suggested signal conditioning circuit

The intended application in this investigation is regarding respiration. From the fact that different persons have different lung expansion, and also suggest a solution which fit several applications, it is desired to have alterable amplification in the realization.

The suggested solution should be able to respond to a fast stimulus, and therefore it is desired to have a short time constant, but the system needs to have enough low frequency characteristics to handle respiration. From this a system with capacitance of $100nF$ and resistance of $20M\Omega$ is used in the feedback loop, which both increases the amplification of the charge amplifier and have sufficiently low time constant to detect respiration. As an operational amplifier TL072 was used, which will be justified further on. A schematic of the suggested signal conditioning circuit is seen in figure 4.4.

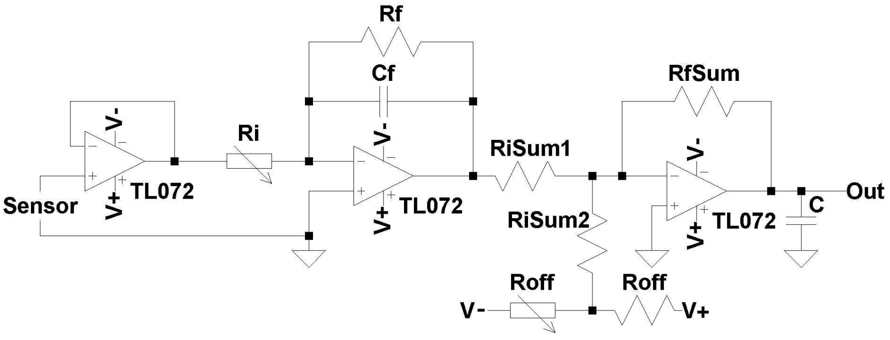


Figure 4.4: The solution to measure different applications where the amplification can be altered. By altering the bias through the voltage divider in the end, requirements of the ADC can be matched. Note also the capacitor in the end filtering high frequency noise.

4.3.1 Frequency sweep, transfer function and transmitting unit

The final circuit is presented in figure 4.4. When performing a frequency sweep of the suggested circuit with nonideal operational amplifiers figure 4.5 is generated. In this image the gain of the charge amplifier has been varied, where an increased R_{in} results in lower amplification. In the figure it is seen that the cut off frequency is low, compared to theoretical value of respiration. By decreasing the capacitor on the charge amplifier the cut off frequency can be increased. However, in the realized signal conditioning circuit nonideal components and noise handling has been taken into consideration which resulted in a system that can handle the required frequencies, and especially respiration at normal frequencies.

The transfer function is also derived for the system. Note that the summing amplifier has a virtual ground at the negative input hence the ending capacitor is included in the summing amplifier, parallel to R_{fSum}. The resulting transfer function is derived in equation 4.1.

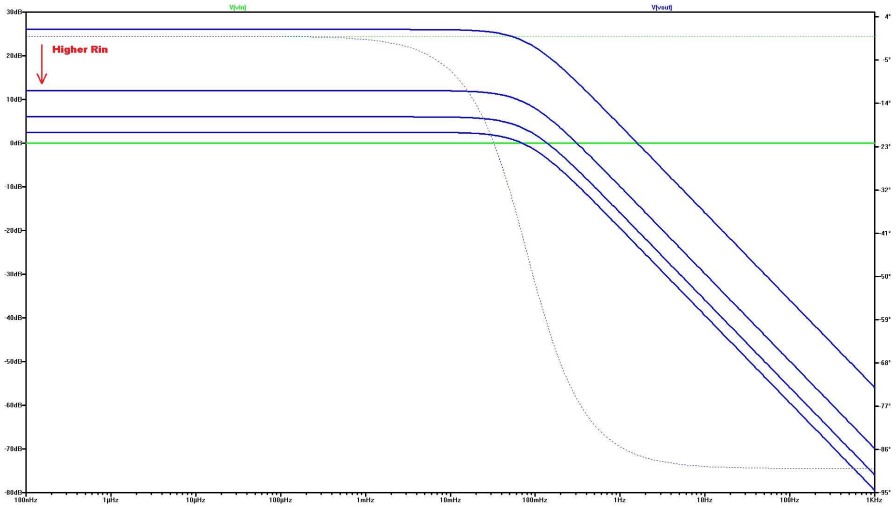


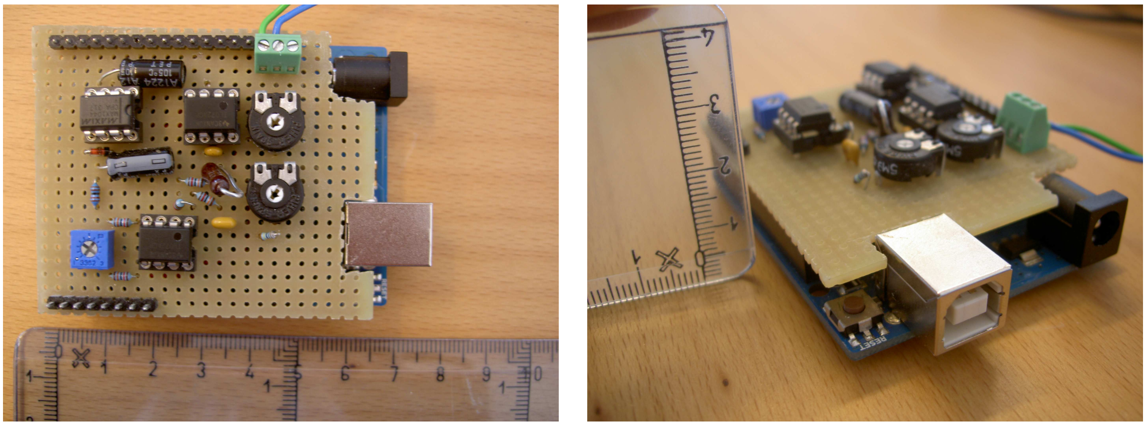
Figure 4.5: Sweep of the simulated system. Green is input and blue is output, in the sweep the only parameter altering the output is R_{in}, in theory due to the placement of the capacitor. Note that the high cut off frequency is lower than expected due to requirements, which have been investigated in reality to find suitable value regarding amplification, noise and response time.

$$H(j\omega) = \frac{R_f R_{fSum}}{R_{in} R_{iSum1}} \frac{1}{1 + j\omega(C_f R_f + C R_{fSum}) - \omega^2 C_f R_f C R_{fSum}} \tag{4.1}$$

The created system after soldering is seen in figure 4.6, for corresponding circuit components see appendix E. In the realized circuit one channel is implemented, but this can be extended until output power of the board or number of analogue inports is reached. To be able to understand the size of it a standard metric ruler is seen in the images. Note that the Arduino board connected is not a wireless board, it is of type UNO with the same characteristics as BT, but has USB connection to computer. The solution is not dependent on the board, whereas it is the same physical characteristics for the bluetooth Arduino board. Due to breakdown the BT board could not be used. The created signal conditioning circuit is nevertheless editable to match criteria of other boards if other ADC requirements are needed. Therefore a wireless type of board can relatively easy be implemented.

4.4 Measurement results of the suggested signal conditioning circuit

In the following section the suggested solution is presented. The main focus is on the piezoelectric system that has been created, to present suitable components and solutions to be able to measure respiration. According to Ratnarathorn [3] it is possible to detect respiration using the piezoresistive system that was developed earlier, which also is verified by measurements on test person. Result whether it is possible to detect heart beats using any of the system is also presented.



(a) Top view

(b) Side/corner view

Figure 4.6: The finalized system with Arduino board attached.

4.4.1 Measure respiration using the suggested circuit

In figure 4.7 the test person is wearing the modified sample tightly around the chest and breaths normally. In the figure the breathing peaks are relatively low, indicating that the amplification is set to match higher inhalation volumes. Note that the chest circumference differs relatively much between normal breathing and maximum inhalation, where maximum inhalation requires low amplification to avoid saturation. In figure 4.8 the same situation is seen, but two periods of yawning is included. Due to the high force, from an increased circumference when yawning, which increases the force applied to the fabric, the operational amplifier is saturated. By lower the amplification it could be possible to avoid saturation. Note also the normal breathing in the first part of the graph. By lowering the amplification to match yawning, normal breathing pattern might not be sufficiently amplified to be seen.

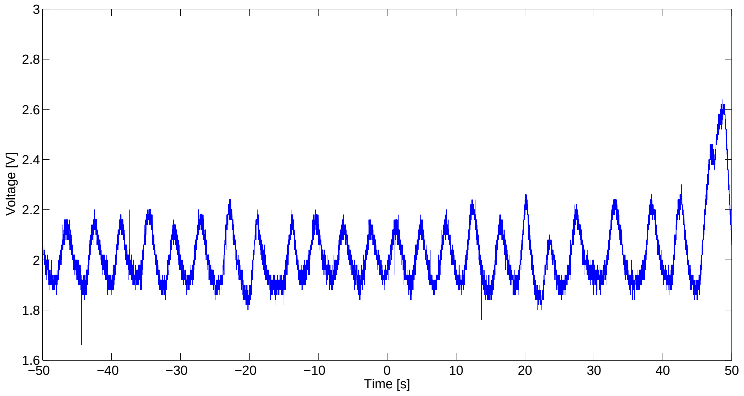


Figure 4.7: Output signal collected with oscilloscope during normal breathing on a test person. During the measurement the test person is sitting still typing on computer. Note the signal increment in the end, this is due to movements related to test person turning and moving arms.

In figure 4.9 a test have been performed using the same settings without editing amplification between the different breathing patterns. In the first figure, figure 4.9(a)

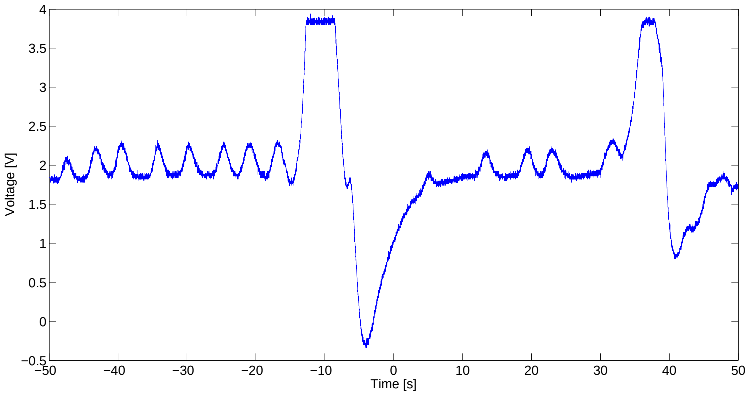
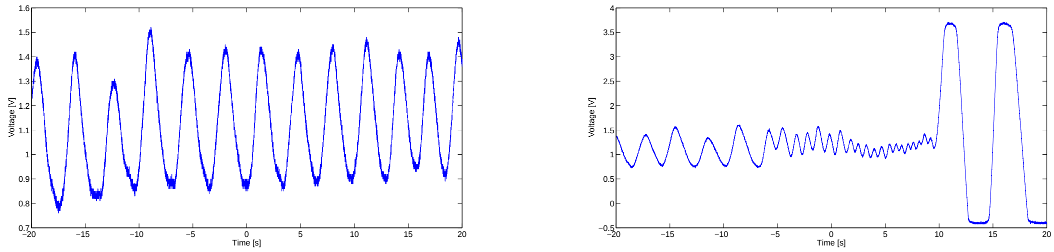


Figure 4.8: Output signal collected with oscilloscope during normal breathing on a test person, and two periods of yawning. During the measurement the test person is sitting still typing on computer. Note that the operational amplifiers saturate at full yawning.

the test person is breathing in a controlled and relaxed pattern. Note that the signal is basically the same over the interval. In figure 4.9(b) the test person is instead starting by normal breathing, and then suddenly goes into faster and shallower breathing. After additional time the person under test is taken deep breaths, note that the pattern differs, which is expected.



(a) Controlled breathing in normal speed. Note that the amplitude is does not cover all ADC range.

(b) Breathing in varied patterns. Note that different kinds of breathing can be detected, but the deep breaths at the end is saturating the amplifiers hence alterations in the highest peaks cannot be detected.

Figure 4.9: Different breathing patterns and their outputs.

From the test it is seen that it is possible to detect and see different breathing patters using the circuit. Note however that the signal needs to be in the correct range to not saturate the amplifiers. At different situations different amplification is needed, depending on the stretching of the textile and what textile sample that is to be used.

4.4.2 Measuring cardiac activity

To derive whether it is possible to detect the heart beats using either the piezoelectric system or the piezoresistive system textile samples of each type is attached around the chest one by one. In figure 4.10 the sensitivity of the oscilloscope is increased to not be a limiting factor. In the first part of the signal a deep breath is taken by the person. Note that the maximal reading of the oscilloscope is reach, understood by the constant value over several seconds. When the signal level decreases, due to the low frequency characteristics of the signal conditioning circuit, a relatively high frequent signal is noted which is the heart beats (the signal is matched to the pulse of the test person).

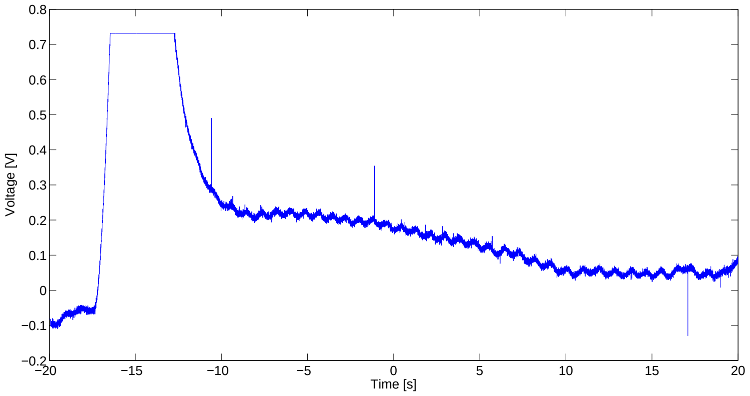


Figure 4.10: Output signal collected with oscilloscope during holding breath. The seen pattern is from the heart beat of the test person. In the first part the test person is taken a deep breath which saturates the amplifier.

To compare this with the piezoresistive solution a similar test is performed wearing a piezoresistive strap around the chest. In figure 4.11 the signal is recorded when the test person is breathing normally in the early part of the signal and then intentionally and directly stops. Using this solution it is not possible to take a deep breath where the expansion of the lungs is high witch saturates the output, and due to relatively good low frequency characteristics the signal does not return fast enough to see the heartbeats. Without large amount of air it is hard to hold breath over long time and noise in the signal is affected. However it is seen that when holding breathe the heart beats are seen, comparable to the piezoelectric solution in figure 4.10.

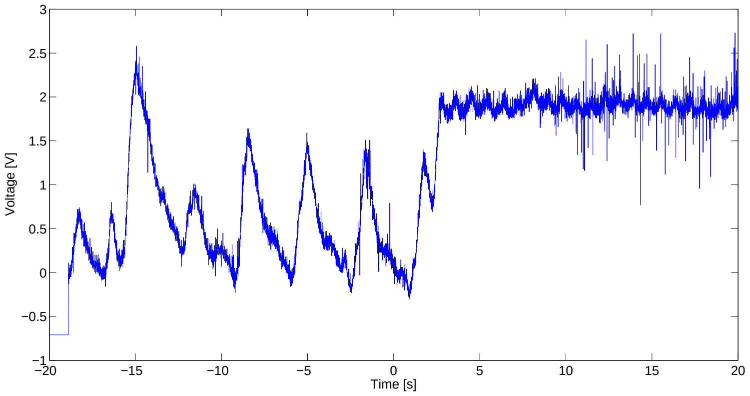


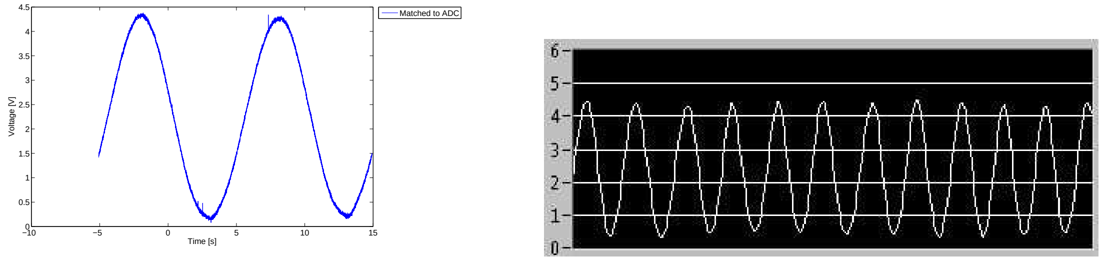
Figure 4.11: In the first part of the figure the person is breathing, then inhales and hold breath. Note that the inhaling needs to be sufficiently low to not saturate the system

In figures 4.10 and 4.11 it is seen that both solutions are sensitive enough to measure the heart rate, under the condition that other movements are low. When the person is breathing the signal from the heart beats are not seen, which limits the possibilities of heart beat measurements. By transferring the signal to a computer it could be possible to perform some signal processing to extract this signal, by for example correct filtering since the seen signals are of different frequency.

4.4.3 Visualization on computer

To be able to visualize the output signal of the signal conditioning circuit on a computer it is required to convert this signal to digital domain using ADC and transfer the signal to a computer. Since the ADC is having certain characteristics it is required to match the output signal to not only be below saturation of the operational amplifier but also to the characteristics of the ADC. Since the ADC can handle voltage level of 0 to $5V$ the output signal is required to be in this range and also high enough to avoid quantization errors. By tuning the potentiometers after the voltage follower in the signal conditioning circuit it is possible to avoid quantification levels when output is low and saturation when the feeding signal is high. Another aspect to consider due to the ADC is the lower boundary at 0. This can be handled by the summing amplifier and the voltage divider in the end of the signal conditioning circuit. By fine tuning of the voltage divider the normal level of the output can be set to the middle of the ADC range for optimal output coverage.

The summing amplifier sums the DC level of the voltage divider and the output signal. The summing amplifier is having an amplification of one to not increase noise which could be introduced in the conditioning circuit. The amplification is instead performed in the charge amplifier which has some low pass filtering characteristics which excludes some high frequent noise. Note that during test performed on person the force applied when stretching can vary between different measurement occasions. Due to this the amplification might need adjustments to be optimally matched between measurements. In figure 4.12 a signal is generated by the sinusoid mechanical setup and the output is simultaneously recorded by both oscilloscope, figure 4.12(a) and a LabVIEW interface created on a computer, figure 4.12(b). Note that the recorded signal varies between 0 and $5V$, the range of the ADC, which has been tuned before the recordings.



(a) Signal matched to the ADC of the Arduino board. Due to the components and drift the signal is not matched to be perfectly 0 and $5V$.

(b) Signal matched to the ADC of the Arduino board and transferred to the software for visualization purposes. The x-axis is $60s$ and continuously updating.

Figure 4.12: Output signal matched to ADC and operational amplifiers and. Stimulus is the sinusoid mechanical setup.

4.5 Comparison between piezoresistive and piezoelectric textile solutions using mechanical setups

In figure 4.13 both textile systems was tested by the same stimulus of a ramp followed by a step. Note that the output of the circuits is different and that the expected/theoretical shape of the piezoresistive is not present. The expected would be to have the signal coming back to the same steady state as it was prior to the ramp directly after the step, which not occurs. Note also that the fall back time of the piezoelectric are faster than the piezoresistive. This is probably due to limitations in the piezoresistive system and textile characteristics, and out of the scope of this study.

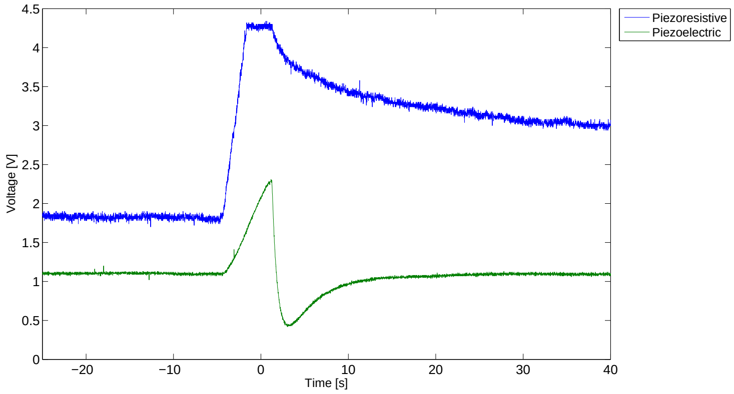


Figure 4.13: A ramp followed by a step. Note the different slope in the ramp phase, note also the fall back time of the systems. Both system started after full settling time

To test the response of a signal which starts from one value and slowly increases to a maximum and freeze extended, a ramp without step was performed. In theory the piezoelectric will follow the increment and then fall off, meanwhile the piezoresistive will increase and remain stable after the ramp. In figure 4.14 both systems instead falls of after the ramp is performed. The piezoelectric system slowly returns to the same steady state following time constants, whereas the piezoresistive is even slower.

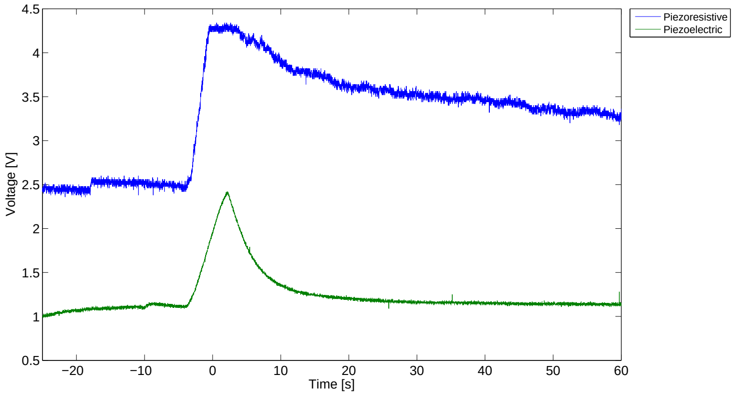


Figure 4.14: A ramp for the two systems. Note that both systems falls of, while the piezoelectric falls faster than the piezoresistive. Note also that the piezoresistive system goes into saturation at maximum extension.

4.6 Justifications of the suggested signal conditioning circuit

In the following sections measurements has been performed to justify the decisions. Findings from the measurements have been used to find component values which are used in the realization.

4.6.1 Measurement on fibres directly

When measuring at the fibres directly using oscilloscope it is possible to see the response of simple actions. In figure 4.15 the result of manually generate a single square signal is seen. In the image the blue is the generated signal and the green is the applied force. This gives the basic information of how the sensor works. Note that when the pulse is started there is a quick rising followed by a fast drop to zero. This is the current flow which normalizes the dipole change in the fibres. The noisy period in between the peaks is when the person is trying hold at constant force, and other noise level is the noise floor where no force is applied.

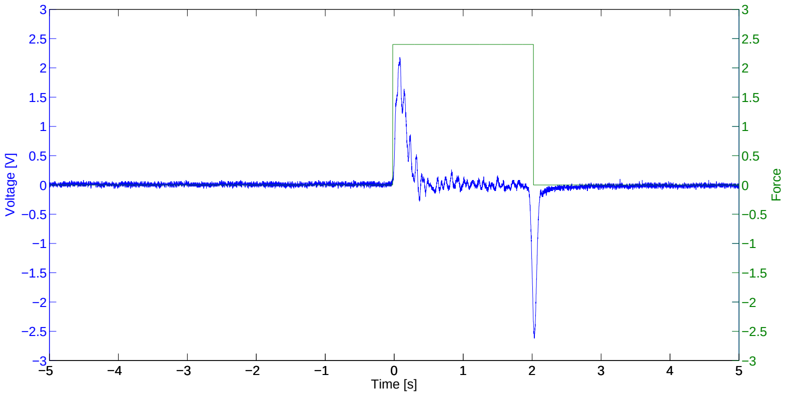


Figure 4.15: Signal achieved when manually pulling the fabric in a square like signal. The green is the applied force and the blue is the generated signal.

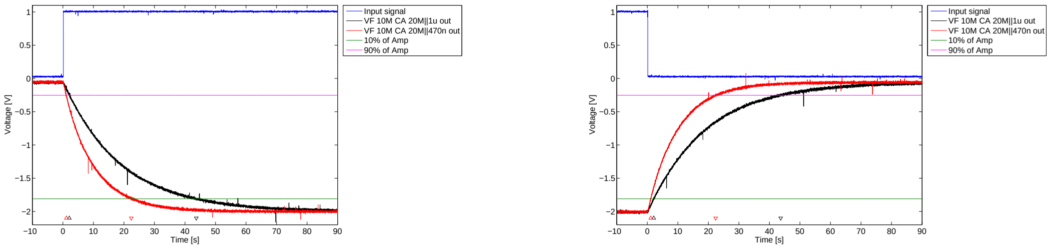
In the figure it is seen that a dynamic force has to be applied to generate a signal. It is also seen that an extension of the fibre gives a specific direction of the peak. In the image it is seen that the change is quite instant, when a force is applied and only measurement system is connected there is short rise time which should occur from a step in a RC-circuit, see figure 2.7.

4.6.2 Signal conditioning circuit and electrically generated feeding signal

While testing the signal conditioning circuit it is seen that the signal that is achieved needs to be sufficient high to be higher than noise level. Different electrically generated feeding signals was used to find relevant parameters such as time constants.

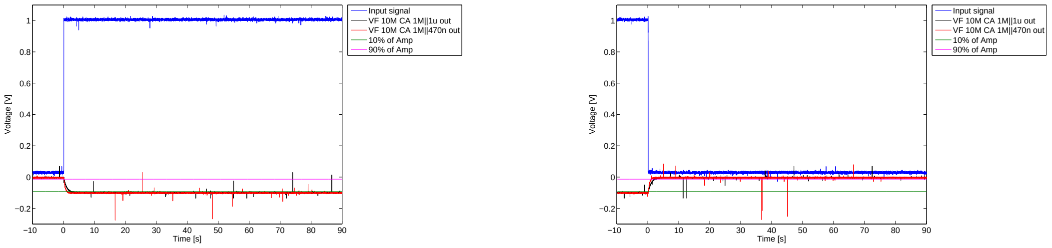
4.6.2.1 Voltage step

From the literature study and theory it is found that a specific choice of component generates certain characteristics, which is verified in figure 4.16. In the figure it is seen that a charge amplifier inverts the feeding signal and that the capacitor are main responsible for frequency characteristics, and the input resistor and the feedback resistor pair is affecting the amplification. By comparing the output signal between the circuit of $20M\Omega$ and $1M\Omega$ it is seen that the signal in the first is 20 times as high, as expected. It is also seen that by increasing the capacitor a slower system is created. This is a drawback since the system needs to run for a longer period before steady state is reached. But also positive in the sense that the system can react to lower frequencies, which in some applications are of vital importance.



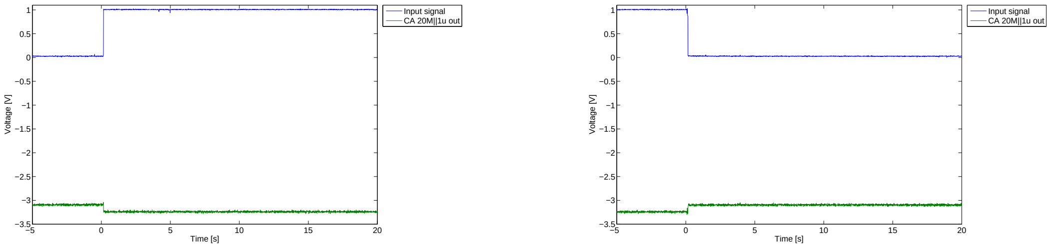
(a) Step 0 to 1V, $20M\Omega$ as feedback resistor and $1uF$ or $470nF$ as feedback capacitor.

(b) Step 1 to 0V, $20M\Omega$ as feedback resistor and $1uF$ or $470nF$ as feedback capacitor.



(c) Step 0 to 1V, $1M\Omega$ as feedback resistor and $1uF$ or $470nF$ as feedback capacitor.

(d) Step 1 to 0V, $1M\Omega$ as feedback resistor and $1uF$ or $470nF$ as feedback capacitor.



(e) Step 0 to 1V, $20M\Omega$ as feedback resistor and $1uF$ as feedback capacitor.

(f) Step 1 to 0V, $20M\Omega$ as feedback resistor and $1uF$ as feedback capacitor.

Figure 4.16: Rise time of the circuit with different amplification in the feedback loop, 2 in figures a and b, while 0.1 in figures c and d. Note that measuring at only the charge amplifier results in an almost instant response, but the signal is biased (green curve at bottom) and the signal has decreased (lower step). The input signal is one example, but is similar for all tests. Sample rate $100S/s$

It is seen in the figures in 4.16 that different times has passed before the output signal has come into steady state. After transients due to the capacitor, the maximum amplification can be found. This appearance is expected from theory, see section 2.4.

From the achieved data it is found that, having a voltage follower in front of the charge amplifier and a resistor of $10M\Omega$ as an input resistance, different outputs are achieved see table 4.1. The charge amplifier in figure 4.16(e) and 4.16(f) is not having the expected output since the signal is not amplified as the ones including voltage follower prior to the charge amplifier (this result is also noted in figure 4.22, section 4.6.3.1). This is an indication that a voltage amplifier is needed as an input stage of the signal conditioning circuit.

Table 4.1: Characteristics of different circuit choices and the resulting amplification, rise time and corresponding level at high and low value.

Circuit config.	Rise time [s][1]	Low [V]	High [V]	Amplification
VF $20M\Omega\|\|1\mu F$	42	−0.059	−2.004	1.94
VF $1M\Omega\|\|1\mu F$	2	−0.004	−0.102	0.10
VF $20M\Omega\|\|470nF$	21	−0.059	−2.004	1.94
VF $1M\Omega\|\|470nF$	1	−0.004	−0.102	0.10
$20M\Omega\|\|1\mu F$	0[2]	−3.093	−3.24	0.15

---

[1] 10% to 90%. Note that signal is noisy forcing an estimation of level passing. Note also that a charge amplifier with same feedback configuration has no amplification

[2] Less than sampling time of $10ms$

4.6.2.2 Square wave

To test the signal conditioning circuit using a square as feeding signal a generator with the ability to generate symmetric, nonsymmetric and biased square waves have been used. The circuit uses a charge amplifier with TL072 as operational amplifier with an input resistance of $1M\Omega$ and feedback including $1uF$ and $20M\Omega$. The component values are chosen to generate a low cut off frequency, but with a high input resistance to lower the amplification which otherwise would saturate the operational amplifier before any pattern could be seen.

Symmetric square without DC level
To test the system and the reaction to a square wave that is symmetric without a DC level, such a measurement is seen in figure 4.17. In the figure it is seen that when the signal is symmetric without any offset the resulting signal keeps the same shape over time. In the figure two signals is seen, blue is with an oscilloscope connected in parallel to the circuit and green is without. The measurement shows that there is no difference in having an oscilloscope connected or not when feeding signal is generated by signal generator. By using a good approximation to perfect square wave there is no drifting, but the output varies around zero. The time shift seen is due to triggering uncertainty.

Manipulated square wave
When the feeding signal is manipulated to include some nonoptimal characteristics which could possible occur in a piezoelectric signal, the outcome is shifted. In figure 4.18 the same system as earlier are used but the feeding signal is altered to include a DC offset of different amount. In the figure the signal is kept normal until time instance zero

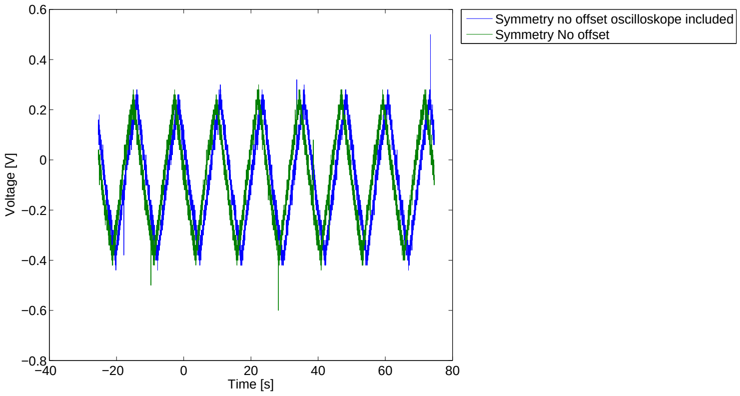


Figure 4.17: A square wave are used as an input signal, and the output signals are seen where it is compared to have an oscilloscope connected simultaneously measuring the feeding signal.

where the change occurs. It is seen that directly after the signal change the signal either increase or decrease depending on if the offset is positive or negative. A positive offset results in decreased signal and the opposite for negative offset. Note that the signal drifts towards a new steady state shifted from the one in figure 4.17.

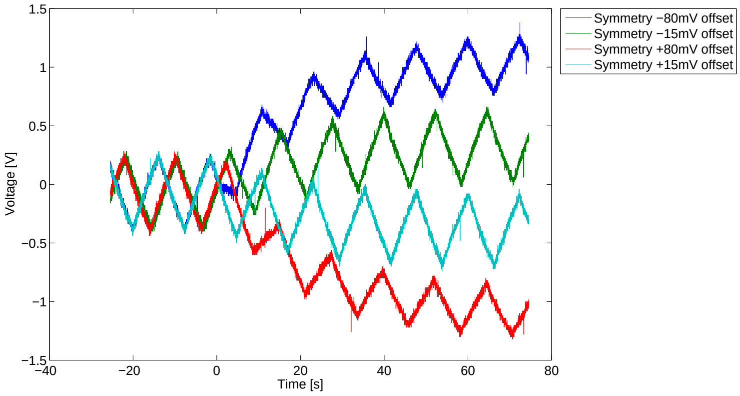


Figure 4.18: A manipulated square wave are used as an input signal. The signal is having a different amount of offset added to the signal. Note that the offset is applied at time instance 0, resulting in a changed signal at that time.

The other situation that can occur for a manipulated square wave is a nonsymmetric signal regarding high/low time. In figure 4.19 the signal is as above altered at time instance zero. Note that the rise/fall time of the signal is altered when the signal alters. The notation is based on time being high or low, where positive symmetry indicates that the signal is more high than low, and negative is the opposite. It is seen that the output reaches a new symmetry line where it fluctuates, and have a signal that is different in the rise and fall time, compared to figure 4.17.

The results from this are expected from theory. When the capacitor is charged a higher current is required to increase the output in the same amount, compared to an uncharged capacitor. These measurements reveal that a stimulus with uneven force over extension/contraction could be measured. Example of a stimulus with uneven symmetry

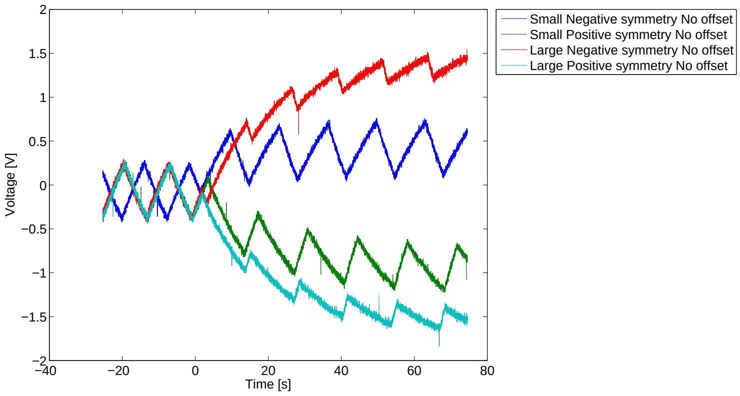


Figure 4.19: A manipulated square wave are used as an input signal. The signal is having a different symmetry regarding high and low. Note that the offset is applied at time instance 0, resulting in a changed signal at that time.

is hysteresis, where charge/uncharge phase is not matched. From the manipulated square wave it is seen that the output of such a measurement is biased but measurable.

4.6.3 Signal conditioning circuit using signal generated from textiles

To verify the suggested signal conditioning circuit the mechanical setups presented was used to generate piezoelectric signals.

4.6.3.1 Sinusoid

From the measurement system seen in figure 3.4, the resulting signal is a sinusoid. This has been applied directly to a charge amplifier with varied components. In figure 4.20 the results of this measurement is seen. For comparable results the circuit and measurement system is kept the same and only operational amplifier is switched. In the figure a charge amplifier with feedback resistance of $20M\Omega$ and feedback of $1\mu F$ capacitor have been used and oscilloscope in parallel.

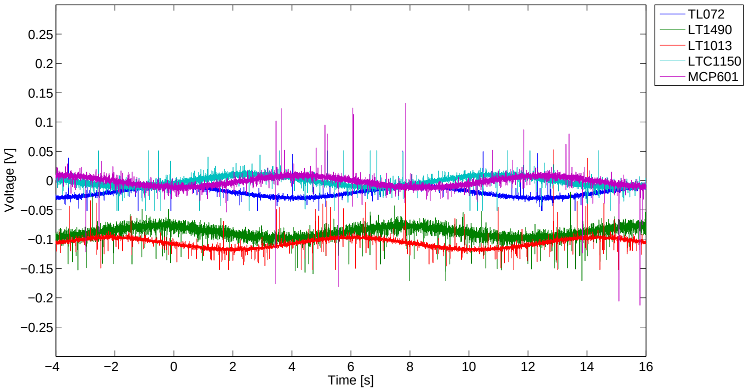


Figure 4.20: Different components in a single charge amplifier circuit. Note that frequency and amplitude are the same whereas a DC offset are changed when altering components.

It is desired to have as low noise and low offset as possible due to SNR and amplification. Low offset is desired to be able to amplify the signal; a heavily biased signal cannot be amplified in the same extent as an unbiased signal. In a theoretical system this offset is not present, giving a signal that can be amplified as much as desired. In these real systems the offset is limiting the amplification possibilities to not saturate the amplifiers.

In figure 4.20 it is seen that the curves has approximately the same amplitude, indicating that the amplification is not a matter of operational amplifier, as expected. It is also seen that the frequency is the same for all curves, as expected since the stimulus applied to the fabric is the same for all measurements. Differences between the curves are also noted. From this a few differences can be seen, timing difference, bias level and noise level added to signal. The timing is based on the triggering of the signal and is not of importance, whereas the offset and the noise are important. In the figure the offset is varying, resulting in lower possible amplification for LT1013 and LT1490, compared to the three others. By comparing the noise that is present in figure 4.20 with the noise in the feeding signal, figure 4.21 it is seen that depending on component different noise amplification is achieved.

For green curve (LT1490), the noise is highest, whereas blue (TL072) and red (LT1013) is of the lowest noise, note that there are many outliers affecting the signal, forcing a decision of which type of noise to avoid. From the result of only having a charge amplifier where the DC offset and the noise is regarded, it is seen that TL072 is preferred to use in such a configuration. In the measurement system an oscilloscope have been measuring both feeding and output signal simultaneously, using $20M\Omega$ and $1\mu F$ as feedback, and different operation amplifiers.

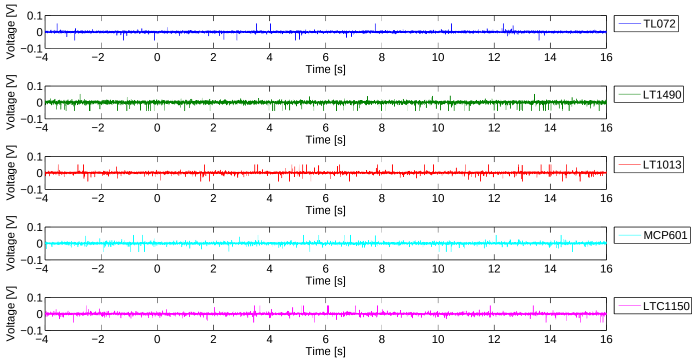


Figure 4.21: The received signal measured over the fabric before processing. Note that the noise is basically the same for all measurements.

In figure 4.22 it is seen that including a resistor in front of the charge amplifier does not amplify the signal. However, having a voltage follower followed by a resistor makes it possible to amplify the signal. Because of this, such circuit is to be used to enable amplification tuning.

To be able to derive if it is possible to measure frequencies in the range of respiration a frequency sweep is performed. Due to the setup, where voltage over DC motor is used to alter the frequency, small frequency steps have been used. The system is limited to be in the range that the motor can handle, which is a rather small range, but can be lower than respiration. In figure 4.23 the result of eight different frequencies are seen. Note that the frequencies related to respiration are at $0.1Hz$ whereas the measurement

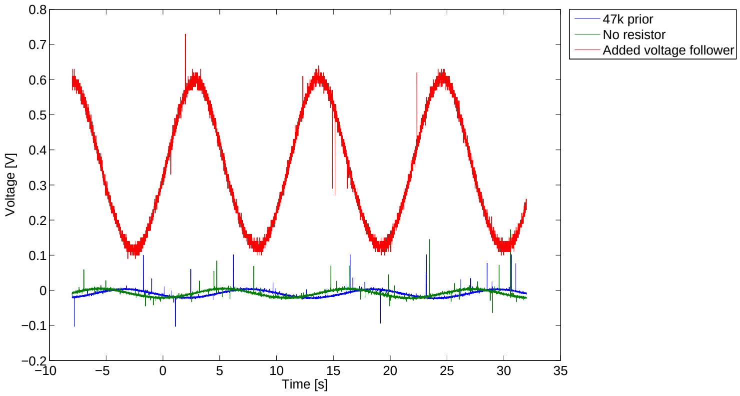


Figure 4.22: Differences of having an resistor in front of the charge amplifier. Note that there is no amplification of the signal, instead the signal is lower than feeding signal.

system goes down to about $17mHz$, well below the respiration frequency. Note that the two lowest frequencies have different time scale. In the measurement the same system have been used, no alterations other than the voltage across the motor. The circuit that been used is a voltage follower, resistor of $360k\Omega$ and charge amplifier using TL072, $1\mu F$ and $20M\Omega$.

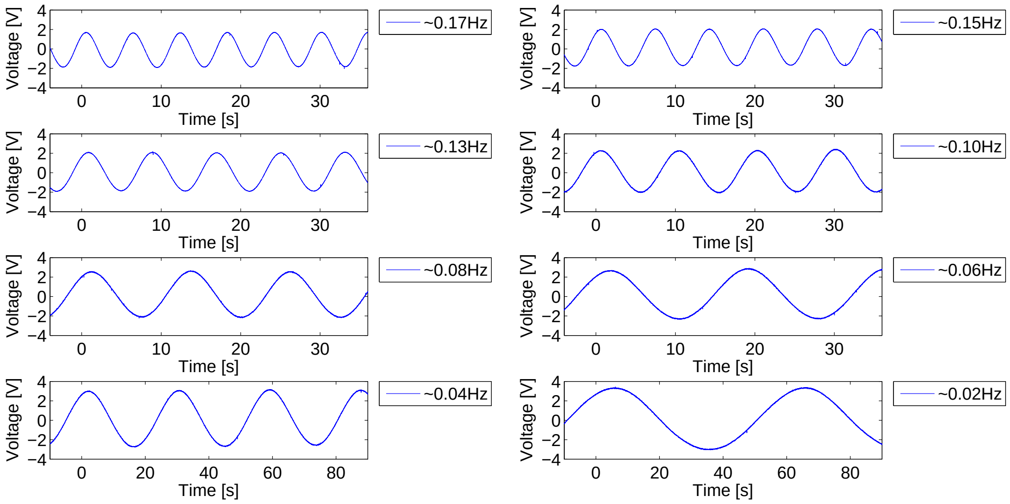


Figure 4.23: Sweep of frequencies of sinusoids. Note that the time axis differs for the two with lowest frequency.

4.6.3.2 Settling time by sinusoid

Due to the properties of the fabric to not measure static force there is some settling time required to get into the ”correct” level where it elongates around the base level. In figure 4.24 it is seen that if the system is set at steady state in an extreme case of the sinusoid the output will be biased, similar to the manipulated square wave. In the figure the blue curve has been running for a long time letting the system come into normal

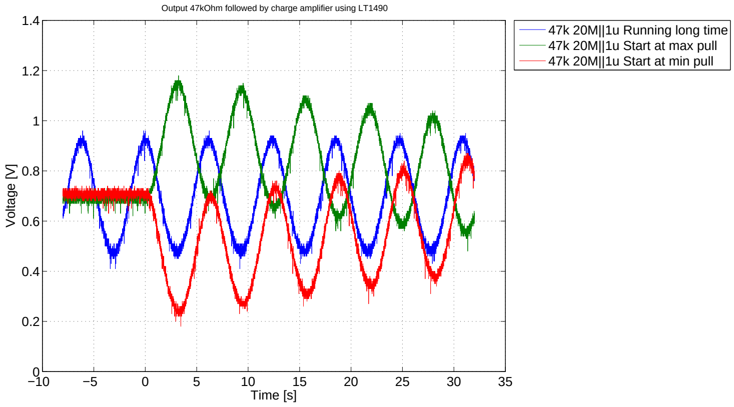


Figure 4.24: Three measurements using the same components. A specific offset is received when the system is in steady state, no matter if it is in a static extreme case or dynamically changed. The time it takes to get into basic level is related to the rise time.

state, whereas the green and red curve represents the two extreme cases, max pulled respectively minimum pulled. In the curves of the extreme cases the system has come into steady state at one of the extreme and then the motor has been started. It is seen that after a long time the system reaches into a state in the middle of the extreme cases. This normal average state can be seen in the starting sequence of the extreme cases, as well as a mean of the blue curve.

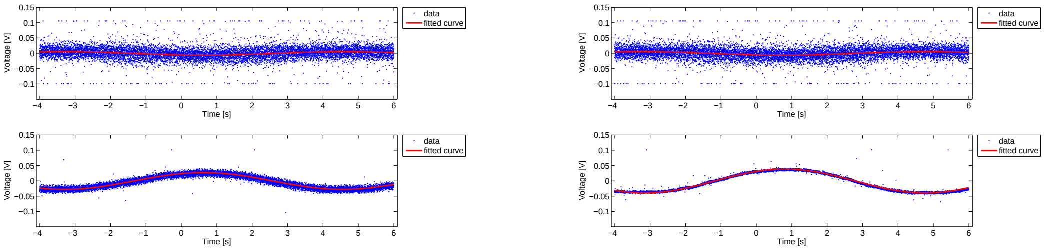
Due to this it can be seen that the system requires its mean as starting point or some settling time for the system to correctly relate the signal to the force. This also proofs that a piezoelectric system is not suitable for static measurements since the system will attend a specific value no matter applied force. The time it takes to reach the basic level is related to the rise time described in section 2.6.2.

4.6.3.3 Time lag due to feedback components

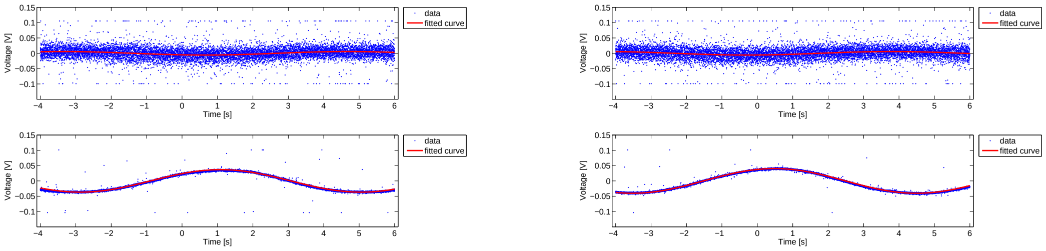
From section 4.6.2.1 it is found that the step response is dependent on the feedback components which are used. A system with larger components results in slower system. One of the main drawbacks of having low cut off frequency and therefore a sensitive system is that the system reacts slowly. In figures 4.25 and 4.26 a resulting lagging of having long memory in the system is seen. In figure 4.25 the resistor in the feedback loop is $1M\Omega$ and capacitor varied. In figure 4.26 it is instead $20M\Omega$ and capacitor varied. Other circuit components are voltage follower TL072, and the input resistance is matched to generate similar output voltage despite altered capacitors. This can be done since amplification is altered by a potentiometer which has low capacitive alterations.

Note that the charge amplifier inverts the signal. To measure the lag of the system a fit of sinusoidal order one has been applied to both feeding signal and output signal. This has been done to achieve well defined maximum and minimum points from the noisy data. This performance is not perfectly accurate but is regarded as good enough to indicate that a slower system makes a longer lag time, which can be a crucial aspect. From maxima and minima of the figures the resulting lagging is calculated and stated in table 4.2.

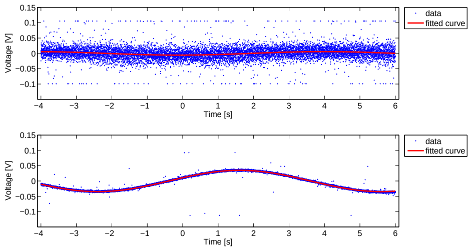
From table 4.2 and the corresponding figures it is seen that it is a trade-off between low cut off frequency and low lagging time. Depending on the application this parameter



(a) $1M\Omega$ and $10nF$ (b) $1M\Omega$ and $100nF$



(c) $1M\Omega$ and $470nF$ (d) $1M\Omega$ and $1\mu F$



(e) $1M\Omega$ and $10\mu F$

Figure 4.25: Comparison of different time constant in the signal conditioning circuit, $1M\Omega$ used as feedback resistor. Capacitors are changed between each measurement.

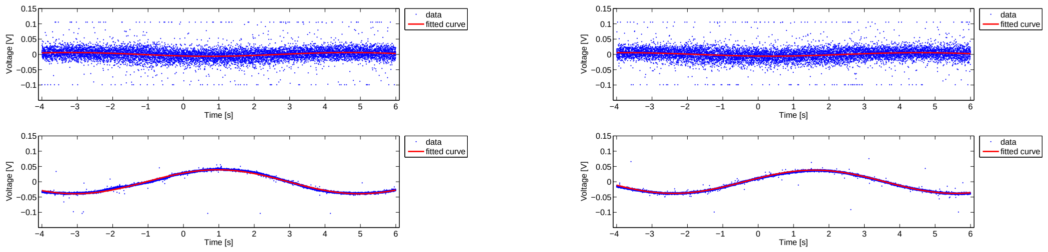
Table 4.2: Lagging time of different feedback components, otherwise the same configuration. Data from figures 4.25 and 4.26.

Resistance \Capacitance	$10nF$	$100nF$	$470nF$	$1\mu F$	$10\mu F$
$1M\Omega$	$29ms$	$65ms$	$441ms$	$776ms$	$1723ms$
$20M\Omega$	$215ms$	$1233ms$	$1716ms$	$1991ms$	$2002ms$

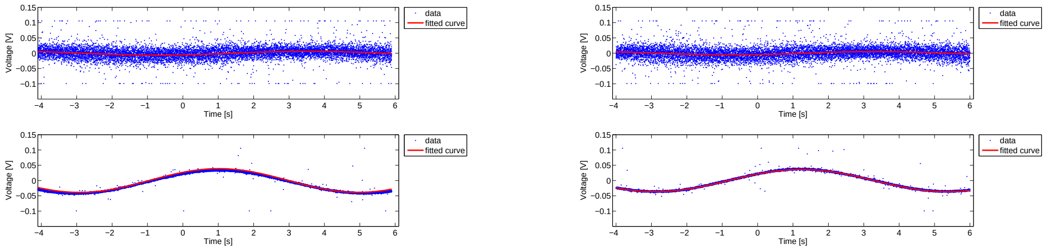
needs to be tuned to match all the relevant criteria.

4.6.3.4 Voltage follower

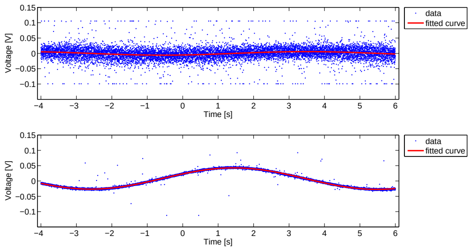
As seen in figure 4.20 a low signal is achieved when long time constant is required. For processing possibilities it is necessary to amplify the generated signal. Dependent on the application and feeding signal different amount of amplification is needed. From above it is noted that consideration has to be taken regarding the offset of the signal which is



(a) $20M\Omega$ and $10nF$ (b) $20M\Omega$ and $100nF$



(c) $20M\Omega$ and $470nF$ (d) $20M\Omega$ and $1\mu F$



(e) $20M\Omega$ and $10\mu F$

Figure 4.26: Comparison of different time lag due to the long time constant in the signal conditioning circuit, $20M\Omega$ used as feedback resistor. Capacitors are changed between each measurement.

dependent on the operational amplifier.

To separate the charge amplifier from the measurement system and increase the impedance seen from the fabric a voltage follower are introduced in front of the charge amplifier. As stated in the theory it works as a buffer which enables signal processing possibility without alter the achieved signal.

To compare the components in the system a circuit consisting of charge amplifier with gain are used. In figure 4.27 the result of changing operational amplifier in the voltage follower are seen. The charge amplifier that are used are having a $47k\Omega$ resistance as an input resistance which controls the amplification. This is lower than previously since the oscilloscope is connected in parallel to the circuit.

In the figure it is seen that different component choices alters the offset and the noise in the system. By compare figures 4.27 and 4.20 it is seen that the relative noise added is different, some component pairs are therefore better to combine than others. By comparing MCP601 and LT1490 in the figures it is seen that LT1490 has lower SNR

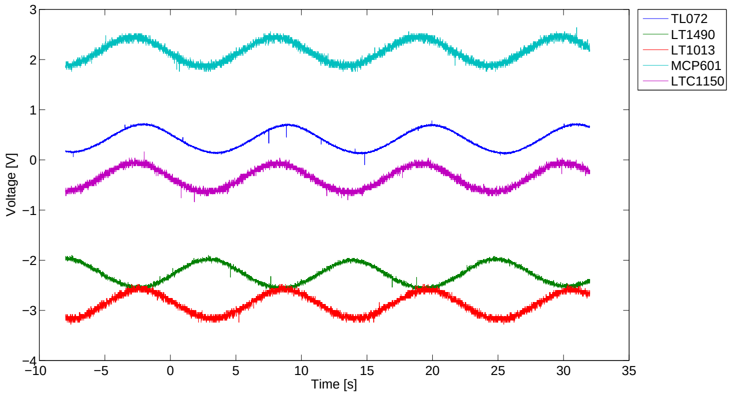


Figure 4.27: Comparison between components used in voltage follower in front of charge mode amplifier.

in the first figure but higher in the second, compared to MCP601. Because of the altered relations it is seen that adding a voltage follower in front of the charge amplifier amplifies the signal, and also have a positive effect of the SNR of the signal.

4.6.3.5 Drop mass

In figure 4.28 it is possible to see how the voltage follower follows the signal that is induced in the fabric when the mass is dropped. By comparing the different components it is seen that it is not a big difference between the operational amplifiers when used as voltage followers. This also present the input signal used when dropping a weight of $200g$. Oscilloscope is used to measure both the feeding signal and the output of the follower.

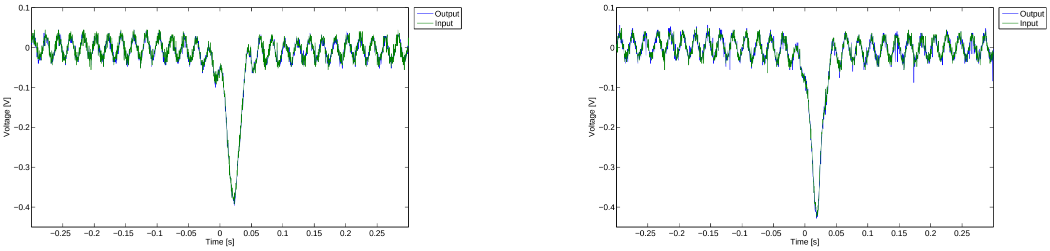
In figure 4.29 the resulting signal after dropping the weight is seen with different components in a charge amplifier circuit. By altering the components involved in the amplifier it is possible to alter the amplification and rise time, i.e. the low cut off frequency of the circuit.

In the comparison of figure 4.30 it is seen that there is a different offset voltage between the components. This is the same as seen in the figures regarding sinusoids. In the figure it is seen that the response is sudden, but note that the feeding signal is not measured. Due to this any lagging is not seen.

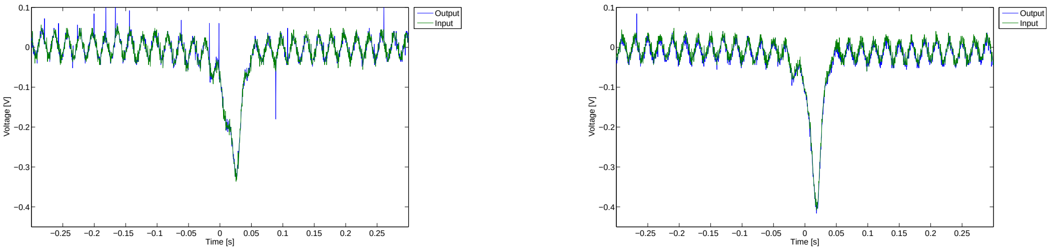
It is also possible to compare different feedback components to find how the drop off is affected due to system response. In figure 4.30 it is seen how the output signal alters when the feedback components consist of varied components (resistor values of $1M\Omega$ and $20M\Omega$, capacitor values of $100nF$, $470nF$, $1\mu F$ and $10\mu F$).

4.6.3.6 Ramp and step

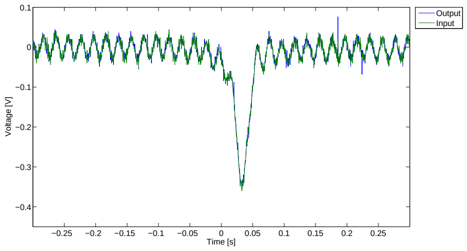
In figure 4.31 it is seen that when the arm, of the mechanical setup of a ramp and step is pulled backwards the signal increases until it is suddenly dropped. In the quick response of the signal, the output has similar shape as in section 4.6.3.5 where it quickly falls of but flattens in the end of the peak. One noticeable observation is that the signal increases slightly after the dropping, compared to the ground level. The reason for



(a) TL072 (b) LT1490



(c) LT1013 (d) MCP601



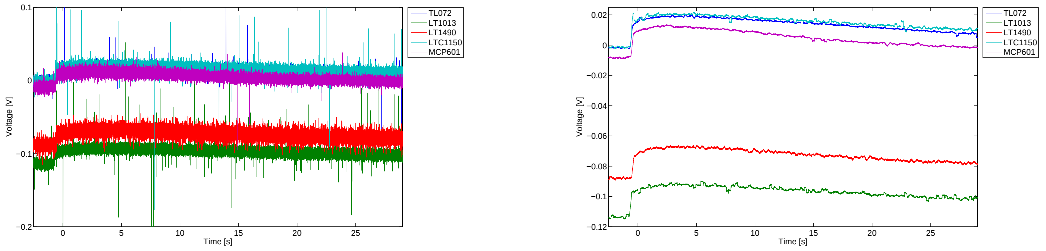
(e) LTC1150

Figure 4.28: Comparison between the voltage followers that can be used, green is input and blue is output. Sample rate $250 S/s$.

this is due to the longer charging of the capacitor during the pulling of the arm. As the capacitor charges there is also some leakage from it through the resistor. When it is quickly released all current is coming basically instantly, whereas low leakage can appear. Since the time and therefore also leakage is different the signal after the step is higher. However, this appearance is not expected in the case of the drop in section 4.6.3.5.

4.6.4 System sensitive to component samples

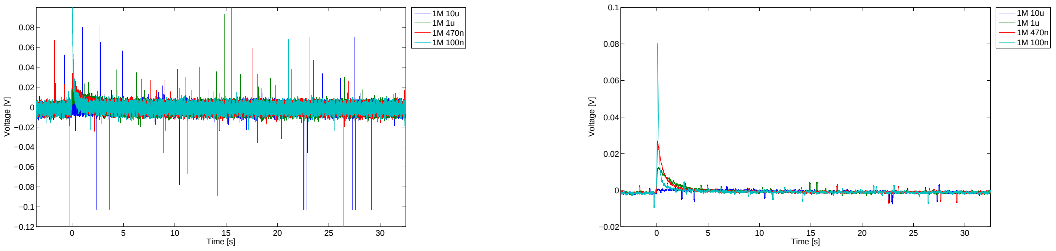
It is understood from the different ground voltage of the operation amplifiers that the system is sensitive, see figures 4.20, 4.27, 4.28, 4.30 and 4.31. Due to the differences in the operational amplifiers and the amount of amplification that is needed to process the signal some differences are seen. In figure 4.32 it is seen that the resulting signal is not only dependent on the component type that is used, but also dependent on the individual sample. Due to differences in the samples a switched operational amplifier may result in altered characteristics. It is therefore important to be aware of the change and to recalibrate the system after alterations.



(a) Original data from dropping a weight of 200g.

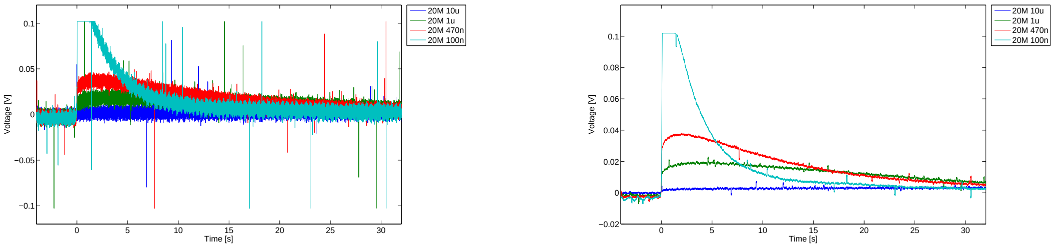
(b) A running average over 50 samples of the varied components to make it possible to distinguish the different outputs.

Figure 4.29: Resulting output when a weight is dropped and a single charge amplifier is used with different operational amplifiers used. In the feedback loop the components are the same for all measurements, $20M\Omega$ and $1\mu F$.



(a) Original data from dropping a weight of 200g.

(b) A running average over 20 samples of the varied components to make it possible to distinguish the different outputs.



(c) Original data from dropping a weight of 200g. Note that at low value of capacitor the amplification reaches roof of sensitivity of the recording oscilloscope.

(d) A running average over 20 samples of the varied components to make it possible to distinguish the different outputs. Note that the oscilloscope recording roof is reached for the specific sensitivity.

Figure 4.30: Resulting output when a weight is dropped and a single charge amplifier is used with different operational amplifiers used. In the feedback loop the components are the same for all measurements, $1M\Omega$ in a and b, and $20M\Omega$ in c and d.

Due to the sensitivity of component samples, a comparison between having the components in sockets or not, when using them in the bread board, are seen in figure 4.33. The circuit is having a voltage follower and charge mode amplifier with input resistance of $47k\Omega$ and feedback loop using $20M\Omega$ and $1\mu F$. By comparing the graphs it is seen that there is basically no changes between the curves, indicating that the system is not dependent on usage of sockets or not. Note that this measurement was performed using

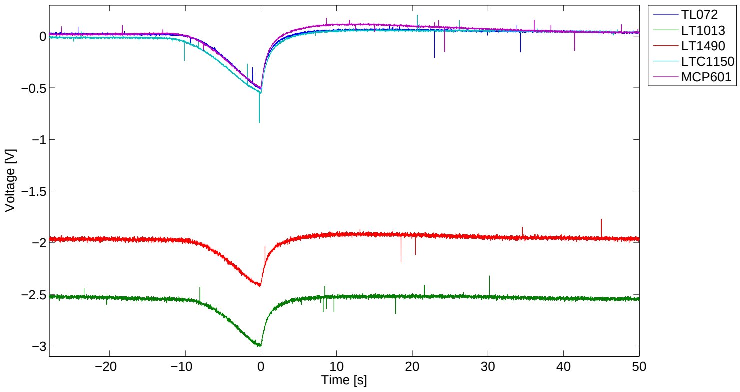


Figure 4.31: Different operational amplifiers used in charge amplifier configuration with a voltage follower in front.

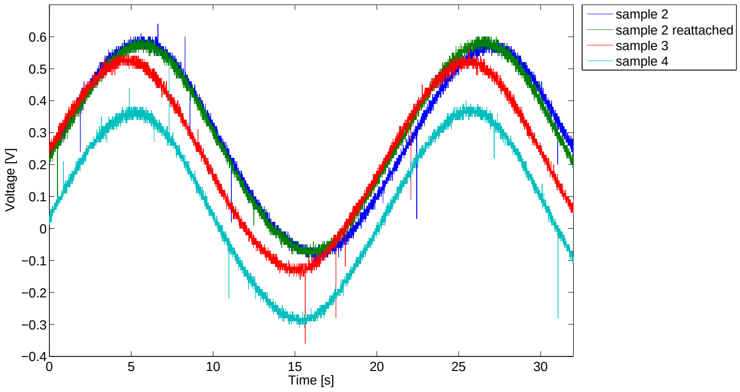


Figure 4.32: Difference between different unique samples of TL072 in the voltage follower when sample numbered 1 is in the charge amplifier.

an oscilloscope connected to measure the feeding signal. The small change between the curves may be, but does not have to be, related to the change in system setup; some drifting in the system have been noted, see figure 4.34.

In the signal there is some low frequency component that appears which is unknown. In figure 4.34 the negative slope of the signal have been captured but after longer time the signal flattens and starts to increase again. This data is recorded when the system has been running for a long time and all transient signals should have disappeared. This needs further investigation for explanation.

4.7 Frequencies present in the signal

In the signal that is achieved it is seen that the signal is noisy. To be able to find relevant frequencies that are present in the signal an FFT of one of the signals achieved from the sinusoid stimulus is seen in figure 4.35(a). Comparing this with figure 4.35(b) where a ramp and step has been used, it is seen that the signals differs as expected. It is also seen some peaks at about $50Hz$ which is signals picked up from the power grid. Observe that the frequency axis is limited to the Nyquist frequency.

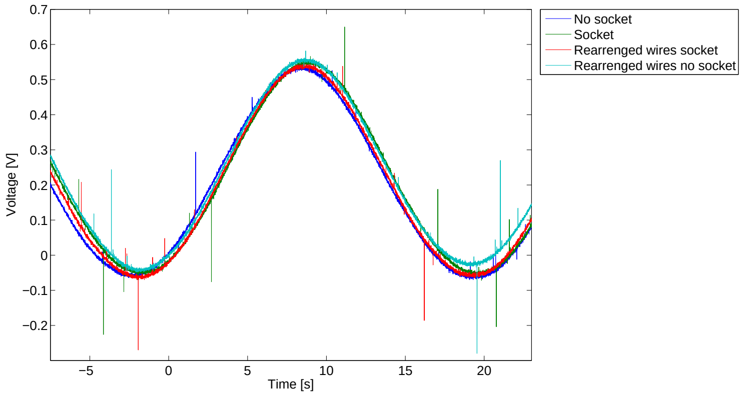


Figure 4.33: Difference between using a socket or not and altering the system setup.

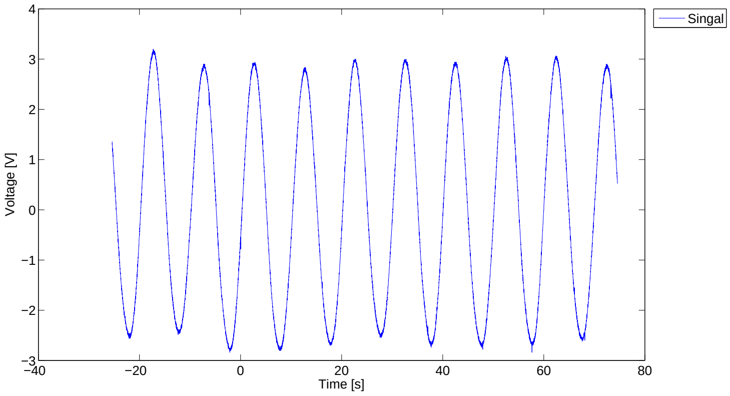
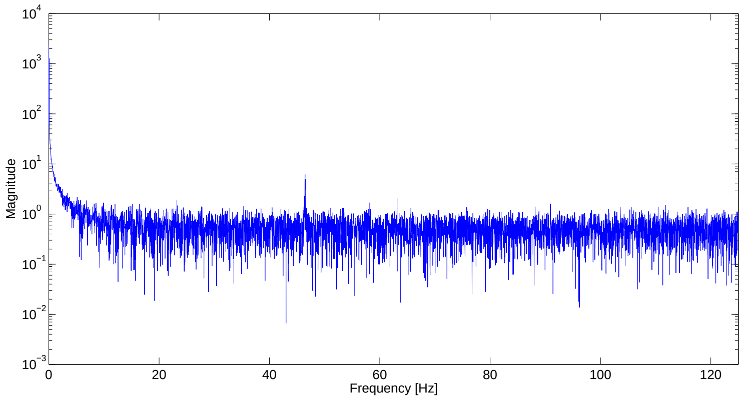
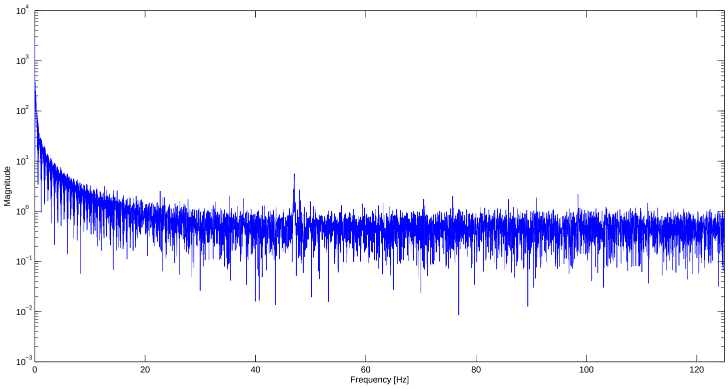


Figure 4.34: Sinusoidal signal where the system has been running for a long time. Note the voltage at top shifts from start to end. This is due to some unknown effect and been seen during the measurements and have been taken into consideration.

In the figure it is seen that a sinusoid is clearer at the low frequencies than the triangular signal and the triangular has a slower fall-of of the frequencies. It is also seen that the noise is reaching amplitude of 2, which is starting to appear at about $7Hz$ for the sinusoid and $15Hz$ for the triangular. The reason for this is due to the amount of frequencies that are present in the signal. Since the triangular has more frequencies these are more prominent at higher level.



(a) Sinusoid



(b) Step

Figure 4.35: FFT of the signals achieved in using the different measurement system. Sample rate $250Hz$ resulting in highest correctly recreated frequency is $125Hz$.

5 Discussion and future work

In this section the different parts and findings will be discussed, including suggestions for improvements or future development.

Commercial charge amplifiers

Commercially available alternatives which are compact enough to use as charge amplifiers in the intended application could not be found. This could be to the fact that a charge amplifier, to its construction, is a relatively simple circuit with a wide range of use. From a commercial point of view it can be hard to find solutions that are adjustable to fit the large number of applications where a charge amplifier can be used, with all its different characteristics, regarding amplification, lower and upper cut off and so on. From a production point of view it is expensive to create a bank of many components to use, or create a single component with broad capacity. Due to simplicity and economics it can therefore be easier to either create a customized integrated circuit when needed in large scale, or to build it by spare parts. An integrated circuit is of interest when optimization regarding size is the goal since the size then can be lower. Integrated solutions can also be of interest when it comes to power consumption since such often is more power efficient than spare parts. This could otherwise be the explanation of not finding commercial alternatives.

Model of piezoelectric sensor in simulations

Through the simulations it was possible to get a basic understanding about different circuit solutions and how the feeding signal and signal conditioning circuit characteristics alter depending on the component choices. The signal that was generated by the piezoelectric fibres differed to the simulations, probably due to the ruff simplification of the sensors as a voltage source in series with a capacitor. For optimal simulations it was desired to mimic a true piezoelectric material, but this has not been possible due to no such model was found. This drawback has probably affected the choice of operational amplifiers in a bad manner, but when changing one parameter at a time it is possible to compare the results and find the best in the simulated situation.

Different signal depending on weaving technique

From earlier research it has been found that textile sensors based on different weaving techniques/structures generate different signals. By altering the sample that been used in the report another signal may be received, which may require other system characteristics. Since one sample has mainly been used to perform measurements another sample that is having another weft could possible result in different signals and circuit needs due to other amplification/offset. What type of signal that is generated has however not been in focus of the report, as long as it generates somewhat similar output signal. The created unit is having ability to handle some changes of the feeding signal by amplification and offset change. By having other samples these could be compared and it could be possible to choose one type that is useful for respiratory measurements. Further investigation regarding the sensors needs to be performed to optimize the textile characteristics.

Different need of amplification

It has been seen in the research that different samples, attachments and application generates different amount of signal. In a situation where a large signal is received, which happens if the active area of the fibres is long, many fibres combined or a large force is applied, the signal does not need much amplification.

Therefore, in every situation it is necessary to match the hardware to the sensors that are used. If the sensors are altered it might be needed to alter the hardware as well for optimal performance. In the application regarding breathing it is beneficial to have a low cut off frequency to be able to distinguish and derive the low frequencies of the signal. The created unit has the ability to alter the amplification by turning a potentiometer, which is a rather simple solution, with nonoptimal performance, but sufficient to prove the concept.

Amplification circuits

It would have been interesting to compare the result of different types of amplifiers. For example create a voltage mode amplifier and compare the output to the charge mode amplifier to see how the result of such is in reality. Due to the literature research of the amplifiers it was decided to only realize a charge amplifier, but a comparison to realized voltage mode amplifier would be interesting since theory differs from reality.

It would also be interesting to compare other types of amplification possibilities such as current amplifier, which has not been investigated due to any findings when searching for amplifiers of piezoelectric signals. In applications where there is no need of deriving the total force over time other solutions could be sufficient. An example is if only a generated signal is to be detected. In such situations it could be of interest to use other amplification circuits than the now used. In the intended application it was desired to derive whether it was possible to lower the cut off frequency of the signal and measure a high signal as long as a force is applied. To do this it is not sufficient to only measure if any signal is generated.

Voltage follower

It has been shown that a voltage follower is required as a first step of the suggested conditioning circuit. This is due to the voltage follower having high input impedance, and thus acts as a buffer. Since the piezoelectric signal is very weak it is sensitive to the load that the signal conditioning circuit represent. Using the voltage follower it is possible to control the cut off frequency and amplification of the components which are chosen since the voltage follower is acting as a buffer of the circuit.

The mechanical setups

In the measurement systems several parameters can be discussed. In the sinusoid setup built on a DC motor, the voltage fed to the motor determines the rotation velocity and thus the frequency of the sinus signal to the piezoelectric sensor. Due to small differences in power supply the frequency might have varied during the test, giving somewhat different frequencies which can be seen in some figures, and could possibly affect the comparison. Another aspect to consider is that the strength of the motor could vary dependent on the mechanical output, i.e. at different parts of the sinusoid, resulting in non-perfect signal (at higher force to the motor in the extension phase, the rotational speed lowers, which may result in an imperfect sinus signal). This drawback is appearing in both motor driven systems. In the ramp and step there is also an additional drawback; the flipping arm could be forced sideways which altered the signal generation. This has been known during the measurements and been taken into consideration, where the flip has been manually controlled to be as similar as possible. If any nonsimilarities were noted when recording, the measurement was recreated.

Another aspect in the motor driven setups is the unknown characteristics of the parts included such as elastic band, Meccano, DC motor and the static rope. The primary aspect of these affecting the characteristics is the unknown characteristics of the elastic band which been used. The band is required to make it possible to pull in the fibres since these cannot expand as much as needed when motor is turning. This band is working as a spring which can be considered as a mechanical capacitor which has the ability to store power. Due to this band the system created has some mechanical low pass filtering characteristics. However, the turning frequency is low and the tension in the band sufficiently high, which makes it possible to neglect the high frequency attenuation and consider it to transfer all power.

In the step setup it has been seen that a different mass generates different amount of signal, and the choice of using $200g$ can be discussed, but was suitable and generated a sufficient signal. Having a higher mass would generate a larger signal, but this was not relevant for the purpose since the purpose was to compare how different capacitors alter the cut off frequency. It was also seen that the sliding of the needle could be off different speed depending on how the needle was inserted. A different slide speed or any jags affected the signal; hence a more sophisticated method to generate a step would be desired for similar stimuli. However the solution did generate repeatable and similar response which could be used for comparison. Again, as long as the stimulus is the same and a single parameter is altered, the change can be compared and discussed.

For all measurements settling time has been an important aspect. Since this has been controlled by visual inspection, where a long time has been applied, the differences could be neglected. This could affect all measurements, but has also been considered in the comparisons, where the change in state has been the important aspect. This offset of the operational amplifiers had to be considered when designing the suggested signal conditioning circuit.

Signal recording

Since the output of the fabrics is affected on the applied circuit any measurement system affects the true output signal. Due to this it has been decided to have a constant measurement system for all comparing measurements, whereas similar stimulus as possible should be used. Some small changes might anyway be present, affecting the measured signal. As discussed regarding the measurements setup there is some differences in the stimulus, and the signal is also somewhat altered dependent on the measurement system. However, by altering a single part of the systems it is still possible to receive a relevant comparison regarding that part.

A parameter which however not is possible to control is noise. The noise cannot be considered to be constant over all measurements, but are heavily influencing the measurements, especially the triggering. The triggering is depending on the noise, where typically outliers could affect the recorded signal. A mistake in the triggering can in a worst case scenario generate a signal which is useless. When capturing the signal an oscilloscope has been used, which itself has some parameters affecting the signal.

Depending on the settings in the oscilloscope different sensitivity and sampling rate is derived which can affect the resulting signal when it comes to quantization and maximal amplitude. By visual inspection during the measurement extreme cases are avoided, but smaller alterations has not been possible to detect.

Drifting in the signal and different voltage level from operational amplifiers

It has been seen during the measurements that there is some drifting in the signal, i.e. different output amplitude when stimulus are constant, even after settling time, see figure 4.32. It has not been possible to see any correlation to other disturbances, which is to be considered as strange. Since a constant stimulation signal theoretically should generate a constant signal this drift is not expected. The drifting makes the output vary in amplitude and goes in waves over time, without any known pattern. This needs further investigation to verify whether it is due to the circuit, textile sample or the stimulus generation. In the figures this is seen as amplitude changes when signal in reality should be constant, as in figure 4.34. It is also noted in some figures that the frequency is altered when it should be constant, as in figure 4.32. This shift is probably due to unstable DC feeding the motor, and is not of vital importance since the overall characteristics is relevant and not the specific frequency, normally output amplitude has been a more important aspect than the frequency.

Another aspect that has been seen during the investigation is that the voltage level of the operational amplifiers included in the circuit varies dependent on type and even sample. This effect could be described by the manufacturing technique that has been used when designing the operational amplifiers, but then it should not be such difference between individual samples. This occurrence is increased due to the high amplification in the signal conditioning circuit, but the starting difference needs further investigation for determination.

Noise and disturbances in the system

It has been seen that there is noise disturbances picked up when measuring, which is expected. Noise is a limiting factor when performing the measurements. The higher sensitivity the sensor and measurements system has, the higher noise level is achieved. Since also the fibres are relatively exposed to external sources of disturbances such as motion artefacts and power grid these signals are also measured. When performing measurements it has been desired to minimize the number of sources of noise and disturbances affecting the signal. This is done by tight connection to the fabric and minimizing movements in other directions than the longitudinal which avoids extra parameters in the system. The measurements have also been visually expected to exclude unexpected occurrences which can alter the system. Comparative measurements have been performed as close as possible in time to lower changes in the surroundings which could affect the comparison.

When performing tests on person it is also seen that other movements than respiration can generate the same type of signal as respiration, which is to be avoided. Examples of such movements are shoulder movements and back bending. Due to this it can be hard to distinguish the true respiratory signal when performing normal activities. The sensors are indications of chest expansions, but chest expansions do not have to be due to inhalation. Other muscle activities can also give rise to a similar signal. This has to be considered for fully and precise respiratory measurements. By other measurements it is possible that other signals can be measured and used to distinguish the respiration. However, in the performed measurements other movements have been lowered by a focused test person.

Different transmission techniques

In order to transmit the signal from the signal conditioning circuit to a computer for visualization an ADC and transmitter over USB-cable was used. The currently used USB-version is limiting the portability and usage. However, by the use of a type of transmission board which enables wireless transmission it could be possible to avoid the cable. Since the created unit is having several possible tuning parameters it is possible to match other types of ADC's. From this point of view it is only a needed to alter physical properties to match the new board and its requirements, whereas the conditioning circuit properties can remain.

Areas of application

From the results it is understood that it is possible to measure respiration and heart beats under certain circumstances. However, since other movements also causes chest movements it can be hard to determine what corresponds to respiration. This technique, measure respiration from chest movements, is nevertheless used in commercial products by using pressure sensors. This utilize that it can be considered ”good enough” to use these movements, even though some signal processing might be used in the products. In situations outside of sports, which usually include movements which is undesired for monitoring something specific, other applications can be considered. In most situations where it is desired to only derive if there is any movement at all, and comfort is beneficial, smart textiles can be used. Examples of this can be taken from the hospitals, and especially in neonatal care. The technique could possibly be used to determine/monitor whether neonates, in critical situations, is breathing or moving. By incorporate piezoelectric fibres in a mattress or in clothes it might be possible to have alerts if movements stop. Such incorporations would theoretically be as comfortable as normal mattresses or clothes as long as elasticity of fibres is taken into consideration. Other situations could be in clothes for monitoring movements of other parameters than chest movements, or implemented in carpets to detect if someone is walking on it. Further research is needed to derive in what applications it can be beneficial to have a textile solution. Nevertheless it is highly probable that the concepts of smart textiles will be extended and used in many applications in the close future and forward.

Future work

From the discussion above it is understood that there is many aspects that needs further development. In the following some aspects are presented.

Optimization of circuit

Since the aim of the study has not been optimizing but to verify whether it is possible, some tuning could be performed for closer match of the application. Parameters that are desired to optimize is specially regarding size and power consumption but is not limited to these. This can be done by having smaller components, more operational amplifiers in one package and optimize the components on board. Another possibility is to use surface mounted components which normally are smaller but harder to use in a laboratory environment. When it comes to power consumption it could be possible to find components that are using lower power. By higher power efficiency it could be possible to extend the measuring time when the unit is entirely wireless. Other interesting areas of power consumption is to only increase the signal ground from the zero level in a more practical way instead of voltage divider. It can also be considered to use a single feeding voltage instead of voltage inverter to possible lower the consumption.

Other areas of optimization are regarding the intended application. When deciding for a specific application it is possible to optimize the amplification and lower cut off frequency for good matching. This could be done for increased performance, but has to be done in each specific situation. Also the visualization could be of interest to optimize. In the solution a LabVIEW interface was created, which had low updating intervals. By other programming languages it could be possible to increase the sampling frequency of the software, or even connect to portable devices such as smart phones or tablets. For good usage it would also be interesting to store the generated signal for later visualization in out of lab environments.

Automatic adjustment

For increased performance it would be desired to have a unit that can have an automatic adjustment of amplification and offset tuning instead of manually tuning the offset and the amplification. This needs some digitally controlled amplification depending on the desired maximum/minimum output. It is possible to adjust the maximum amplification of the unit by extend the textile to its maximum, from a normal ground state to avoid saturation of the amplifier. In a similar manner it is possible to adjust the lowest amplification by a stimulus which of smallest extension, which is to rise above quantification levels of the ADC.

It is also desired to have an alterable offset. This offset are not as vital since this is mostly dependent on the components in the circuit and the specific sample that is used, which not is altered between measurements. Therefore it would be beneficial to have some tuning possibility, even if this does not have to be automatic.

Another automatic property that could be of interest is an adaptive amplification. Using such techniques it could be possible to amplify small signal in a large extent but large signals less. By this performance it is possible to increase the range of measurable stimuli, and lower the risk of saturation. Such a solution could make it possible to use the same circuit to react at small signals, e.g. to measure heart beats, and sufficiently low amplification to fully examine yawns without saturation.

Alternative amplification solutions

In this report the research area has been looking into the use of charge amplifier as an amplifier circuit. Since other ways of amplifying the signal exists this could be of interesting to investigate whether this can be used. In theory it should be possible, but for certainty this needs to be verified by further investigation.

Depending on the application it can be of interest to compare the output of different voltage amplifiers to find optimum performance, but also to compare the results when current is used as a source for amplification. In some application it is only desired to notice any signals, which could lower the demand on the system. Since the choices was based on literature where not specifically piezoelectric fibres was used it could be of interest to compare other amplifiers to find an optimal solution for other applications as discussed above.

Fabric interface

In the solution the interface between the fabric and the electronics is based on crocodile clips. This solution is practical when performing test in a lab but not in a real situation. For better connection and a more stable solution it is required to have something that can transfer the signal from the fabrics to the electronics directly. Troubles occurs due to different stiffness in the fabric and the electronics, which result in mechanical bending and wearing, ending in lost connection after some time. This is an important area to solve to be able to extend the usefulness of the smart textiles.

Signal processing

To be able to expand the usage of the fabrics it could be possible to do some signal processing to extract signals of different frequencies and distinguish for example the heart beats even if it is hidden in the signal. Further work is required for optimization, and by using a good sensor with low disturbances, processing can possible be performed in digital domain.

Again, depending on the application, it could be possible to use the signal for detection of any movements. It is often not only interesting to view the signal live, but to derive some information about it. As an example it could by the realized system and some signal processing be possible to detect whether a person is breathing or not and derive conclusions about for example stress level of the patient. By measure the respiration and find patterns in the signal, or lack of signals it could be possible to have an alarms if it alters too fast or too slow. By looking at either threshold values or derivatives of the signal it could be possible to find if someone is breathing. The created unit therefore needs further development to be fully useful, however it is shown that it is possible to use smart textiles in respiration and heart beat detection.

6 Conclusion

It has been shown that it is possible to measure respiration with both the piezoresistive and the piezoelectric systems which has been in focus in the thesis. The piezoresistive sensor has ability to register lower frequencies, but is not stable at constant stretching, and has poor high frequency response. The piezoelectric system has instead bad low frequency behaviour where a static force cannot be measured, even if lower cut off frequency is dependent on components involved, but rather good response at the higher end of the frequency range involved in body movements. From the evaluation it has been seen that the piezoresistive system are more sensitive to how the sensors are attached to the body, where too high stretching tend to saturate the ADC. In the piezoelectric system, higher tension in the ground state results in increased signal which also generates a more sensitive measurement system. Therefore the sensor based on piezoelectric textile has wider application range, is easier to attach but the signal amplification level needs to be adapted to the application and the poor low frequency characteristics needs to be considered.

In the case of monitoring respiration, both systems will pick-up most movements of the body, specially the chest, which not necessarily has to be due to respiration but can be related to e.g. shoulder/arm movements. To be able to measure respiration these movements needs to be minimized.

It has also been shown that it is possible to see the heart beats using any of the systems. This requires, however, that other disturbances are minimized. Even the breathing signal results in movements that tend to make the heart activity difficult to detect. Using the current systems it has not been possible to see any heart rate simultaneously as the subject is breathing. Under the condition that other movements are minimized either systems can be used to monitor the heart rate, but further investigation is needed see whether it is possible to extract the heart beats while breathing using signal processing techniques.

As a conclusion it is seen that the required amplification and lower cut off frequency are heavily dependent on the intended application. In a situation where a large signal is generated, which happens if the active area of the fibres is long, many fibres combined or a large force is applied, the need of amplification is smaller compared to if the generated signal is small. It has also been proven that the low frequency characteristics of the piezoelectric textile can be improved by suitable signal conditioning circuitry. By using a signal conditioning circuit consisting of voltage follower, charge amplifier and summing amplifier it is possible to transfer the signal generated from piezoelectric sensors applied to the chest for detection of movements related to respiration and heart activity and visualize these on a computer.

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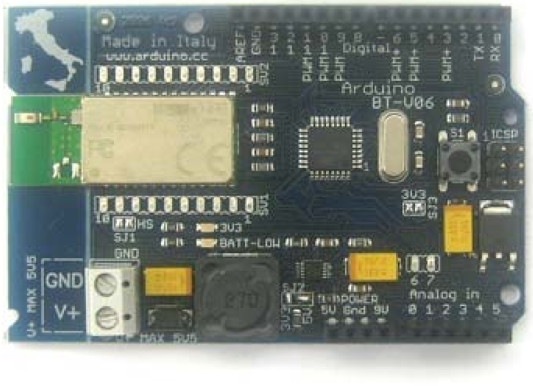
Appendix A Datasheet of the Arduino board

Arduino BT (Bluetooth)



Overview

The Arduino BT is a microcontroller board based on the ATmega168 (datasheet) and the Bluegiga WT11 bluetooth module (details and datasheet [pdf]). It supports wireless serial communication over bluetooth (but is not compatible with Bluetooth headsets or other audio devices). It has 14 digital input/output pins (of which 6 can be used as PWM outputs and one can be used to reset the WT11 module), 6 analog inputs, a 16 MHz crystal oscillator, screw terminals for power, an ICSP header, and a reset button. It contains everything needed to support the microcontroller and can be programmed wirelessly over the Bluetooth connection. Instructions are available for getting started with the Arduino BT.

Summary

Microcontroller	ATmega168
Operating Voltage	5V
Input Voltage	1.2-5.5 V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	16 KB (of which 2 KB used by bootloader)
SRAM	1 KB
EEPROM	512 bytes
Clock Speed	16 MHz

Schematic & Reference Design

Reference Design: arduino-bt-reference-design.zip
Schematic: arduino_bt06.pdf

Power

The Arduino BT can be powered via the V+ and GND screw terminals. The board contains a DC-DC convector that allows it to be powered with as little as 1.2V, but a maximum of 5.5V. **Higher voltages or reversed polarity in the power supply can damage or destroy the board.**

The power pins are as follows:

- **9V.** The input voltage to the Arduino board (i.e. the same as the V+ screw terminal). You can supply voltage through this pin, or, if supplying voltage via the screw terminals, access it through this pin. **Warning: despite the label, do not attach 9V to this pin. It will damage the board.**
- **5V.** The regulated power supply used to power the microcontroller and other components on the board. This can come either from V+ via the on-board DC-DC convertor, or be supplied by a regulated 5V supply.
- **GND.** Ground pins.

Memory

The ATmega168 has 16 KB of flash memory for storing code (of which 2 KB is used for the bootloader). It has 1 KB of SRAM and 512 bytes of EEPROM (which can be read and written with the EEPROM library).

Input and Output

Each of the 14 digital pins on the BT can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms. In addition, some pins have specialized functions:

- **Serial: 0 (RX) and 1 (TX).** Used to receive (RX) and transmit (TX) TTL serial data. These pins are connected to the corresponding pins of the Bluegiga WT11 module.
- **External Interrupts: 2 and 3.** These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.
- **PWM: 3, 5, 6, 9, 10, and 11.** Provide 8-bit PWM output with the analogWrite() function.
- **SPI: 10 (SS), 11 (MOSI), 12 (MISO), 13 (SCK).** These pins support SPI communication, which, although provided by the underlying hardware, is not currently included in the Arduino language.
- **BT Reset: 7.** Connected to the reset line of the Bluegiga WT11 module, which is active high.
- **LED: 13.** There is a built-in LED connected to digital pin 13. When the pin is HIGH value, the LED is on, when the pin is LOW, it's off.

The BT has 6 analog inputs, each of which provide 10 bits of resolution (i.e. 1024 different values). By default they measure from ground to 5 volts, though is it possible to change the upper end of their range using the AREF pin and some low-level code. Additionally, some pins have specialized functionality:

- **I^{2}C: 4 (SDA) and 5 (SCL).** Support I^{2}C (TWI) communication using the Wire library (documentation on the Wiring website).

There are a couple of other pins on the board:

- **AREF.** Reference voltage for the analog inputs. Used with analogReference().

See also the mapping between Arduino pins and ATmega168 ports.

Bluetooth Communication

The Bluegiga WT11 module on the Arduino BT provides Bluetooth communication with computers, phones, and other Bluetooth devices. The WT11 communicates with the ATmega168 via serial (shared with the RX and TX pins on the board). It comes configured for 115200 baud communication. The module should be configurable and detectable by your operating system's bluetooth drivers, which should then provide a virtual com port for use by other applications. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the Arduino board over this bluetooth connection. The board can also be reprogrammed using this same wireless connection.

The WT11 is specially configured for use in the Arduino BT. Its name is set to ARDUINOBT and passcode to 12345. For details, see the complete initialization sketch.

Communication

The Arduino BT has a number of other facilities for communicating. The ATmega168's UART TTL (5V) serial communication is available on digital pins 0 (RX) and 1 (TX) as well as being connected to the WT11 module.

A SoftwareSerial library allows for serial communication on any of the BT's digital pins.

The ATmega168 also supports I2C (TWI) and SPI communication. The Arduino software includes a Wire library to simplify use of the I2C bus; see the documentation on the Wiring website for details. To use the SPI communication, please see the ATmega168 datasheet.

Programming

The Arduino BT can be programmed with the Arduino software (download). For details, see the reference and tutorials.

The ATmega168 on the Arduino BT comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol (reference, C header files).

You can also bypass the bootloader and program the ATmega168 through the ICSP (In-Circuit Serial Programming) header; see these instructions for details.

Physical Characteristics

The maximum length and width of the BT are approximately 3.2 and 2.1 inches respectively. Three screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.

14/10/09

WT11 *Bluetooth®* Module™

Key Features

- *Bluetooth* Class 1
- Two antenna options: integrated chip antenna or U.FL connector
- Enhanced Data Rates (EDR) with data throughput up to 2-3Mbps
- Support for Adaptive Frequency Hopping (AFH) and 802.11 co-existence
- USB version 2.0
- UART with bypass mode
- 8Mbits of flash memory
- Supported *Bluetooth* profiles: SPP, DUN, OBEX OPP, HFP v.1.5, DID, HID + HCI
- Industrial temperature range from -40°C to +85°C
- RoHS compliant
- Simple iWRAP™ firmware for controlling *Bluetooth* wireless technology
- Fully qualified end product with *Bluetooth* 2.1 + EDR, CE, FCC and IC

Description

WT11 is a next-generation, class 1, *Bluetooth* 2.1 + EDR module. It introduces three times faster data rates compared to the existing *Bluetooth* 1.2 modules even with a lower power consumption. WT11 is a highly integrated and sophisticated *Bluetooth* module, containing all the necessary elements from *Bluetooth* radio antenna to a fully implemented protocol stack. Therefore WT11 provides an ideal solution for developers who want to integrate *Bluetooth* wireless technology into their designs with limited knowledge of *Bluetooth* and RF technologies.

WT11 module combined with Bluegiga's complete development, testing and verification services and excellent developer support; OEMs and designers ensure that their products reach the market rapidly and cost-efficiently in relation to time and resources. Bluegiga has extensive in-house knowledge of both software and hardware, offering customers a single point of contact to all *Bluetooth* related issues.

By default, WT11 module is equipped with powerful and easy-to-use iWRAP firmware. iWRAP enables users to access *Bluetooth* functionality with simple ASCII commands delivered to the module over serial interface.

With iWRAP software you have several implementation options:

- iWRAP can be configured to operate autonomously, - as a *Bluetooth* cable replacer
- To create sophisticated applications - a host system can be used to control iWRAP with ASCII commands
- The GPIO interface in WT11 module can be used to connect host and iWRAP

Besides the iWRAP firmware, Bluegiga also offers several other firmware options for WT11 module. Standard Host Command Interface (HCI) firmware is supported and an ideal solution for systems where the host system is capable of running the entire *Bluetooth* stack and profiles and WT11 is utilized as the physical radio over UART or USB interface.

blue giga

Bluetooth®

TECHNICAL DATA

Firmware

- iWRAP™ command interface to access the *Bluetooth* functionality and to configure the parameters with simple ASCII commands
- HCI firmware available for UART and USB interfaces
- Possibility to use / develop custom firmware
- 128-bit *Bluetooth* encryption available for all firmware options

Hardware

- *Bluetooth* Class 1 radio (range up to 200 meters)
  -Nominal output power +15 dBm
  -Nominal sensitivity -82 dB
  -Uses 2.4 GHz ISM band
  -Based on CSR's BC04 chipset
- Integrated antenna or U.FL connector
- Host processor interface with UART or USB
- SPI interface for firmware and parameter upgrades
- 6xGPIO, 1xAIO
- PCM interface for audio applications
- Supply voltage: regulated 3.2 – 3.4 VDC
- PCB form factor: 35.3 x 14 x 2.3 mm
- Operating temperature: -40 °C to +85 °C
- Metal shielding
- Reference designs available for HCI, cable replacement and audio applications

Product Codes

iWRAP Firmware, chip antenna	WT11-A-AI
HCI Firmware (USB), chip antenna	WT11-A-HCI
Custom Firmware, chip antenna	WT11-A-C
iWRAP Firmware, U.FL	WT11-E-AI
HCI Firmware (USB), U.FL	WT11-E-HCI
Custom Firmware, U.FL	WT11-E-C

Development and Evaluation

- WT11-A Evaluation Kit EKWT11-A
- WT11-E Evaluation Kit EKWT11-E
- CSR's BlueLab Professional SDK

Other Products

- WT12 Class 2 *Bluetooth* Module™
- WT32 *Bluetooth* Audio Module™
- Bluegiga Access Server™ 2291, 2293

Certifications

- *Bluetooth* 2.1 + EDR
- CE, FCC and IC

Applications

- Cable replacement
- Point-of-sales systems
- Barcode readers and pay terminals
- Telemetry and machine-to-machine devices
- Logistics and transportation systems
- Automotive inspection and measurement systems
- Medical systems
- Fitness and sports telemetry devices
- PDAs and other portable terminals
- PCs and laptops
- Audio applications

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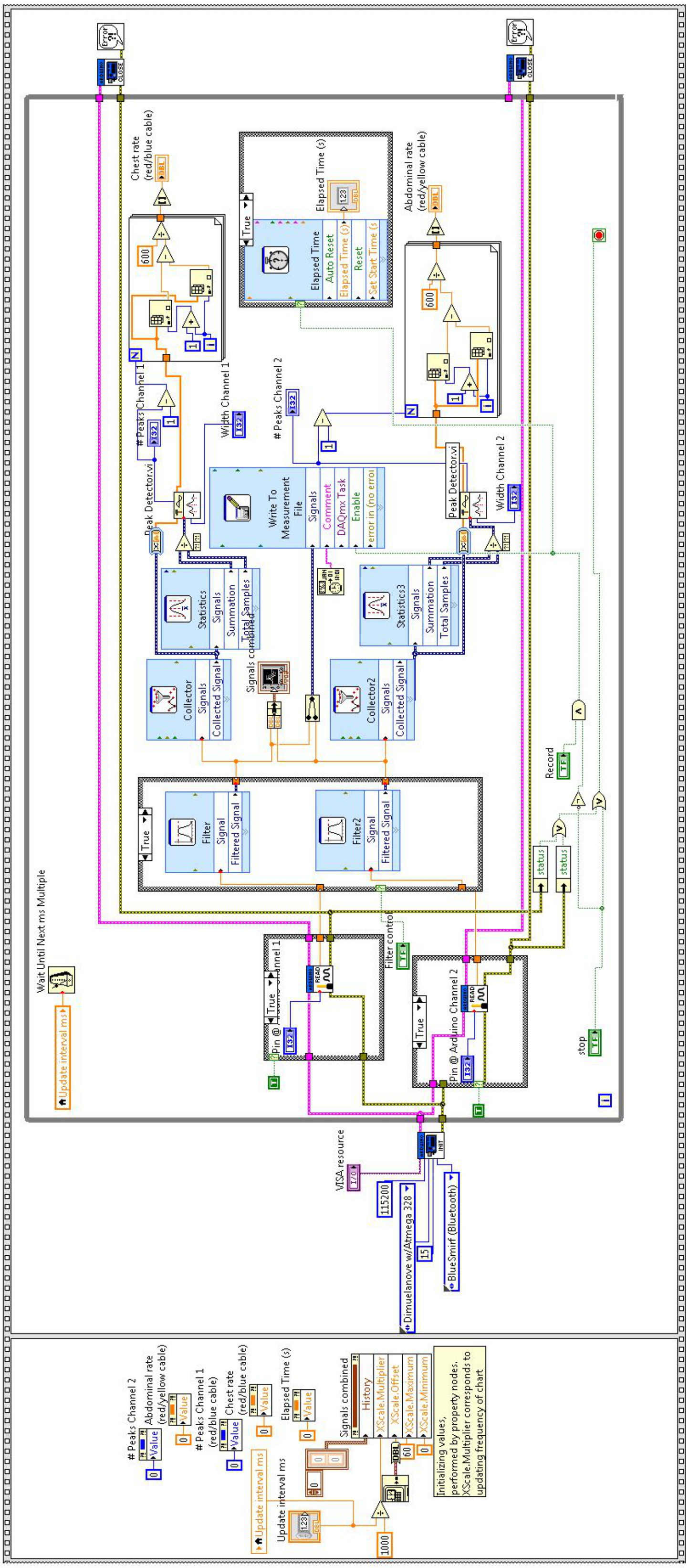
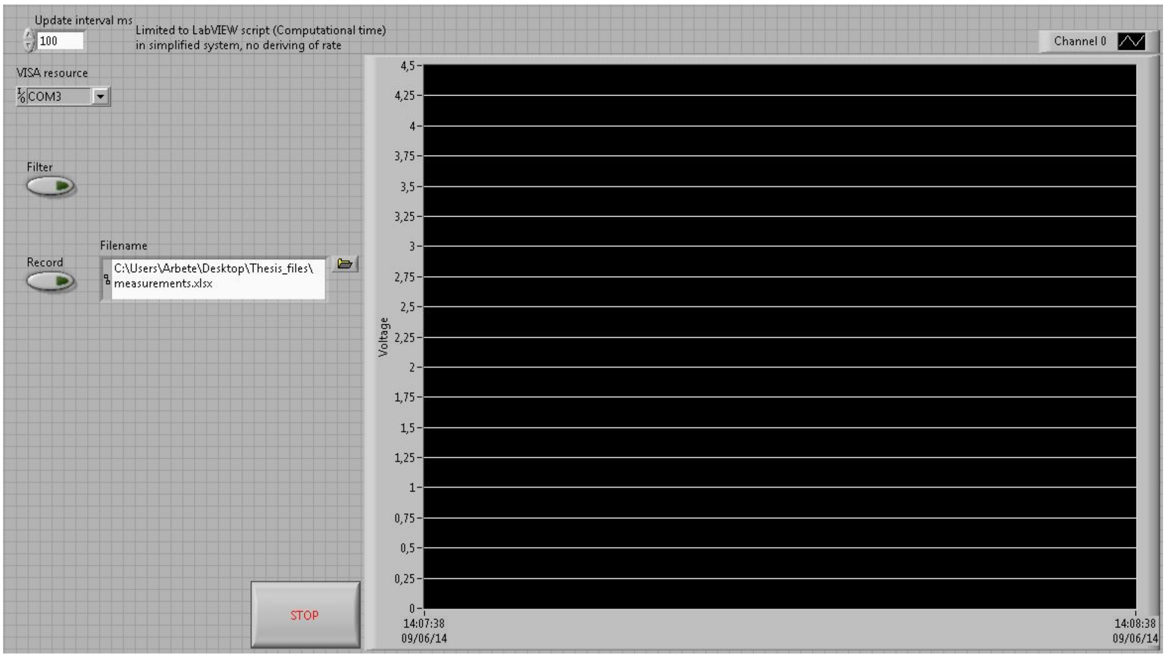
Appendix B The labview program for the piezoresistive solution, two channels and frequency calculations using peak detection.



Appendix C The labview program for the piezoelectric solution. Simplified to lower computational time which increase possible update frequency, one channel.

C.1 Front panel



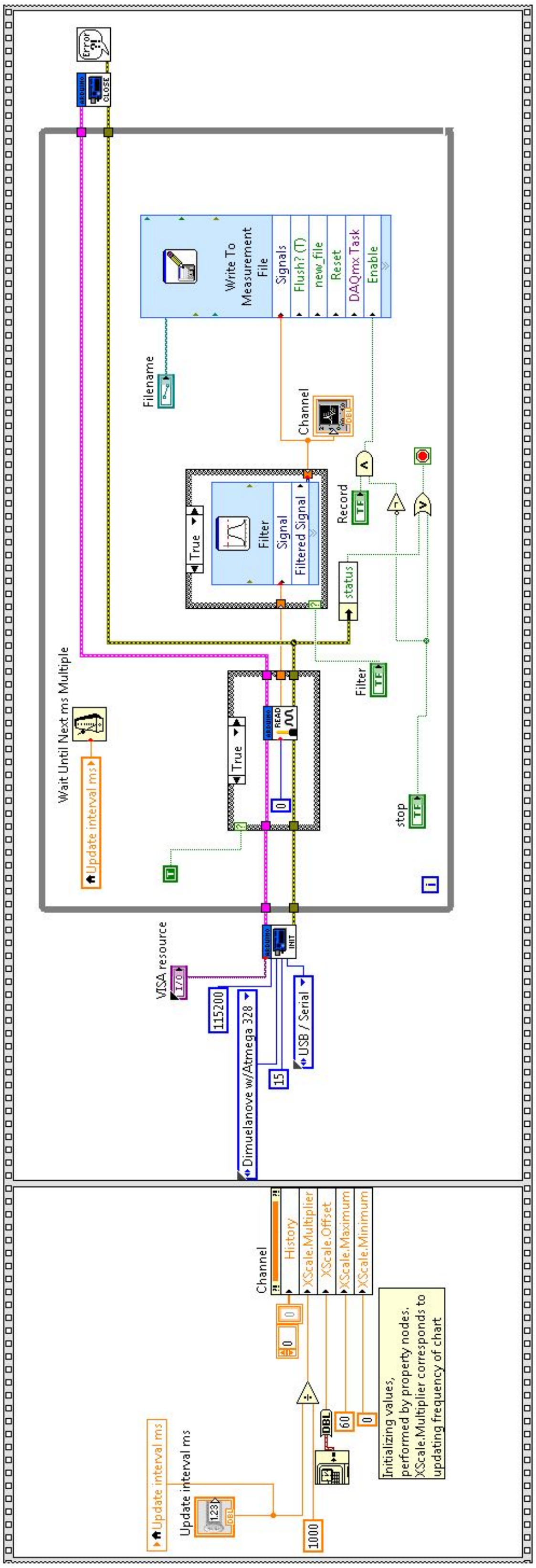
Update interval ms: 100

Limited to LabVIEW script (Computational time) in simplified system, no deriving of rate

VISA resource: COM3

Filename: C:\Users\Arbete\Desktop\Thesis_files\measurements.xlsx

C.2 Block diagram



Initializing values, performed by property nodes. XScale.Multiplier corresponds to updating frequency of chart

Appendix D Preparations for the Arduino BT, similar in the UNO (Windows)

Step by step instructions:

1. Installing Arduino from http://arduino.cc/en/Main/Software

2. Install LabView 2009 or newer, to be able to use Arduino board LabVIEW interface.

3. Install latest version of NI-VISA Drivers for Windows http://www.ni.com/download/ni-visa-5.1.1/2659/en/

4. Install VI Package Manager for LabVIEW from http://jki.net/vipm/download

5. Install LabVIEW Interface for Arduino tooolkit, download from
https://lumen.ni.com/nicif/us/evaltlktlvardio/content.xhtml
or https://lumen.ni.com/nicif/confirmation.xhtml

6. Upload the Arduino instruction file called *LIFA_Base.ino*, located in under the LabVIEW folder as:
LabVIEW 2013*vi.lib**LabVIEW Interface for Arduino**Firmware**LIFA_Base*

Observe!

- A. A LabVIEW version from 2009 or newer needs to be used due to that the Arduino interface was not implemented until then.

- B. To update the files onto the Arduino micro-controller the reset button on the board needs to be pushed shortly before uploading to the board from the Arduino software (Blue tooth version of Arduino).

Appendix E Corresponding circuit components