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# MASTER THESIS

**TITLE:** Design and development of an electronic interface circuit for piezoelectric sensors applied to impact detection

**MASTER DEGREE:** Master in Science in Telecommunication Engineering & Management

**AUTHOR:** Gunther Monté Muñoz

**DIRECTOR:** Vittorio Ferrari

**DATE:** 25-02-2011



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## **Resum**

La detecció d'impactes és una tecnologia molt important en la indústria i la ciència actual. Té moltes aplicacions, des de provar estructures d'edificis fins a detectar l'impacte d'una moneda en una màquina distribuïdora automàtica.

L'objectiu d'aquest projecte és dissenyar un circuit electrònic de baix cost per al condicionament del senyal de diversos sensors piezoelèctrics per detectar impactes.

Per començar, hem fet un estudi de la tecnologia piezoelèctrica, que és la més utilitzada per detectar impactes actualment. També s'ha fet un estudi del model matemàtic d'un impacte. Un cop tenim clar que esperem mesurar, hem decidit fer servir "buzzers" piezoelèctrics, en lloc de sensors comercials, ja que tenen un comportament similar però un cost molt més baix. Per continuar, s'ha fet un estudi per caracteritzar els "buzzers" com a sensor, per poder dissenyar el circuit. Tot seguit, hem dissenyat i simulat el circuit de condicionament per als sensors. Un cop teníem el circuit dissenyat l'hem muntat amb components comercials per verificar el seu funcionament mitjançant un parell d'experiments. Aquest experiments han servir per ajustar paràmetres del circuit i aprendre conceptes sobre la detecció d'impactes.

Per a continuar aquest treball, es podria fer el mateix circuit amb alimentació portàtil (bateries) i amb components SMD per ocupar menys espai.

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## **Overview**

Impact detection is a very important Technology in today's industry and science. It has many applications, from testing building structures to detecting the coin impact in an automatic distribution machine.

The aim of this project is to design a low cost and low power consumption electronic circuit to condition the signal from different piezoelectric sensors.

To begin, we made a study of piezoelectric technology, which is the most used in impact detection. We have also studied the mathematical model of an impact. Once we know clearly what we want to measure, we decided to use piezoelectric buzzers, instead of commercial sensors, because they have a similar behavior but a lower cost. To continue, we have studied the buzzer features, to design the circuit. After that, we have designed and simulated the sensor signal conditioning circuit. Once we have the circuit design, we have mounted it using commercial components, and we have tested it with a couple of experiments. Those experiments served as feedback to adjust the circuit parameters and to learn concepts about impact detection.

To carry on with this project work, the whole system could be designed to be portable, powered with batteries and with SMD components in order to make it smaller.

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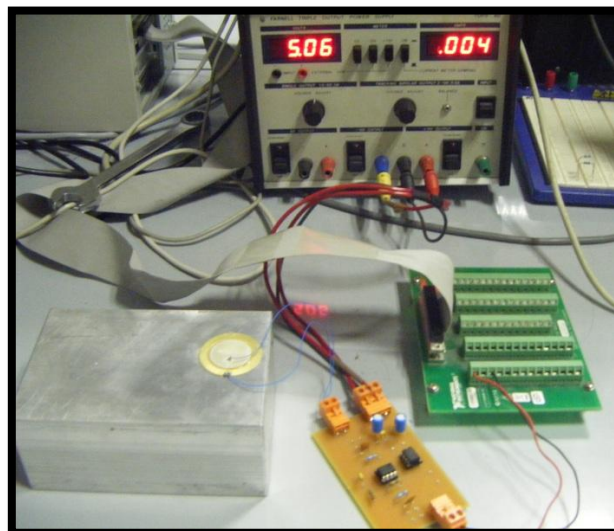
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## INTRODUCTION

Impact detection is very important and, nowadays it has many applications. For example, structure modal testing that is useful when designing vehicles such as cars, motorbikes or even airplanes. Modal testing is a complex process because it studies the dynamic behavior of a structure. Impact detection is also used for simpler tasks, for instance to discriminate a false coin in automatic distribution machines, to create switches without moving parts, or even to detect a failure on an automatic tool, machine or an engine.

This project aims at creating a low cost impact detection system using piezoelectric buzzers. We do not have a clear application on mind, because we focused on creating a circuit able to detect impacts. So, all the experiments we made are just to test the circuit and adjust its parameters, specially the gain and the frequency response. Our system needs a power supply and the output information is ready to be read with a DAQ. One possible continuation project would be to design a portable system, powered with batteries, and to adapt the output, for instance to a wireless transmitter and receiver. Another project to carry out on the work we made would be the impact analysis and detection using signal processing methods.

This document is divided into six chapters. We have an introduction to impact detection and to the piezoelectric technology to start. On chapter two we describe the two sensors used in the project and also the system requirements. Once we have our system requirements, on the next chapter, we describe the charge amplifier and the circuit design calculations. Furthermore, we explain how we designed the PCB and we show a list of the chosen components. To continue, on chapter four we present the results of the two experiments we made. Then, on chapter five we explain the conclusions we obtained doing the project, and also we suggest future lines of investigation and possible improvements. To end up, on the last chapter we have the annex, including detailed calculations for the experiments, the matlab code to plot and manipulate the data, etc.



## **CHAPTER 1. IMPACT DETECTION**

### **1.1. Impact detection introduction**

Nowadays impact detection is very used in many applications. For impact detection we understand from a heavy car crash, to a light contact into a touch screen.

Apart from impact, the same technology is very useful for vibrations, as they are very similar, as we would see on this chapter. For instance, we can attach a sensor to a running engine, and this engine would have a working frequency. If a failure happens, that frequency will change, and thanks to our sensor we can remotely detect the failure.

One important application is modal testing (1), which is used to find the frequency response of any structure. We understand from structure from a long and big bridge, to a little motorbike. There are different techniques to obtain the frequency response, but one popular technique is single point excitation. Using this technique, one pulse impact is applied (with a shaker or with a simpler impact device like a hammer) to the structure and then some sensors attached to the structure read the signal. Doing the FFT of the output, we can obtain the structure frequency response.

Another impact sensor application is to detect cracks at silicon wafers during the manufacturing process (2). Those wafers are used as photovoltaic solar panels, and any little scratch at the surface describes its performance. To control those imperfections, they apply an ultrasonic vibration and using a sensor calculates the frequency response of the wafer. If an imperfection exists, the frequency response changes, so it is an easy way for wafer manufacturers to control its own production.

We have explained a couple of examples, but impact detection has a wide range of uses, such as, car crash tests, coin detection on distribution machines, security switches, airbag sensors, seismography, etc.

We have mentioned some examples to see that impact detection is really useful in our world. The most used sensing technology for impact detection is piezoelectric technology.

### **1.2. Piezoelectric effect**

The piezoelectric effect is a reversible effect that exists on some materials, like crystals or ceramics. Those materials generate an electrical charge in response



to mechanical movement, or vice versa. The piezoelectric effect was first discovered by Jaques and Pierre curie in 1880 (3).

The basic theory behind piezoelectricity is based on the electrical dipole. At the molecular level, the structure of a piezoelectric material is typically an ionic bonded crystal. When resting, the dipoles formed by the positive and negative ions cancel each other due to the symmetry of the crystal structure, and an electric field is not observed. When stressed, the crystal deforms, symmetry is lost, and a net dipole moment is created. This dipole moment forms an electric field across the crystal. In this manner, the materials generate an electrical charge that is proportional to the pressure applied.

Piezoelectric materials have a wide range of applications, such as lighter igniters, buzzers, energy harvesting devices, and, of course sensors. Piezoelectric sensors are used to measure different magnitudes, for instance sound, acceleration, pressure, vibration and force. One important thing to notice is that they are suitable to measure dynamic quantities but not to measure static ones, for instance a constant pressure. That is because the charge that is produced due to the mechanical effort leaks through its internal resistance.

There are three different operation modes, depending on how the piezoelectric material is cut.

- Transversal effect

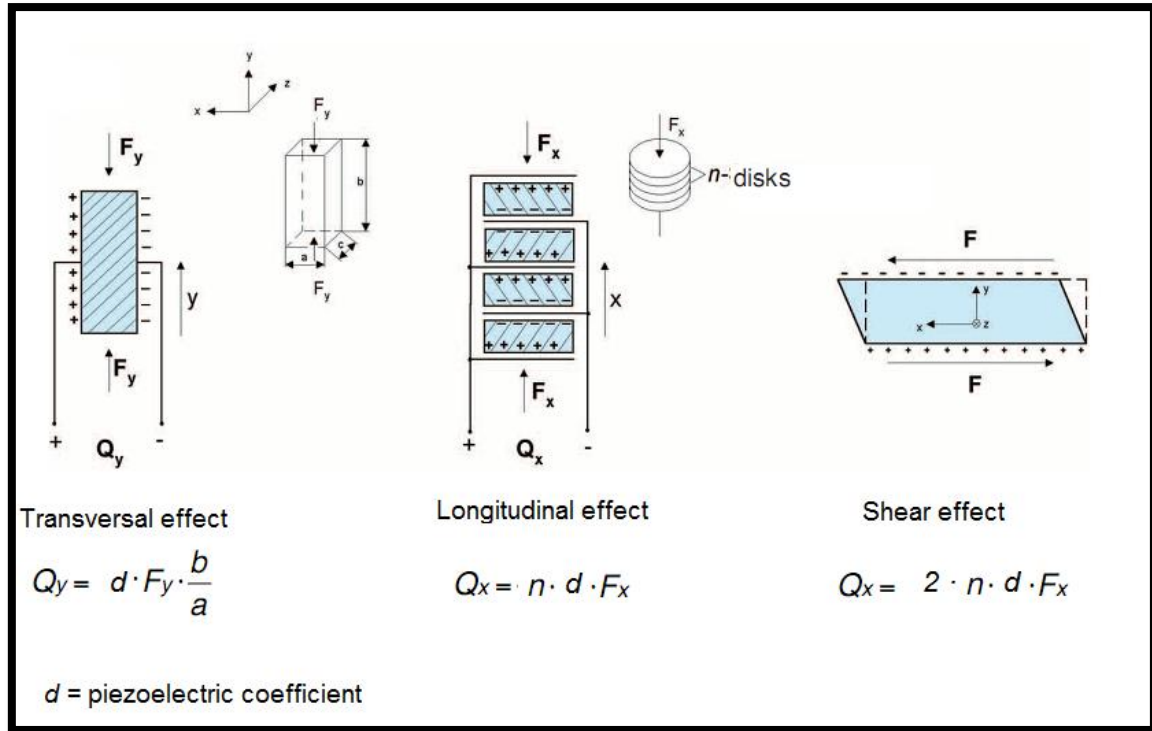
The force is applied along axis Y and the charge output appears perpendicularly, on the X direction. The charge is dependent on the material thinness.

- Longitudinal effect

On that case, the charge output is dependent to the force applied, but it is not dependent to the material geometry. Normally they are disk shaped material, and the only way to increase the charge yield is to connect several disks mechanically in series, electrically in parallel.

- Shear effect

Again, the charge is proportional to the force, but independent to the material shape or dimensions. The charge output occurs at the charge contact surface.



**Fig. 1.1** The three piezoelectric effects

There are different piezoelectric materials, with different properties. There are different material properties we have to consider depending on which application we will use.

$$k_{3n} = \sqrt{\frac{Y}{\epsilon}} \cdot d_{3n} \quad (1.1)$$

Where:

$k_{3n}$  = piezoelectric coupling coefficient

$Y$  = Young modulus

$\epsilon$  = dielectric constant

$d_{3n}$  = piezoelectric deformation coefficient

The coupling coefficient is an indicator of the material ability to convert electrical to mechanical energy or vice versa. The young modulus ( $Y$ ) indicates the material rigidity and the resistance ( $R$ ) the maximum pressure that material can resist before it breaks down.

We can classify piezoelectric materials into two big groups, crystal and ceramics. The first known piezoelectric material was quartz, but nowadays, better properties materials are being used. One common piezoelectric material is PVDF (polyvinylidene fluoride). Another common material is PZT (lead

zirconate titanate) which has better properties than PVDF but it is also more rigid and fragile. So we have to choose each material depending on the application. Another interesting material is PZN-PT (lead zinc niobate- lead titanate) is a material formed just by one crystal and very similar to PZT. It is a recently used material, from 2002, so nowadays it is expensive. On the following table we can see a brief comparison of different piezoelectric materials.

**Table 1.1** Different piezoelectric materials property

Property	PZT	PVDF	PZN-PT	Units
$d_{31}$	320	20	950	$10^{-12}$ m/V
$k_{31}$	0.44	0.11	0.5	CV/Nm
$\epsilon_r$	3800	12	4500	$\epsilon/\epsilon_0$
$Y$	5	0.3	0.83	$10^{10}$ N/m <sup>2</sup>
$R_{31}$	2	5.2	8.3	$10^7$ N/m <sup>2</sup>

### 1.3. Signal conditioning for piezoelectric sensors

We have seen that a piezoelectric sensor gives the information using a charge variation. We need to transform that charge variation to a voltage or current signal, in order to prepare the signal to be read by the data acquisition system. When adapting the signal there are some key items, like the signal amplitude, signal bandwidth, the impedance matching, etc.

There are three important signal conditioning circuits suitable for piezoelectric sensors. The charge amplifier, the transimpedance (current to voltage) amplifier and the electrometer amplifier.

A current to voltage amplifier is used for high output impedance signals, or for current signals. Those amplifiers have a low input current, but are suitable for low frequencies signals. If we want to measure an impact, which has high frequency components is better to use a charge amplifier or an electrometer amplifier.

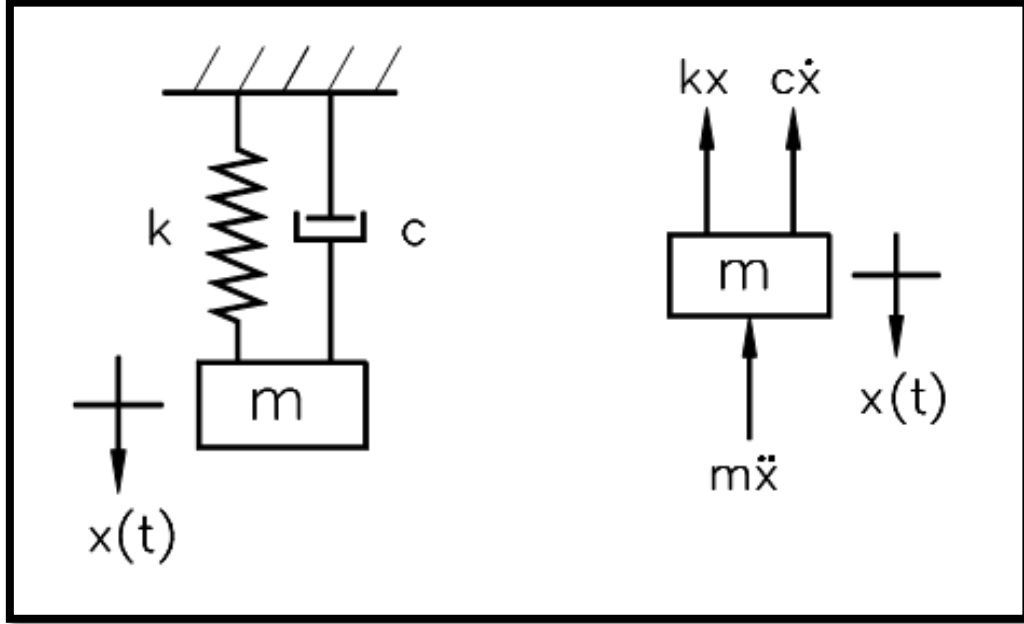
An electrometer amplifier is an amplifier having a large input resistance ( $R_i \gg 1\text{T}\Omega$ ) and low input current. Those amplifiers are used to interface sensors that give a voltage output with large series impedance.

Finally we have the charge amplifier, which is basically an amplifier with a feedback capacitor. The amplifier gain is proportional to the system gain, so it is easier to calculate the circuit. In addition, this circuit is not affected by the input capacitance of the amplifier and the parallel cable capacitance.

We have chosen the charge amplifier to drive our sensor. On chapter 1 we are going to explain the sensor characteristics, and on section 3.1 we will see a detailed charge amplifier explanation.

## 1.4. Mathematical model of an impact

We are going to see the mathematical model for an impact. We can model a single impact as a damped vibration. To model this damped vibration we are going to use the equations for a single degree of freedom (SDDOF) mass-spring damped system.



**Fig. 1.2** Mass spring system diagram

Considering  $x$  the mass movement from its balance position and applying the Newton laws:

$$\sum F = m\ddot{x} + c\dot{x} + kx = 0 \quad (1.2)$$

We have a second order differential equation, assuming the harmonic solution:

$$x(t) = Xe^{st} \quad (1.3)$$

Where  $s=j\omega$  is the Laplace variable. Replacing on equation (1.2), we obtain:

$$ms^2 + cs + k = 0 \quad (1.4)$$

$$s^2 + \frac{c}{m}s + \frac{k}{m} = 0 \quad (1.5)$$

Then we determine the two independent roots, which fall on the three following cases:

$$\left(\frac{c}{2m}\right)^2 - \frac{k}{m} < 0 \quad (1.6)$$

The system is under damped

$$\left(\frac{c}{2m}\right)^2 - \frac{k}{m} = 0 \quad (1.7)$$

The system is critically-damped

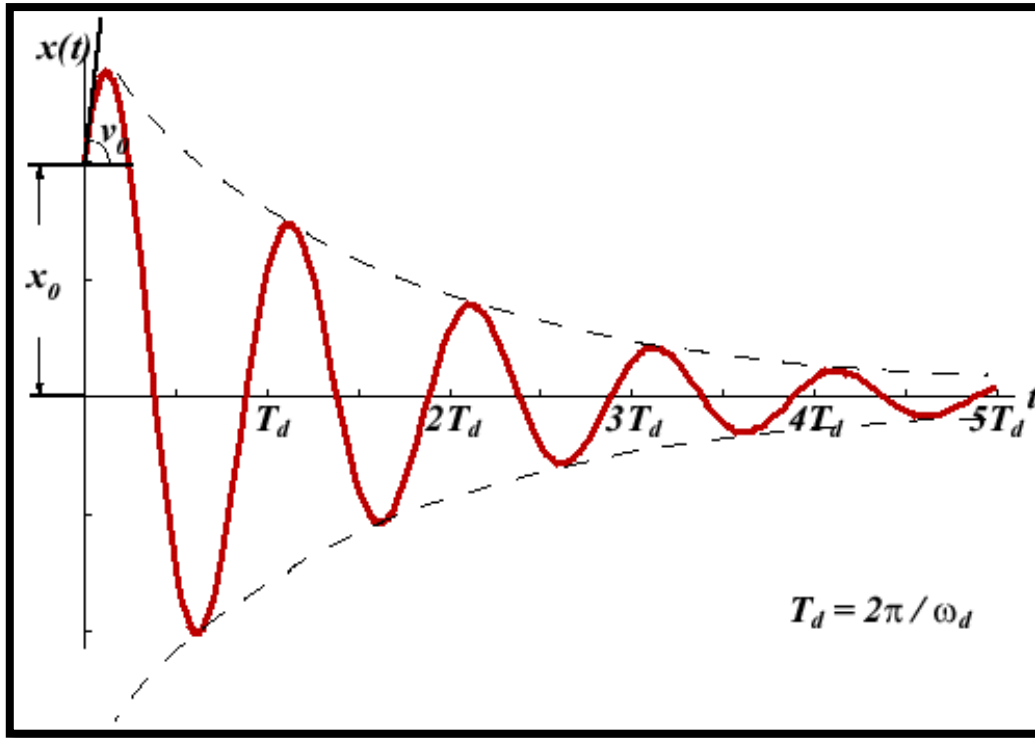
$$\left(\frac{c}{2m}\right)^2 - \frac{k}{m} > 0 \quad (1.8)$$

The system is over damped

We can rewrite the system solution in a more familiar form:

$$x(t) = e^{-\zeta\omega_n t} [Ae^{j\omega_d t} + Be^{-j\omega_d t}] \quad (1.9)$$

For our impact model, we consider just the first case, the under damped system. To simplify the solutions, we define the critical damping  $c_c$ , the damping ratio  $\zeta$ , the damped vibration frequency  $\omega_d$  and the natural frequency,  $\omega_n$ .



**Fig. 1.3** Under damped vibration waveform

$$cc = 2m\sqrt{\frac{k}{m}} = 2m\omega_n \quad (1.10)$$

$$\zeta = \frac{c}{2\sqrt{km}} \quad (1.11)$$

$$\omega_n = \sqrt{\frac{k}{m}} \quad (1.12)$$

$$\omega_d = \omega_n\sqrt{1 - \zeta^2} \quad (1.13)$$

#### 1.4.1. Logarithmic decrement

The logarithmic decrement shows the decreasing velocity of damped vibrations. We obtain that parameter,  $\delta$ , dividing the consecutive amplitudes of an under damped system cycle. On **Fig. 1.3** Under damped vibration waveform, we can divide  $T_d$  by  $2T_d$ , or  $2T_d$  by  $3T_d$ , etc.

$$\delta = \ln \frac{x_1}{x_2} = \zeta \omega_n T_d = \zeta \omega_n \frac{2\pi}{\sqrt{1-\zeta^2} \omega_n} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} = \frac{2\pi}{\omega_d} \cdot \frac{c}{2m} \quad (1.14)$$

If  $\zeta \ll 1$  we can estimate it as:

$$\delta \cong 2\pi\zeta \quad (1.15)$$

This parameter is going to be very useful for us, because we are going to use the sensor to read the impact information. Hence, we will obtain the impact equations parameters experimentally, obtaining the damping ratio, the damping frequency and the natural frequency.

## CHAPTER 2. SENSORS CHARACTERIZATION AND SYSTEM REQUERIMENTS

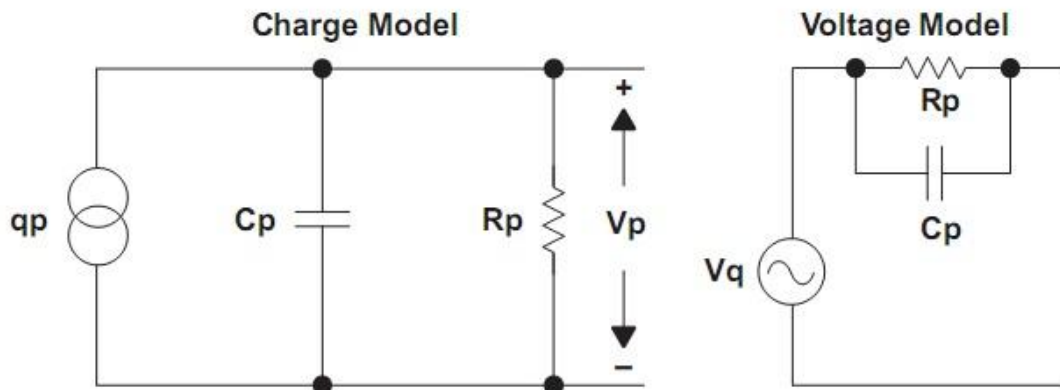
On this chapter we are going to describe the piezoelectric sensor features. Also we are going to show some test results from the output sensor signal which we did to know the sensor behavior. After that we are going to define the system specifications, such as the gain, and the frequency filtering.

### 2.1. Using buzzers as sensors

Piezoelectric buzzers are those ones used as alarm clocks, beepers, timers, or confirmation as user input. Buzzers are economic and easy to find, so in this project we used two different types of buzzer as impact sensors. We can do that because the piezoelectric effect is reversible, but on the other hand buzzers are not designed for sensing applications so they have some limitations.

#### 2.1.1. Sensors model

As we explained on section 1.2, the sensor generates an electrical charge proportional to the pressure applied, so an AC voltage appears across the terminals. That piezoelectric sensor can be modeled in two forms, as a charge source with a shunt capacitor and resistor or as a voltage source with a series capacitor and resistor, as we can see on **Fig. 2.1**



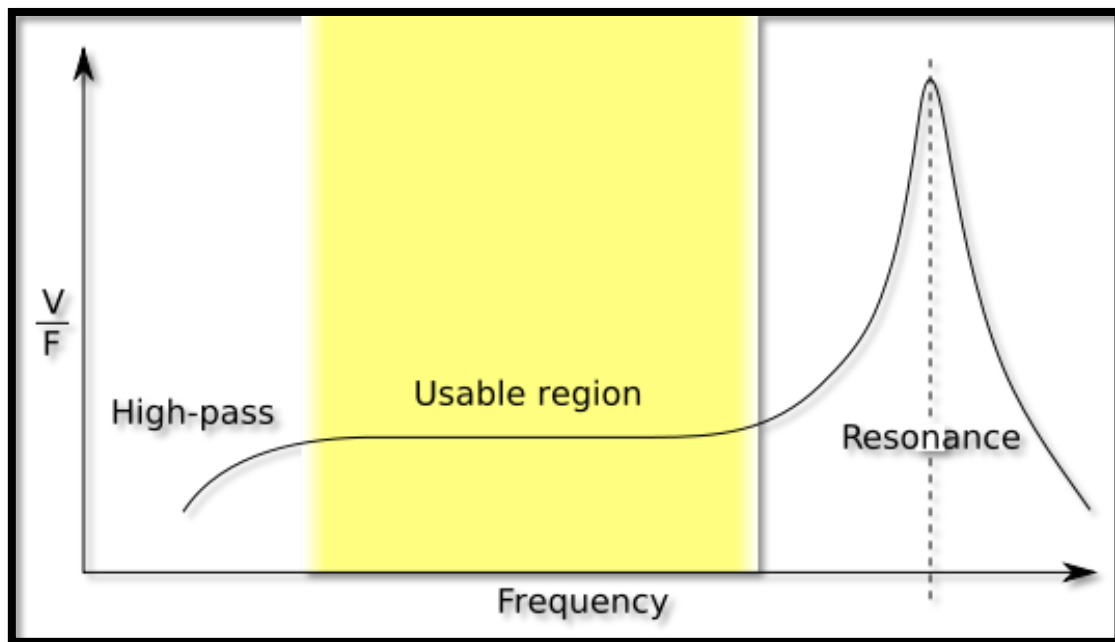
**Fig. 2.1** Charge and voltage model for a piezoelectric sensor

Piezoelectric sensors have a high pass filter response, so we must always work below its mechanical resonant frequency. Furthermore, the output signal must be low pass filtered to prevent the amplifier saturation.



### 2.1.2. Sensor frequency response

Piezoelectric sensors show a high resonant peak in their frequency response. This is because when a dynamic force is applied the only damping source is the internal friction in the material. That means that we must always work below the sensor resonant frequency, and also we must low pass filter the signal to prevent the amplifier saturation.



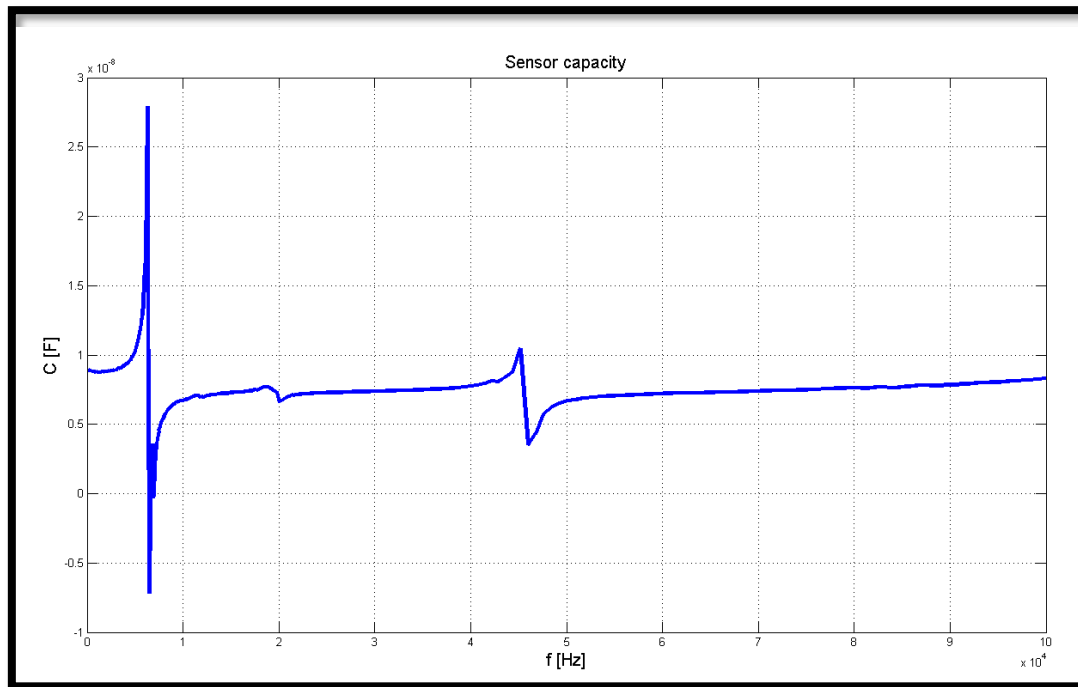
**Fig. 2.2** Piezoelectric sensor frequency response

## 2.2. Sensors characterization

The buzzers are made off PZT, and manufactured by Murata, but the specifications on the datasheet (4) are not detailed neither precise, so we decided to measure them with the YHP 4194A (5) impedance gain analyzer. We obtained the capacitance, resistance and resonant frequency parameters to model both sensors.

**Table 2.1** Summary of sensor properties

Parameter	Sensor A	Sensor B
Model	7BB-35-C	7BB-20-6
Resonance frequency (theoretical)	2.8KHz	6.3KHz
Resonance frequency (measured)	2.8KHz	7KHz
Resistance at 1KHz	7K $\Omega$	15K $\Omega$
Capacitance	23nF	8nF
Plate diameter	35mm	20mm
Electrode diameter	23mm	12.8mm

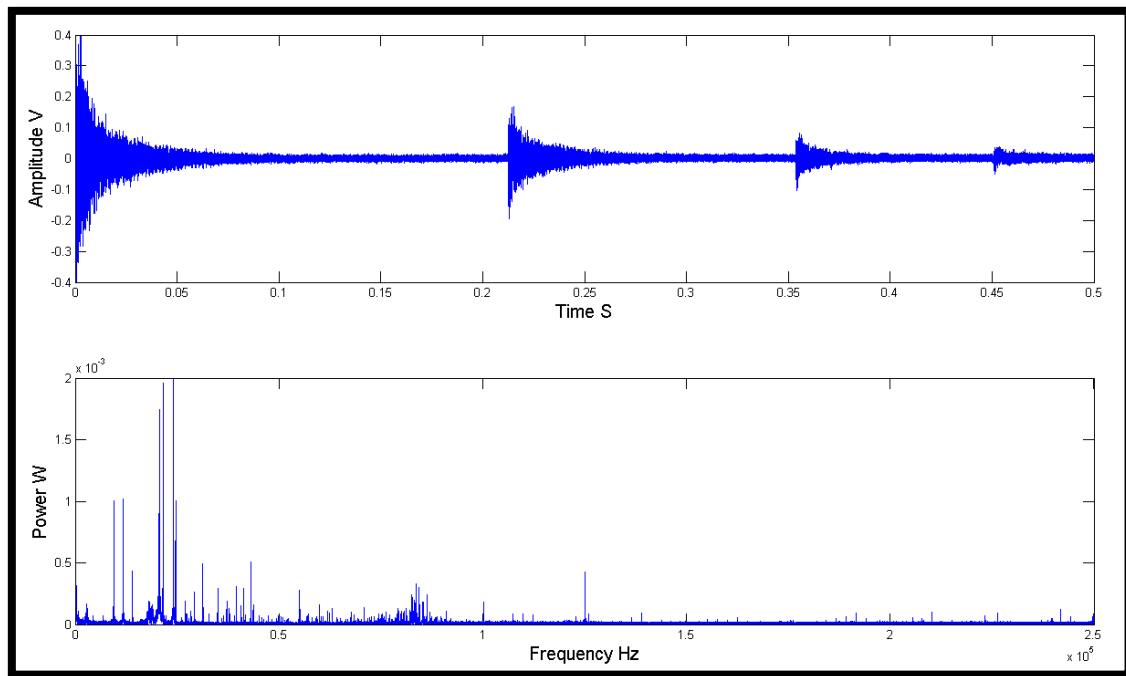
**Fig. 2.3** sensor B measured capacitance

On that graph we can observe the sensor B capacitance from 0 to 100 KHz. We clearly see the sensor resonance at 7 KHz.

## 2.3. Measuring tests without signal conditioning circuit

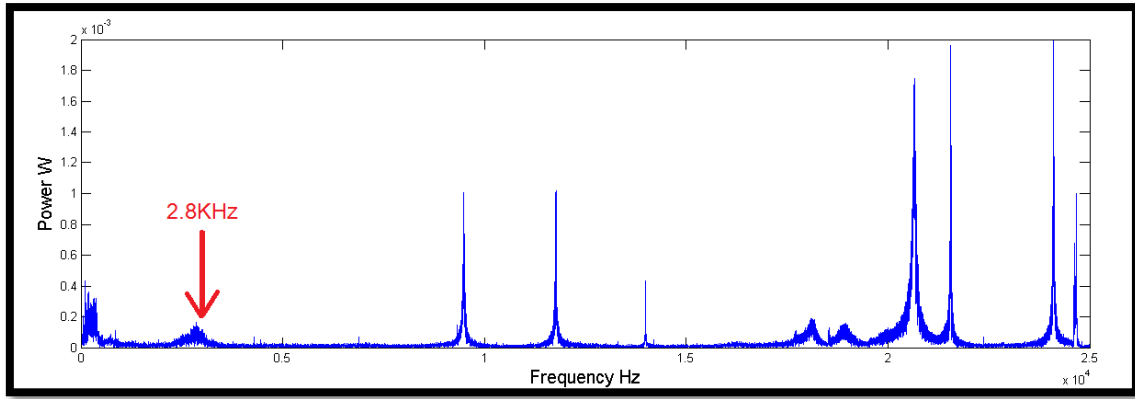
Once we have the equivalent model of our sensors, the following step is to see its output signal in order to design the suitable signal conditioning circuit. So we made some test measurements with the sensor directly connected to a LeCroy LT374M oscilloscope using a passive voltage probe, without attenuation. The oscilloscope has been configured to use a sample frequency of 500KHz.

That test was only made buzzer A. We measured the impact of some coins to the bar where the sensor is hooked.



**Fig. 2.4** Output signal of the piezo buffer without signal conditioning circuit

On **Fig. 2.4** we see the impact and three rebounds. Observing the amplitude signal it is 0.8Vpp on the transient but, we can consider it 0.4Vpp. The signal was opened with matlab and then we made the FFT to obtain the power spectrum. If we look at the frequency spectrum, we can see that there are frequency harmonics up to 130.000 Hz. That is so much high than the buzzer resonant frequency that is 2.800 Hz.



**Fig. 2.5** Power spectrum zoom up to 25.000Hz

On **Fig. 2.5** we can see that there is much information above 2.800Hz. We have to note this because, for the moment, the signal is not filtered, so we do not still know if that information is signal information or noise.

## 2.4. System requirements

The first step to design a circuit is to know the system requirements. We want a low power consumption system, and to do this project we are going to connect it to a DAQ. But in a future we would like to use the same circuit with a microcontroller or a wireless transition system.

The power supply unit it is a laboratory source, and we are going to use 10Vpp so we are going to use -5V and 5V power inputs. These values are “low power” and, also in a future can be easily achieved with batteries and the use of power regulators, charge pumps, etc.

### 2.4.1. The DAQ dynamic range

To read the data, we are going to use a NI6023 Data Acquisition System board (6) which has a 200 KHz sampling frequency, and 12 bits resolution. That board has analog to digital converters in order to digitally the data and then we can easily read and process it using a personal computer with Labview or matlab software.

We know that the DAQ has 12 bits, but we must use 1 bit for the sign information, and our dynamic input range is -5V to 5V, so:

$$Q = \frac{5V - (-5V)}{2^{11}} = 4,9mV = 1LSB \quad (2.1)$$

That value is the smallest signal variation that our DAQ is able to detect. That value is important to calculate the SNR, and to see the resolution and accuracy of our system. The problem is that the buzzer is not a sensor, so the sensitivity is not specified in the datasheet, so a calibration process would be required.

### **2.4.2. Frequency response and filtering**

We have seen that the sensor response is high pass filter, so we need to low pass filter it. The best solution would be filtering the signal on the charge amplifier, before the instrumentation amplifier and before acquiring it. That would improve the signal to noise ratio. Despite of that, we decided to digitally filter the signal with matlab once we have the data collected. The reason is that we are using two different sensors with different resonant frequencies, so if we use analog filters, we would need two different charge amplifiers designs. As we want to do the circuit as simple as possible, and we want to test different sensors, it is better to use digital filters, which we can set up easily with matlab, once we have the signal into the computer.

### **2.4.3. Gain**

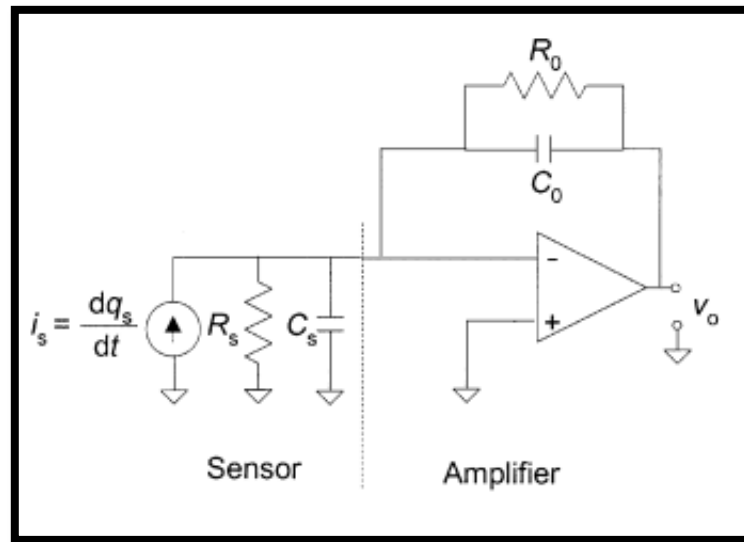
Our system voltage range is 10Vpp. We have seen that the output sensor signal is between 0.4 and 0.8 Vpp, when measuring different impact coins. We insist on that, because depending on which kind of impact we are interested in, the force changes a lot, and also the output signal. So if we plan to measure those impacts, we would need a total circuit gain between 12.5 and 25.

## CHAPTER 3. CIRCUIT DESIGN

On this chapter we are going to explain the signal conditioning circuit design. Also, we are going to explain why we choose a differential design, to continue some considerations about the PCB design, the chosen components and finally the SNR analysis.

### 3.1. Charge amplifier

The charge amplifier was first proposed by W.P. Kistler in 1949 (7). As we can see on **Fig. 3.1** it consists on an operational amplifier with negative feedback formed by a resistance  $R_0$  and a capacitor  $C_0$ . Contrary to what its name may suggest, it does not amplify the electric charge present at its input, actually it obtains a voltage proportional to that charge. We are going to use the current model for the piezoelectric sensor because it is the simplest way to analyze the circuit.



**Fig. 3.1** Idealized charge amplifier

Neglecting  $R_0$ , we will explain later, the output voltage becomes:

$$V_o = \frac{-q}{C_0} \cdot \frac{1}{1 + \frac{1}{A_d} \cdot (C_s + C_0)} \quad (3.1)$$

Where  $A_d$  is the amplifier open loop gain, that is bigger than 1 at low frequencies so we can neglect the sensor capacitance and simplify eq. 3.1

$$V_o = \frac{-q}{C_o} \quad (3.2)$$

And then the gain is:

$$G = \frac{V_o}{V_s} = \frac{-q/C_o}{q/C_s} = \frac{-C_s}{C_o} \quad (3.3)$$

In order to offer a DC return path for the amplifier input bias current, we need the resistor  $R_o$  in parallel with the capacitor  $C_o$ . That feedback node acts as a high pass filter. At lower frequencies the capacitor acts as an open circuit so all the voltage goes through the resistor. On the other hand, at high frequencies, the impedance of the capacity becomes smaller eliminating the resistor effect. On eq. 3.4 we can see the high pass filter cutoff frequency.

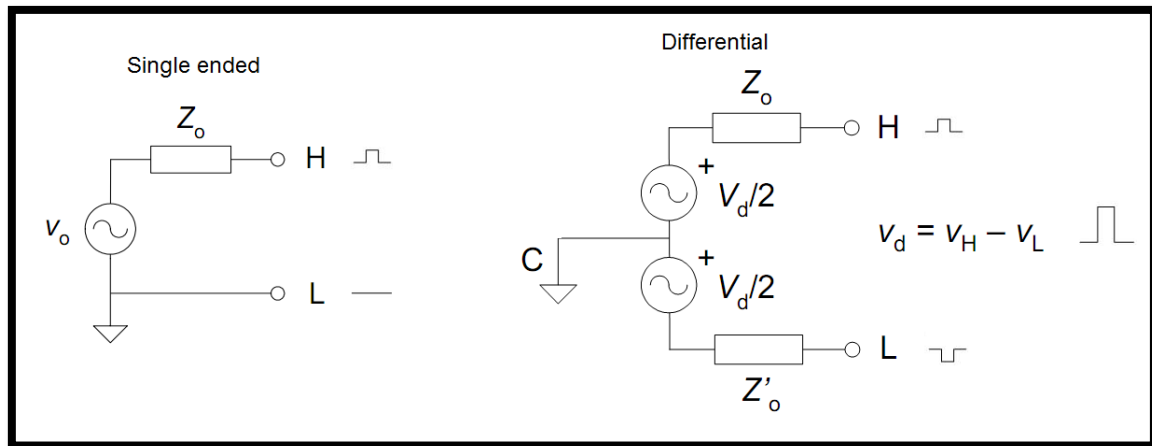
$$f_l = \frac{1}{2\pi R_o C_o} \quad (3.4)$$

The bandwidth is set by the application, so as the capacitance is lowered to increase the gain, the resistance must be increased to keep  $f_l$  low. But increasing the resistor has undesirable consequences like increasing the noise, and adding difficulty to find a suitable component. We have a clear gain bandwidth tradeoff.

## 3.2. Differential circuit

On single-ended mode, the voltage information is always referred to “ground”. Single-ended systems just require a wire to transmit the information, and the return loop is always the system ground. Those systems are mostly used because they are simpler and easier, but, on the other hand they have serious disadvantages such as they are vulnerable to electromagnetic interference and to stray capacitance effects.

Differential mode signals need a pair of wires to transmit the information. One wire transmits the signal and the other one transmits an opposite signal. Each side of differential signal would return through the ground circuit except that since each signal is exactly equal and opposite, the returns simply cancel. To recover the information we have to subtract  $V_+ - V_-$ , as we can see on **Fig. 3.2**



**Fig. 3.2** Single-ended and differential mode signals

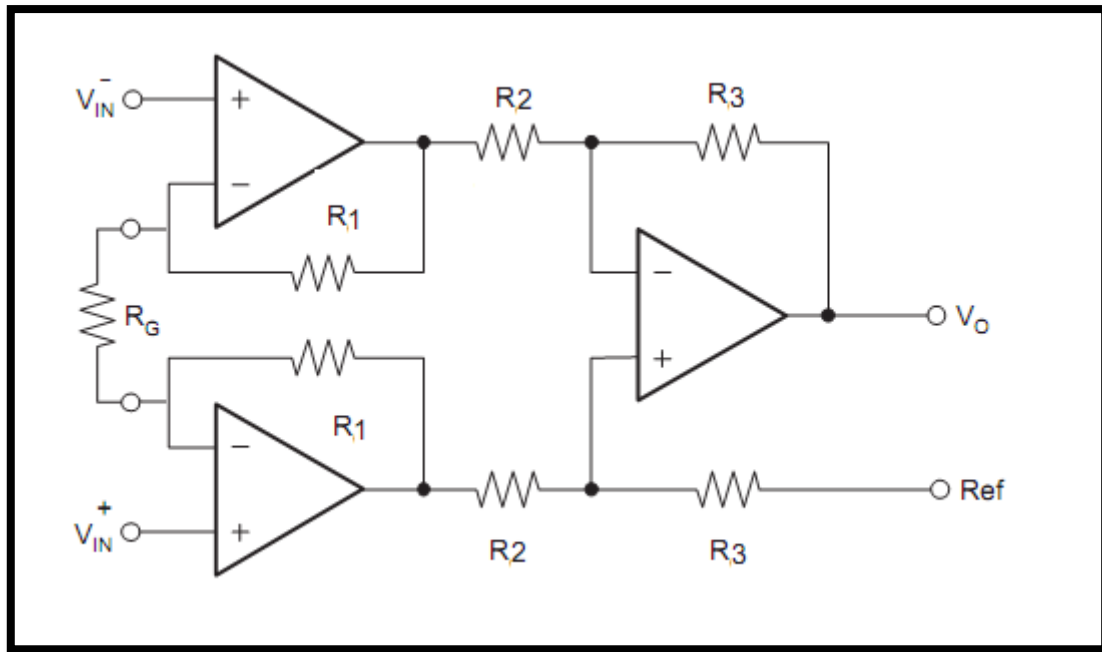
Differential signals have the following advantages:

- The resulting signal is twice large compared to the ambience noise as either of the single-ended signals. We need half less gain per channel to fulfill the system dynamic range compared to single-ended. So we can improve the amplifier gain – bandwidth tradeoff increasing the system bandwidth.
- They are immune to EMI and crosstalk coupling. If any crosstalk coupling appears, it would be coupled for both signals. Those coupled noise becomes common mode voltage, to which the circuit is “theoretically” immune.
- If the sensor is far away from the circuit local ground shifts effects are avoided.
- Some sensors have a balanced output signal, for instance those ones which uses Wheatstone bridge circuits. In that case it is necessary to process the signal differentially.

### 3.3. Instrumentation amplifier

The instrumentation amplifier is a device that allows converting a differential signal into a single-ended signal and also adding a gain. It does a subtraction of the  $V_+$  -  $V_-$  input and then multiplies the result for a factor. Those devices are designed to have high input impedance and a high CMRR (common mode rejection ratio).





**Fig. 3.3** Instrumentation amplifier

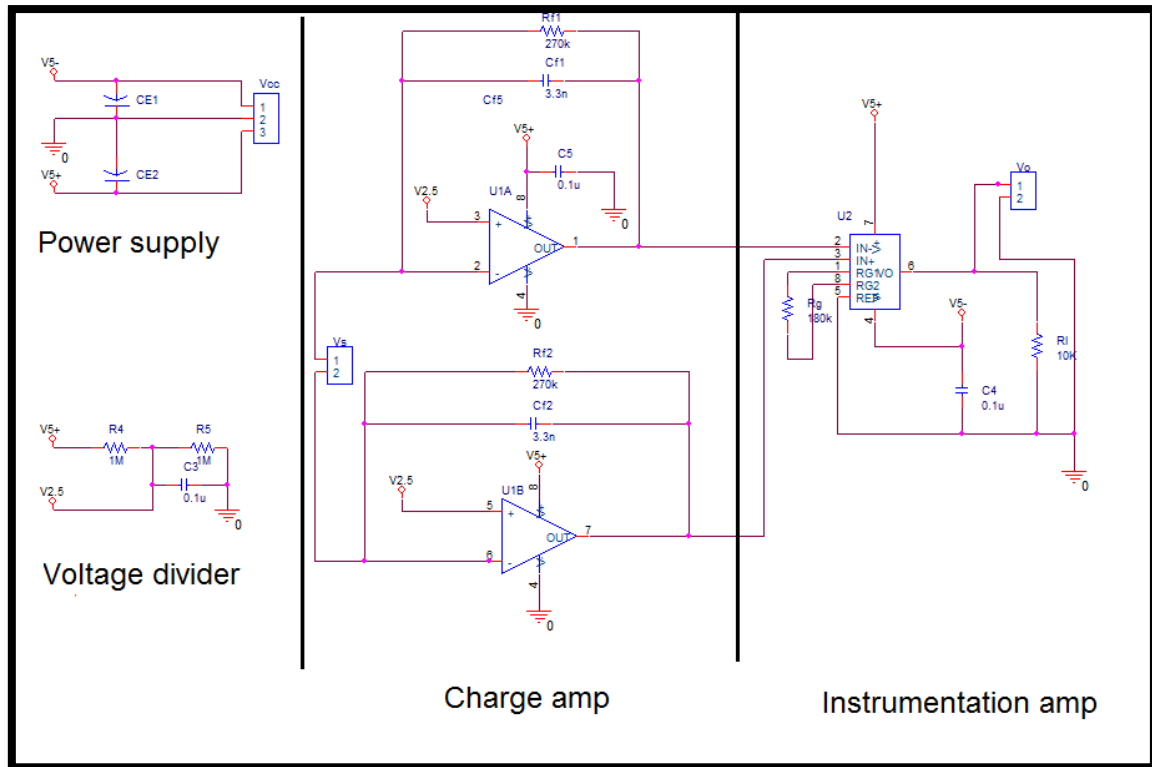
The output equation for the instrumentation amplifier is:

$$V_O = (V_{in+} - V_{in-}) \left( 1 + \frac{2R_1}{R_G} \right) \frac{R_3}{R_2} \quad (3.5)$$

Note that if  $R_2=R_3$  the equation gets simplified.

### 3.4. Circuit design and component selection

We have designed and simulated the circuit with Orcad Capture software. The circuit consists of two stages, as we can see on **Fig. 3.4**. The first stage is the differential charge amplifier and, the second one, the instrumentation amplifier.



**Fig. 3.4** Circuit scheme

The piezoelectric sensor has two outputs. Each output is connected to the negative input of a charge amplifier. On the positive input we have a reference voltage, in our case, the half of power supply voltage. That is because the chosen amplifier is single supply. Then we connect the output of each charge amplifier to the instrumentation amplifier. We can set up the gain of this amplifier changing the  $R_g$  value. This amplifier is supplied from -5 to 5V so its dynamic range is 10V.

Note that decoupling capacitors (0.1  $\mu$ F) between the supply of each amplifier and ground are added. Those capacitors improve the amplifiers performance when high frequency intensity peaks appear.

Also we have added two 100 mF electrolytic capacitors between 5V and ground and -5V and ground in order to filter noise from the power supply, specially the 50 Hz noise.

### 3.4.1. Component selection

We have selected the TLV2772 operational amplifier from texas instruments (8). This operational amplifier has a rail-to-rail output and its power supply range goes from 2.5 to 5.5V single supply.

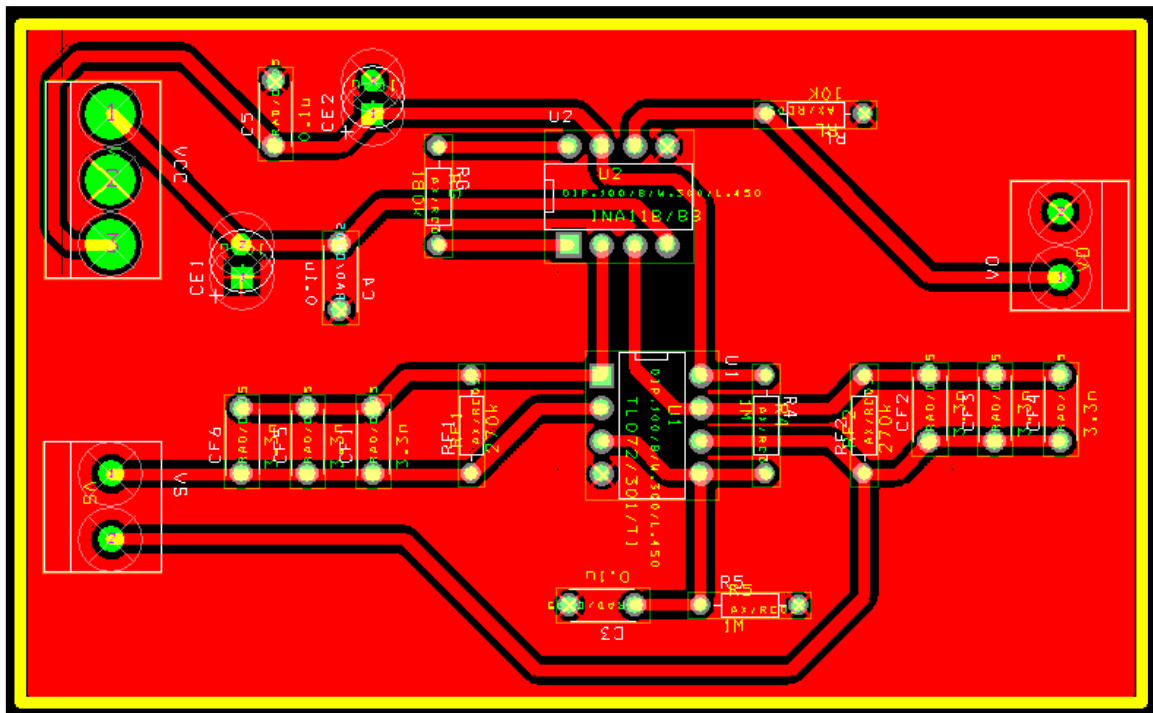
As the instrumentation amplifier, we have selected the INA128, also from Texas Instruments (9). This circuit is based on the instrumentation amplifier we explained in section 3.3 and has the resistor  $R_g$  outside so we can set up the gain easily changing this resistor from 1 to 10,000. The power supply goes from  $\pm 2.25$  to  $\pm 18V$ .

### 3.4.2. Power supply

The system power supply has been designed from  $-5V$  to  $5V$ . Those supply range fully fill the DAQ dynamic range, see section 2, and also is a low power system. In order to obtain the  $2.5V$  for the charge amplifier reference, we need a voltage divider.

## 3.5. Printed Circuit Board design

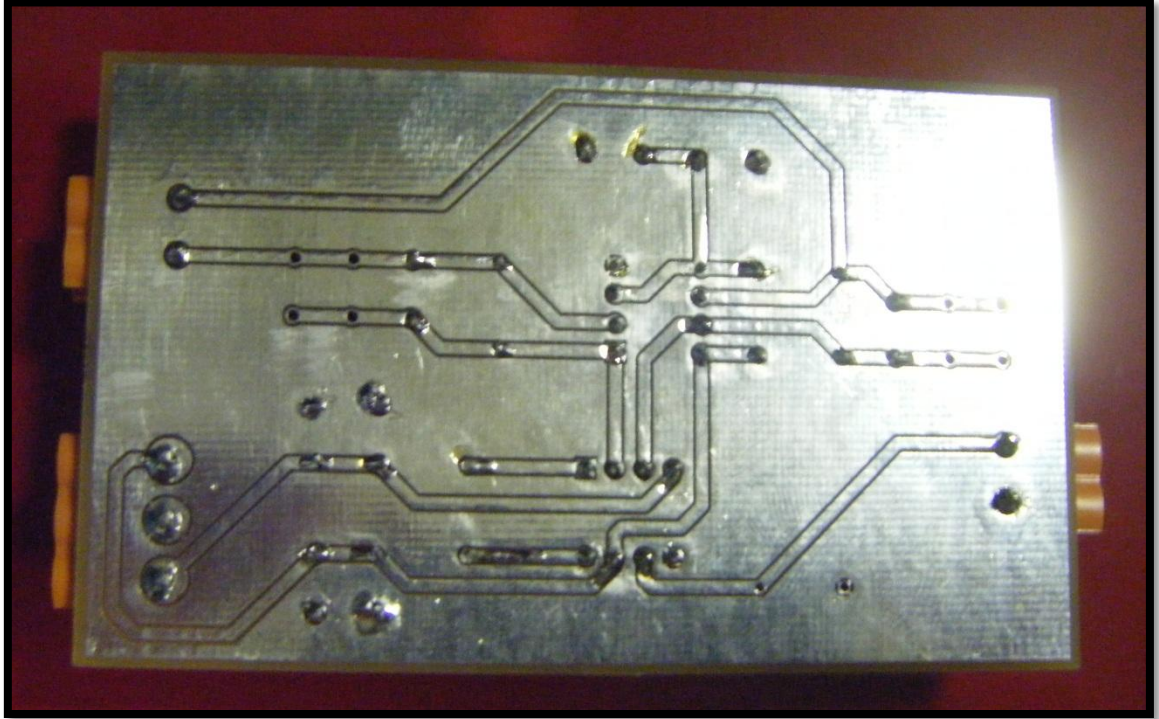
To design the PCB we have imported the Orcad Capture circuit design to the Orcad Layout. This software allows us to place the components, and route them to finally print the PCB template.



**Fig. 3.5** Printed circuit board design

We have one three pin connector for the  $-5V$ ,  $5V$  and system ground, then a two pin connector for the sensor input, and another one for the circuit output.

We have designed the PCB with two spare components per each charge amplifier in case we need them on the future to change the feedback components. Also we have space for a load resistor  $R_L$ , which it is not necessary if we connect the circuit to the DAQ; but it could be useful in the future.



**Fig. 3.6** Real PCB design with components and connectors.

### 3.6. Component values for both sensors

On this section we are going to explain the necessary components for both sensors, and finally the lists of the components with commercial names used in the circuit.

For sensor A we need a gain of approximately 12, see on chapter 2 for detailed explanation. Using equation (3.6) we calculate the feedback capacitor value.

$$G = \frac{-Cs}{C_0} \Rightarrow C_0 = \frac{20nF}{12/2} = 3.34nF \quad (3.6)$$

The next step is to calculate the feedback resistor value. To calculate the resistor value we must calculate the bandwidth, according to equation (3.4):

$$f_l = \frac{1}{2\pi R_o C_o} \Rightarrow R_o = \frac{1}{2\pi f_l C_o} = \frac{1}{2\pi \cdot 3.34nF \cdot 176Hz} = 270K\Omega \quad (3.7)$$

We have set the signal bandwidth at 176Hz, always taking into account that for a large gain we need a smallest capacitor which means a higher value resistor, to have the pole low. Furthermore, increasing so much the resistor has other consequences such as noise increasing and difficult to achieve with real components. In that case we would need to find out other solutions like the use of a T-network to simulate a high resistor value with low resistor components, but it also increases the noise. In conclusion, on circuit cannot measure low frequency signals, especially DC, due to the relationship between the gain, component values and the high pass filter frequency.

The instrumentation amplifier gain would be 1, so we do not need to connect any  $R_G$  resistor.

In order to simplify the circuit we are going to leave the  $C_o$  and  $R_o$  values constant for sensor B, and use a high gain on the last stage, the instrumentation amplifier. Repeating the gain calculation for sensor B we have:

$$G = \frac{8nF}{3.34nF} = 2.39 \quad (3.8)$$

If we use that gain for each charge amplifier we have  $2 \cdot 2.39 = 4.78$ . Looking at the INA128 datasheet (9) we obtain the gain formula:

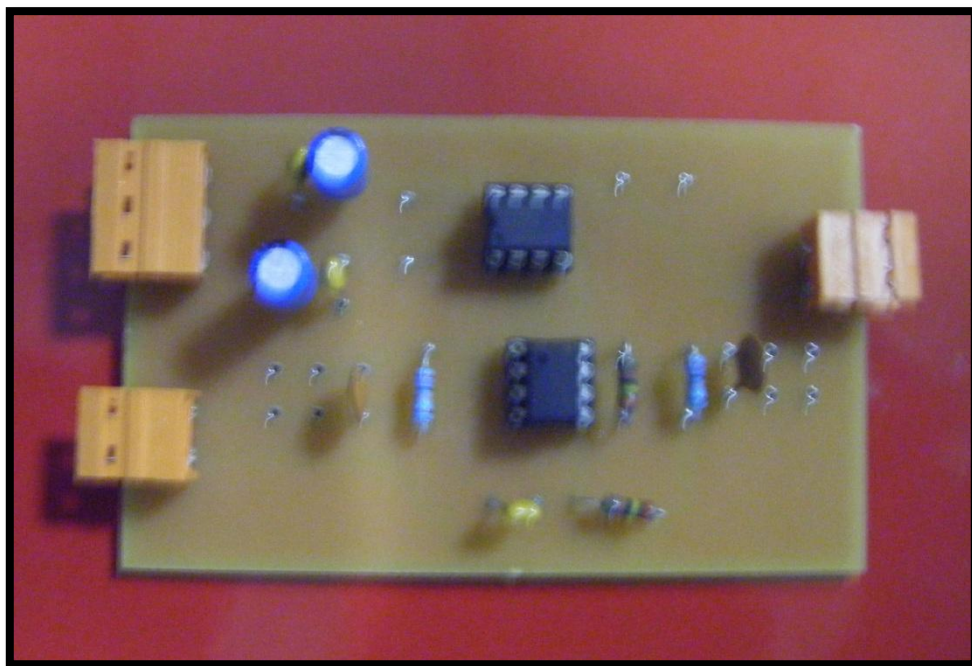
$$G = 1 + \frac{50 \cdot 10^3}{R_G} \quad (3.9)$$

Using commercial resistor values, we selected a 22K $\Omega$  resistor which gives a 3.27 gain for the instrumentation amplifier and a total circuit gain of  $4.78 \cdot 3.27 = 15.64$ .

On the following table we can see all the necessary components to build the circuit.

**Table 3.1** Circuit components

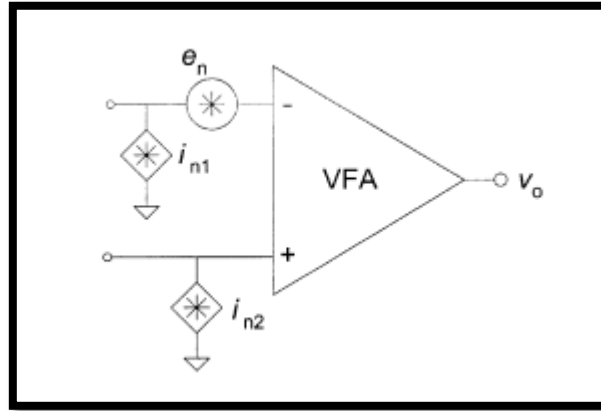
Component	Value	Quantity
Feedback resistor	270 k $\Omega$	2
Feedback capacitor	3.3 nF	2
Voltage divider resistor	1 M $\Omega$	2
Charge amplifier	TLV2772P	1
Instrumentation amplifier	INA128P	1
Electrolytic capacitor	100mF	2
Ceramic capacitor	0.1 $\mu$ F	3
3pin connector	Vcc	1
2pin connector	Vsensor, Vout	2

**Fig. 3.7** The circuit with all components soldered

### 3.7. Noise analysis and power consumption

On this section we are going to analyze and simulate with Orcad the circuit noise. But first to understand the result we need to explain the different noise sources in our circuit. Finally, we are going to see how the noise affects to the sensor measurements.

### 3.7.1. Operational amplifier noise



**Fig. 3.8** Operational amplifier noise sources

As we can see on **Fig. 3.8** we have one voltage noise generator and two current noise generators. The stars inside the generators indicate that the noise signals are random. The voltage source is a pink noise source, or what is the same,  $1/f$  noise. In commercial operational amplifiers the current sources have the same value, so the manufacturer specifies one value for  $i_n$  and  $e_n$ . As the noise is related with the bandwidth the noise figure units are:

$$i_n = \left[ \frac{A}{\sqrt{Hz}} \right] \quad (3.10)$$

$$e_n = \left[ \frac{V^2}{Hz} \right] \quad (3.11)$$

Also we have to take into account the thermal noise across the conductors. The noise across a resistor is:

$$v_n = \sqrt{4kTR} \quad \left[ \frac{V^2}{Hz} \right] \quad (3.12)$$

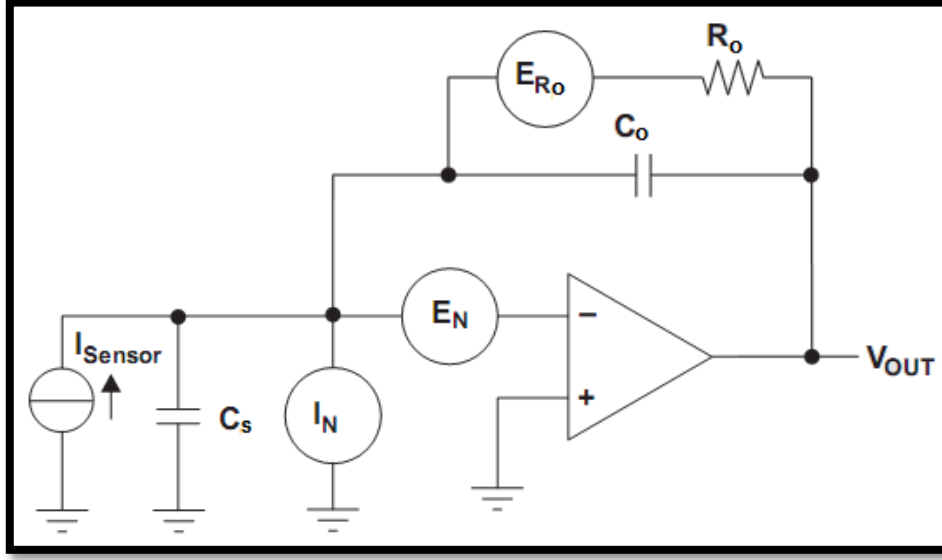
Where:

$k = 1.38 \cdot 10^{-23}$  Boltzmann constant

R = resistor value

T= temperature °K

### 3.7.2. Charge amplifier noise



**Fig. 3.9** Charge amplifier noise sources

On **Fig. 3.9** we can see the charge amplifier connected to a sensor, the amplifier current noise source, the amplifier voltage noise source and the thermal noise due to the feedback resistor. Then the output noise spectral density is:

$$S_o(f) = I_n^2 \cdot |z_o|^2 + E_n^2 \left| 1 + \frac{z_o}{1/(C_s \cdot s)} \right|^2 + E_{Ro}^2 \left| \frac{1}{1 + R_o C_o \cdot s} \right|^2 \quad (3.13)$$

Where:

$$Z_o = \frac{R_o}{1 + R_o C_o \cdot s}$$

$$s = j\omega$$

We can operate the equation replacing the feedback impedance and obtain:

$$S_o(f) = I_n^2 \cdot \left| \frac{R_o}{1 + R_o C_o \cdot s} \right|^2 + E_n^2 \left| 1 + \frac{R_o C_s \cdot s}{1 + R_o C_o \cdot s} \right|^2 + E_{Ro}^2 \left| \frac{1}{1 + R_o C_o \cdot s} \right|^2 \quad (3.14)$$

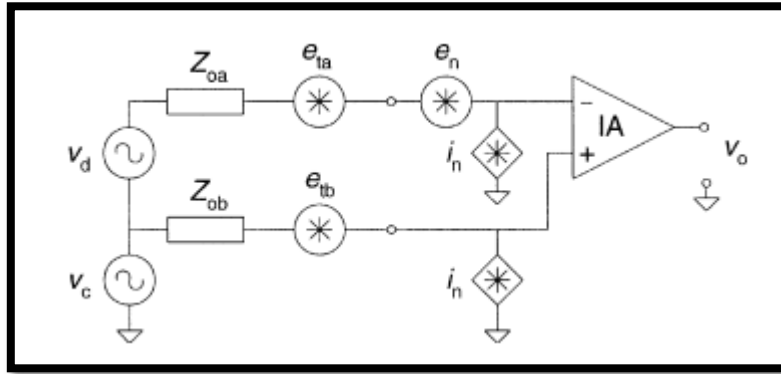
If we consider high frequencies, we can simplify the second term denominator:



$$S_o(f) = I_n^2 \cdot \left| \frac{R_o}{1+R_o C_o \cdot s} \right|^2 + E_n^2 \left| 1 + \frac{C_s}{C_o} \right|^2 + E_{Ro}^2 \left| \frac{1}{1+R_o C_o \cdot s} \right|^2 \quad (3.15)$$

Finally we have the equation with three terms. The first term is the current noise figure multiplied by the feedback components. So an increase of  $R_o$  will make the first term increase linearly. The second term is related with the amplifier voltage noise multiplied by the circuit gain. Hence, the sensor capacity will make the second term of the equation increase. And finally the last term is the resistance thermal noise, so a high value of the resistor would make the term increase as the square root of the resistor value due to the thermal noise.

### 3.7.3. Noise in instrumentation amplifier



**Fig. 3.10** instrumentation amplifier noise model

The noise for instrumentation amplifier does not depend on the feedback networks.  $e_{ta}$  and  $e_{tb}$  are the noise voltages for the source impedances, in our case, the output noise of each charge amplifier. So the output noise would be:

$$E_{no}^2 = (e_n^2 + i_n^2 |Z_{oa}|^2 + i_n^2 |Z_{ob}|^2 + e_{ta}^2 + e_{tb}^2) \cdot |G|^2 \quad (3.16)$$

If we assume that the input sources have the same values we can simplify the equation:

$$E_{no}^2 = 2 \left( \frac{e_n^2}{2} + i_n^2 |Z_o|^2 + e_t^2 \right) \cdot |G|^2 \quad (3.17)$$

We have to note that the charge amplifier noise, despite of being a differential circuit, it is not cancelled at the instrumentation amplifier stage. It is added quadratically. The noise that is cancelled is the common mode noise, as we explained on section 3.2.

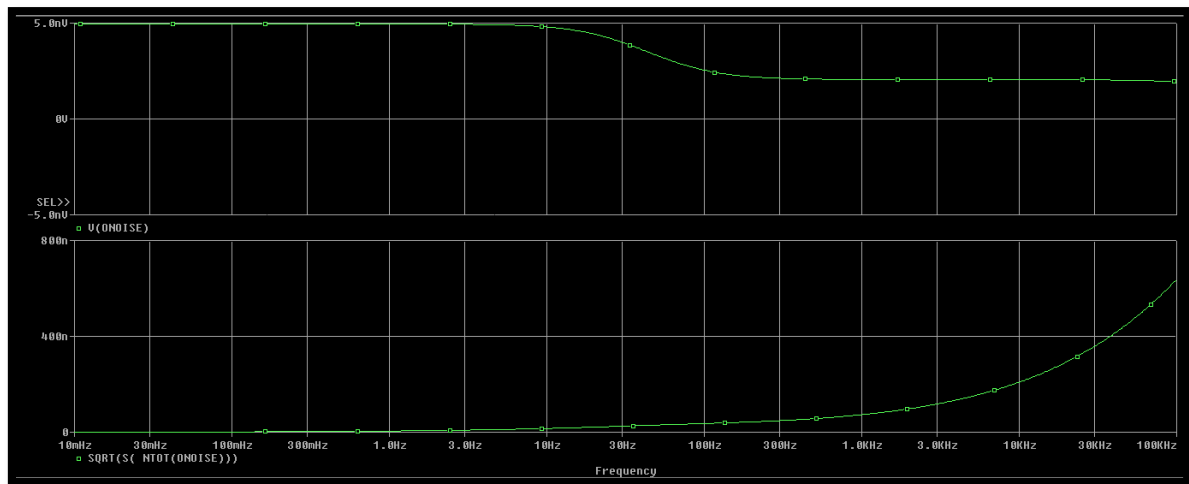
#### 3.7.4. Circuit noise calculation and simulation

We are going to see the circuit output noise. The calculations for our circuit are a little bit complex, but Orcad simulates the output noise, giving us the voltage spectral density and the power spectral density for a given bandwidth. On **Table 3.2** we have the noise values for both the charge amplifier and the instrumentation amplifier. Detailed data about noise for those devices can be found in the datasheets. (8) (9)

**Table 3.2** Noise values for both operational amplifiers

	TLV2772	INA128
$e_n @ 10 \text{ Hz}$	-	$10 \text{ nV} / \sqrt{\text{Hz}}$
$e_n @ 1 \text{ KHz}$	$12 \text{ nV} / \sqrt{\text{Hz}}$	$8 \text{ nV} / \sqrt{\text{Hz}}$
$e_n @ 10 \text{ KHz}$	$17 \text{ nV} / \sqrt{\text{Hz}}$	-
$i_n @ 10 \text{ Hz}$	-	$0.9 \text{ pA} / \sqrt{\text{Hz}}$
$i_n @ 100 \text{ Hz}$	$0.6 \text{ fA} / \sqrt{\text{Hz}}$	-
$i_n @ 1 \text{ KHz}$	-	$0.3 \text{ pA} / \sqrt{\text{Hz}}$

The simulations have been made for both circuits, one for each sensor. The frequency simulation is up to 100 KHz, because the DAQ maximum sampling frequency is 200 KHz. On the previous section 3.6 we have explained the differences between both circuits, but basically those are the sensor value and the instrumentation amplifier gain.



**Fig. 3.11** Orcad noise simulation graph

On the first chart we see RMS output noise for the circuit. We can observe that as the frequency increases the noise decreases because of the operational amplifiers pink noise. But, if we integrate the square root of the circuit noise we obtain the RMS noise value for our circuit and bandwidth.

**Table 3.3** Simulation noise results

	Circuit A	Circuit B
Sensor Capacitance	20nF	8nF
Instrumentation amplifier gain	1	3.27
RMS noise at 100KHz	640 nV / $\sqrt{Hz}$	34 $\mu$ V / $\sqrt{Hz}$

For both cases the noise value is smaller than 1LSB, that as we have seen on section 2 is 4.9mV. We can observe that it is better to have more gain in the charge amplifiers rather than in the instrumentation amplifiers, anyway as both are low now components we do not have to worry about it.

### 3.7.5. Power consumption

The circuit power consumption is very important, especially if, on the future, we want to make it portable with batteries. To measure the power consumption we have simply read the power source ampere meter. The circuit current consumption is 4mA, so applying the power formula we obtain:

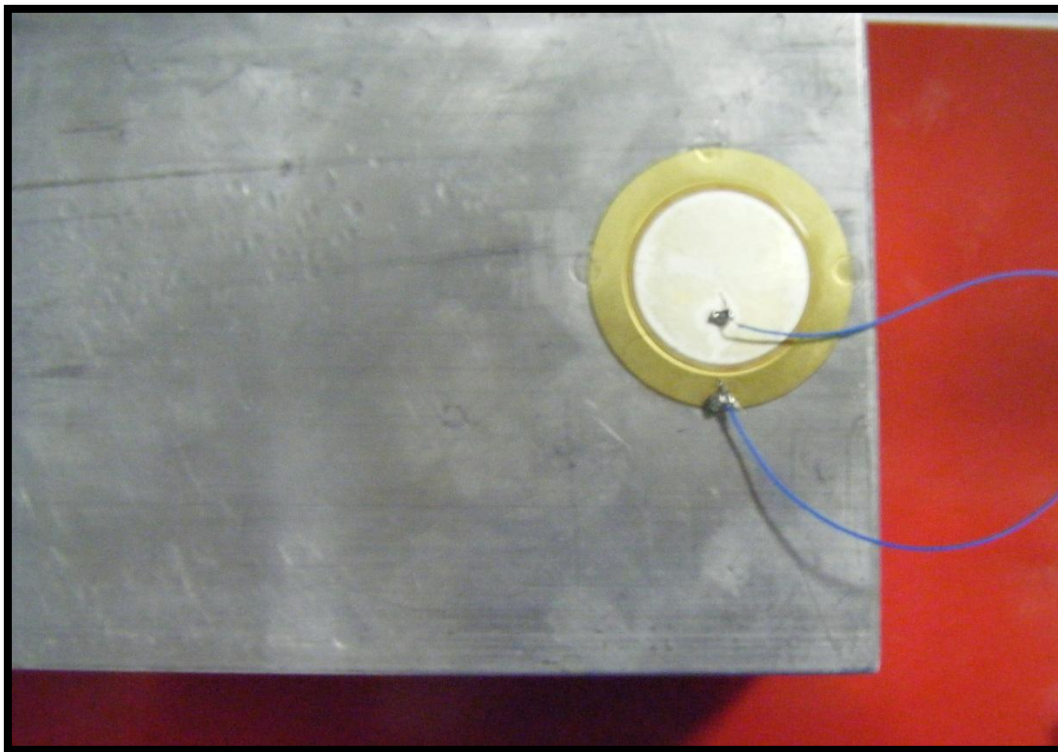
$$P = V \cdot I = 10 \cdot 4 \cdot 10^{-3} = 40mW \quad (3.18)$$

## CHAPTER 4. EXPERIMENTALS RESULTS

On this chapter we are going to present the results of the two experiments we made. As we said previously, we used two different sensors, with different features. We have the detailed data on section 2.2 , but to summary we have sensor A with a capacity of 23nF and a resonant frequency of 2.8 KHz, and sensor B with a capacity of 8nF and a resonant frequency of 6.3 KHz.

To set up our experiment, we need to attach our piezoelectric sensor to a high mass respect the impact mass. That is because if  $m_{\text{sensor}} \gg m_{\text{impact}}$  we can neglect the vibration frequency of the big mass, and we will just see the impact in our sensor. As we said on section 1.4 the natural frequency is inversely proportional to the mass, so if the mass is bigger, the natural frequency tends to be 0.

To stick the sensor to the mass we used standard glue, as we can see on the following picture.



**Fig. 4.1** The piezoelectric sensor stuck to a big mass.

### 4.1. The pendulum experiment

To do this experiment, we set up a pendulum with a mass, and let it impact to the mass where the piezoelectric sensor is glued. This is a simpler but effective

experiment, because controlling the angle; we can vary the acceleration, and impact force of the mass. We have a detailed explanation on annex 6.3.

To do this experiment we used two different mass, one 10 times bigger than the other one, as we can see on the following table.

**Table 4.1** pendulum experiment objects mass

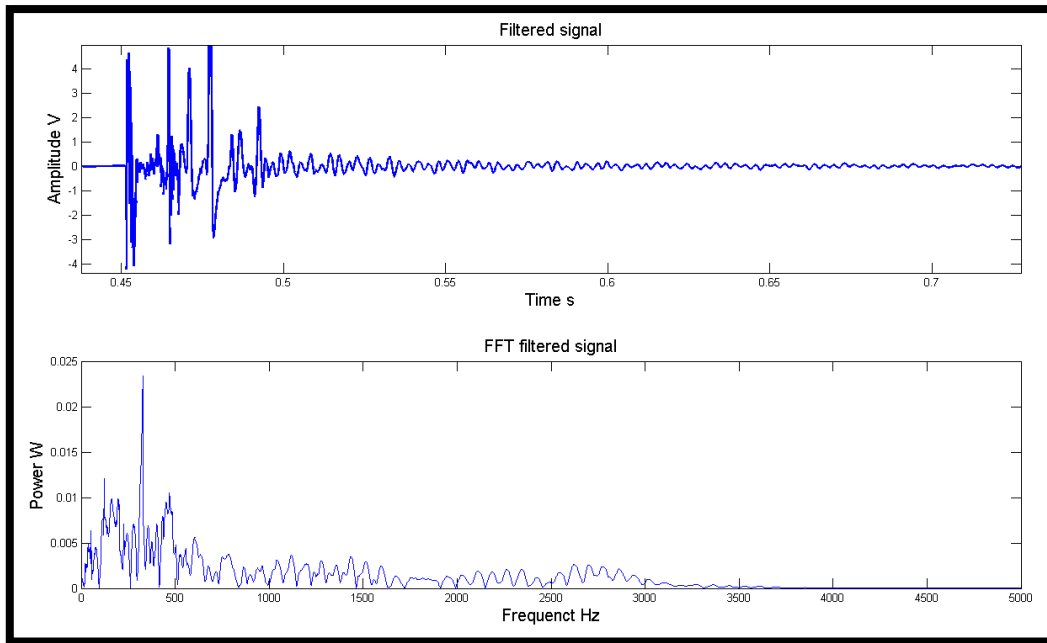
Object	Mass
Mass 1	393g
Mass 2	39.3g
Sensor mass	1996g

The main idea once we designed this experiment was to analyze different impacts from different angles, from  $0^\circ$  to  $90^\circ$ , and find a relationship between the impact acceleration, (or the impact velocity) and the output signal. In fact, we had done the measurements for different angles, with the 2 mass and with the 2 sensors. But instead of the expected damped exponential, the signals were very noisy, even with the digital filter, and we cannot find a pattern to have a final conclusion.

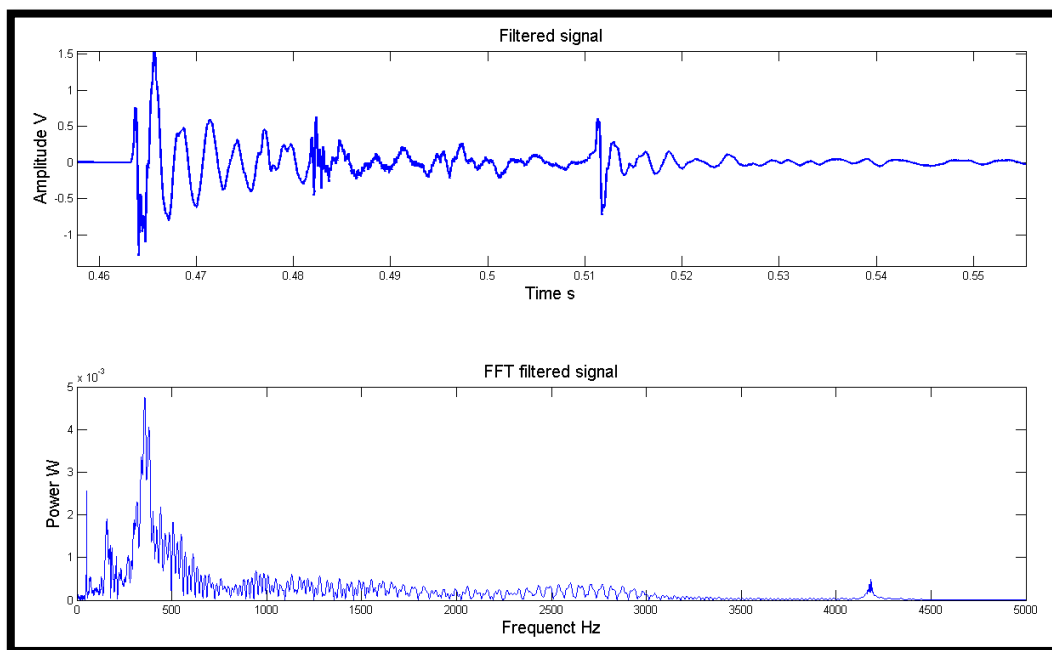
We are going to present some graphs, to see the  $45^\circ$  impact from all possible mass-sensor configurations.

#### 4.1.1. Sensor A

For sensor A we have used the matlab filter with a cutoff frequency of 2000Hz and a stop frequency of 5000Hz, to filter the 2800Hz sensor resonant frequency and above.



**Fig. 4.2** Mass 1 45° impact

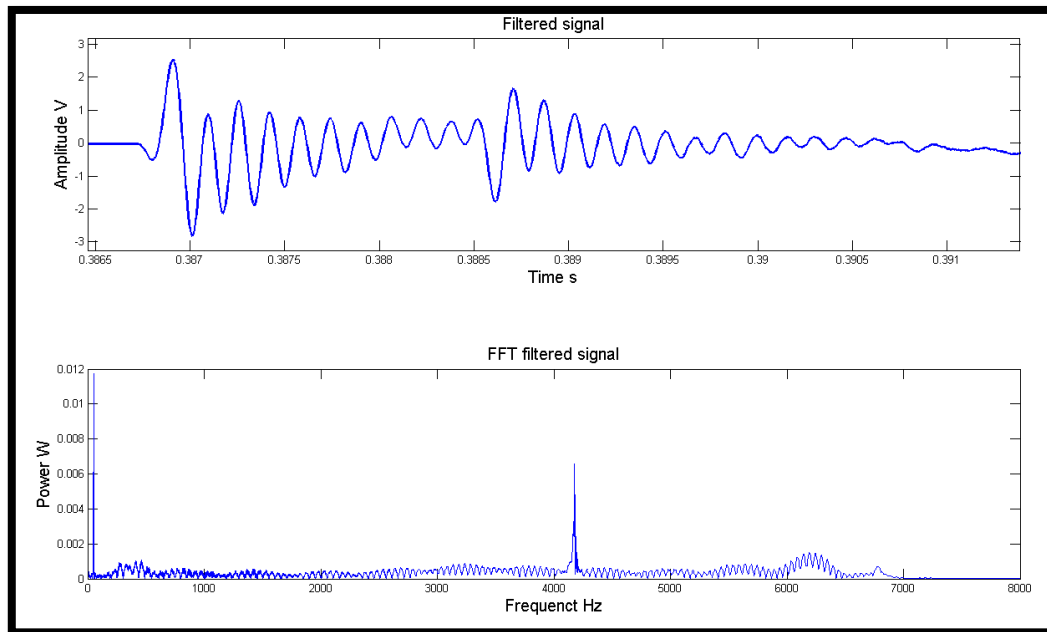


**Fig. 4.3** Mass 2 45° impact

Despite of the signal is filtered, we do not see a clear damped exponential form, as we expected. This is because the distortion introduced by the sensor, so we need a piezoelectric sensor with a higher resonant frequency.

### 4.1.2. Sensor B

For sensor B, we set up the filter with a cutoff frequency of 5000Hz and a stop frequency of 8000Hz.



**Fig. 4.4** Mass 2 45° impact

With sensor B that has higher bandwidth, we see a noiseless signal, but it is not enough clear to see perfectly the damped exponential. That is because we still have high frequency signal components, and are distorted due to the sensor. To clearly see the signal, we would need or higher signal processing, more than a filter, an equalizer, or a high resonant frequency sensor.

It was a very time consuming experiment and we hope to find some relationships between the impact force and the signal, for instance, the logarithmic decrement. But due to the sensor nature, we have not been able to find any important relationship. Anyway this experiment has been very useful for us to understand the impact equations, the piezoelectric sensor behavior, and the digital filter function.

## 4.2. The coin experiment

To do this experiment, we let fall freely different coins from a constant height, and analyzed the impact signal. On annex 6.4 we explain the experiment set up and some calculations.

We used the two sensors, and 20cts, 50 cts, 1€ and 2€ coins.

We are just going to present the results for a 20 cts (lighter) and 2€ (heavier) coins, and comment the experimental differences we observe. On the following table we can observe the coin experiments objects mass.

**Table 4.2** coin experiment objects mass

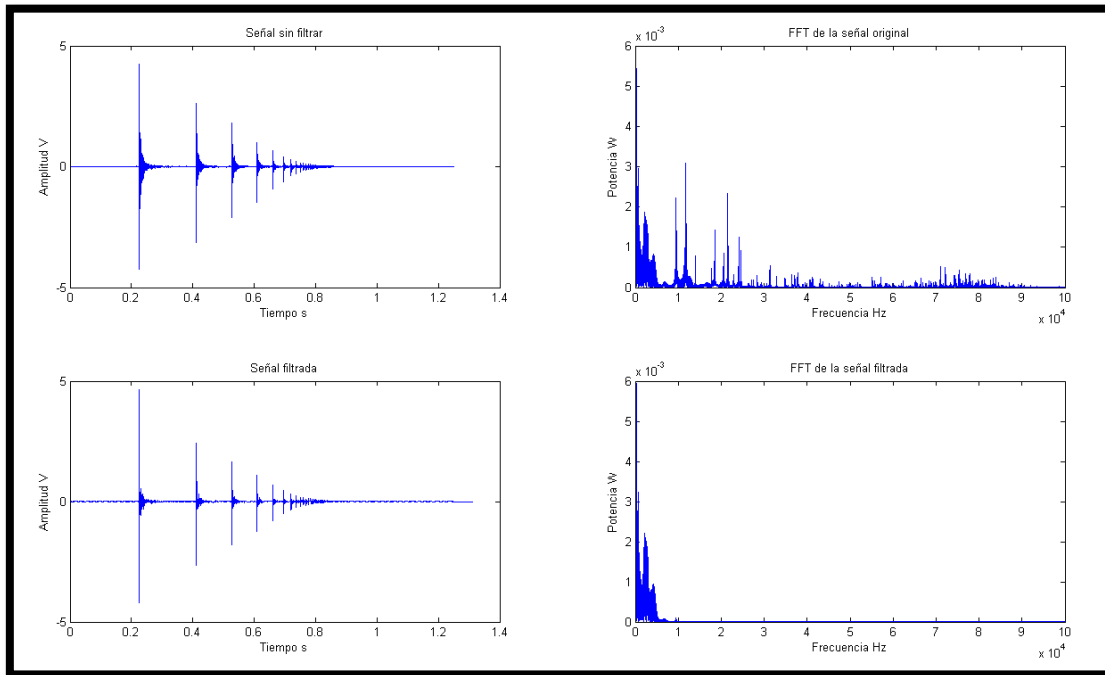
Object	Mass
20 cts coin	5.8g
2€ coin	8.5g
Sensor mass	1996g

To do these tests, we have configured the matlab digital filter with a cutoff frequency of 6 KHz and a stop frequency of 10 KHz, for sensor A, and 7 KHz and 11 KHz for sensor B.

#### 4.2.1. Sensor A

We are going to start showing the time and FFT of a 20cts impact. The upper signals are the direct circuit output, and the downside signals are the filtered ones.

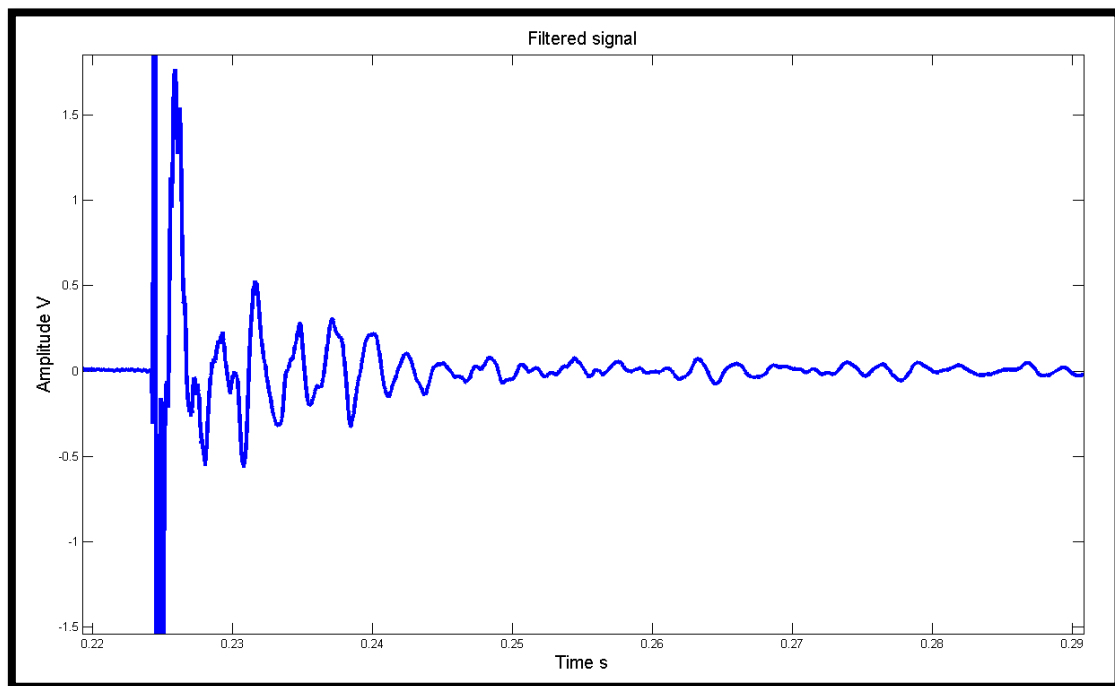
We can see different peaks, and its amplitude decreases progressively, but this peaks are just the bouncing, because the coin bounces a few times before becoming stopped.



**Fig. 4.5** 20cts impact measured with sensor A

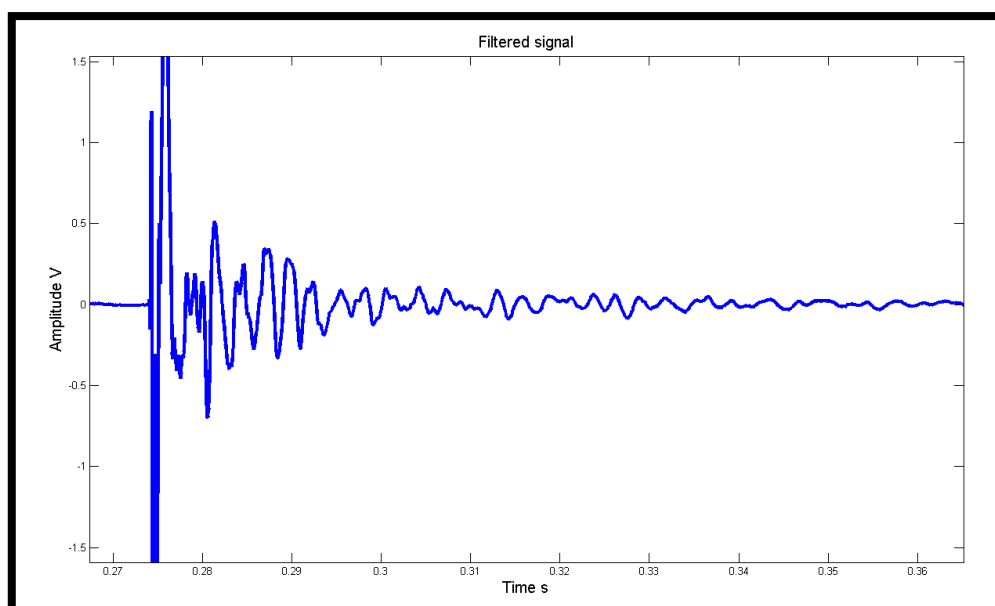


We have zoomed into the first bounce, in the time domain signal, and we note that the waveform decreases exponentially, as we have seen on section 1.4.1.



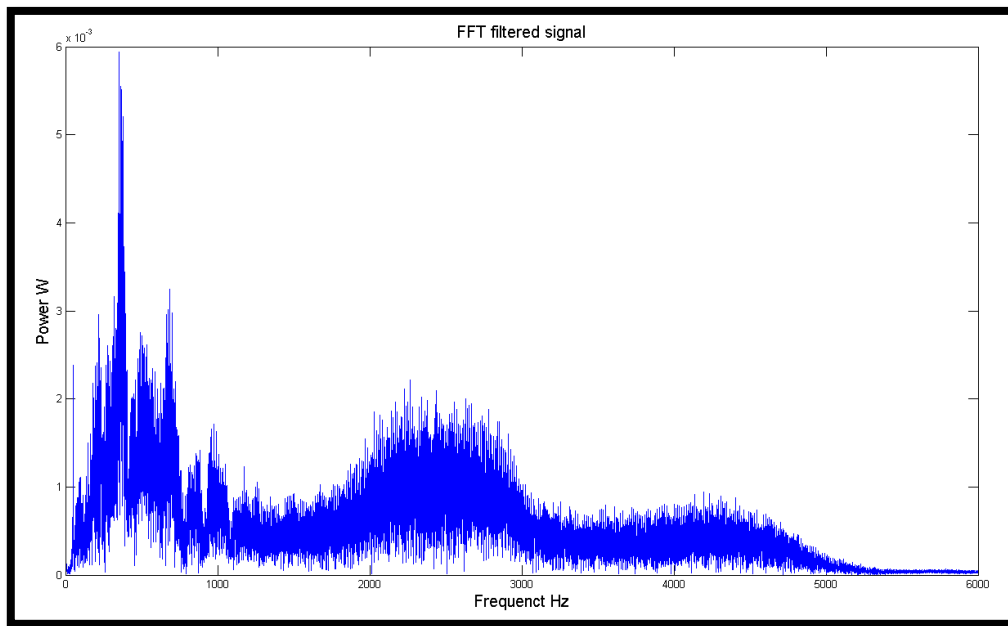
**Fig. 4.6** First bounce zoom 20cts impact, filtered signal

Now we are going to show the impact of the 2€ coin. This time we are just going to show the zoom of the first bounce, and comment the differences.

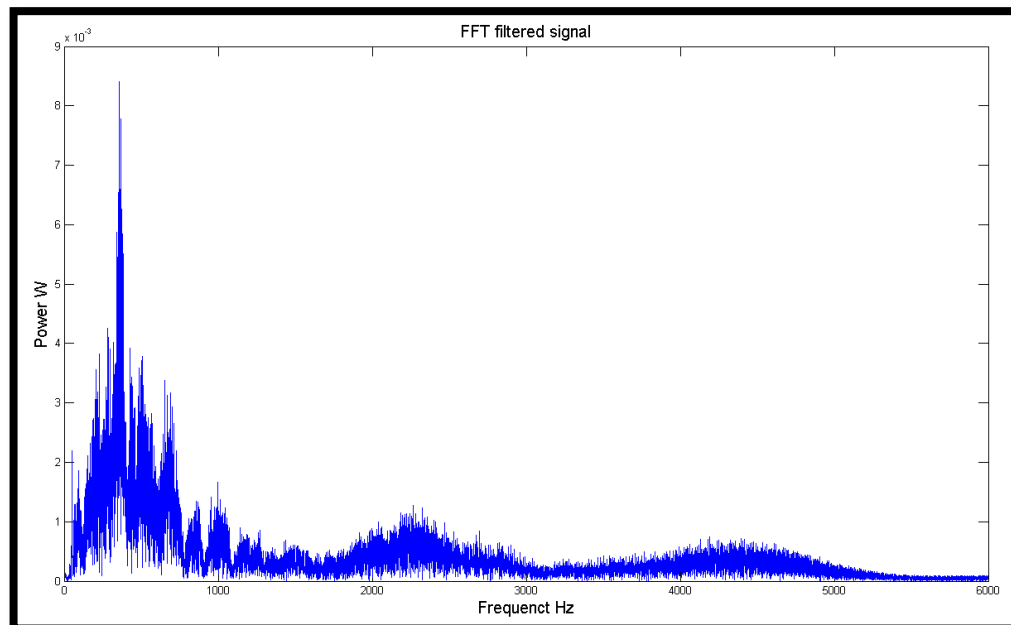


**Fig. 4.7** First bounce zoom 2€ impact, filtered signal

There are no appreciable differences, despite of the 2€ mass is 1.46 times bigger than the 20cts mass. So we are going to take a closer look at the FFT of both signals, to note some differences.



**Fig. 4.8** FFT of the 20cts impact

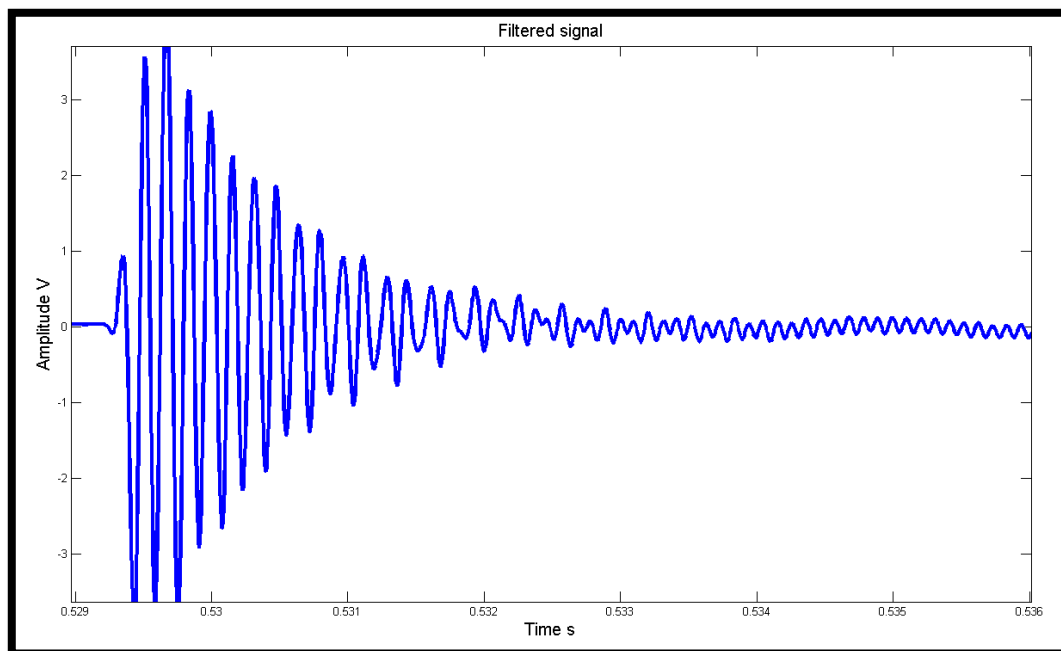


**Fig. 4.9** FFT of the 2€ impact

Comparing both FFT we can see that the 2€ impact has more energy at low frequency, than the 20cts. That confirms what we said before, that lower the mass, higher the frequency. Also we can observe on both pictures, the 2800Hz resonance, due to the sensor resonant frequency.

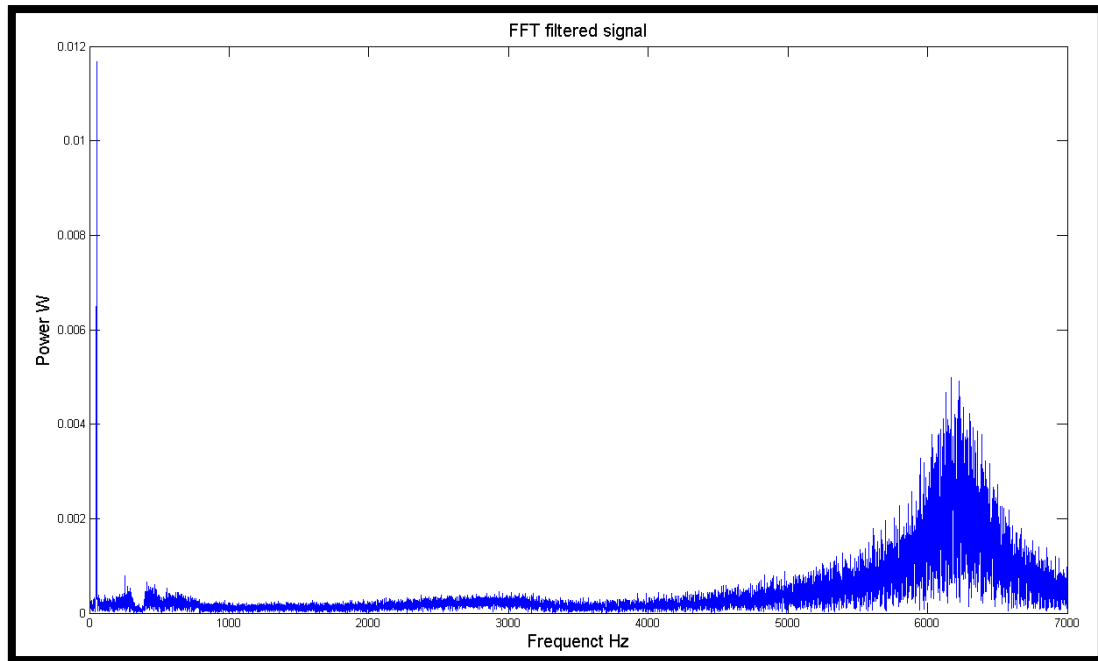
#### 4.2.2. Sensor B

On this section we are going to use the same coins, but this time using sensor B.



**Fig. 4.10** First bounce zoom 20cts impact, filtered signal

On this signal we can appreciate the exponential damped waveform clearer than with sensor A. That is because here it has less noise at lower frequencies, because the resonance is higher, at 6.8 KHz, as we can see on the following picture.



**Fig. 4.11** FFT of the 20cts impact

We can clearly appreciate the resonance, and also the impact natural frequency around 300 Hz, the same we see with sensor A, but in this case it was noisier. So, we can say that using a sensor with a higher resonant frequency is better because we have less noise at low frequencies, where we have the impact natural frequencies.

In conclusion, with the appropriate sensor, in our case sensor B; we can recognize the coin by its natural frequency.

## CHAPTER 5. CONCLUSIONS

In this thesis, we designed a signal conditioning circuit for a piezoelectric sensor, and we made some tests to prove its correct functioning. We have learnt a lot about impact detection, and about piezoelectric sensors.

The circuit has worked as it has adapted the sensor signal to the DAQ desired gain. One important problem of piezoelectric sensors is its resonant frequency, which limits our signal bandwidth. Another aspect we discovered is that the global SNR depends on the feedback network and also on the sensor capacitance.

Despite of being more complicated, the use of differential signals is very important and convenient. It allows us to place the sensor far away from the circuit, avoiding the coupling effects, and also it doubles the signal amplitude, so we need half amplification to achieve the same gain as if it was single ended.

We have some ideas to improve this circuit. One is doing the circuit portable, using batteries, and SMD components. If we use batteries, we need a charge pump, because 10V are expensive. If we do the circuit portable, we can install a microcontroller to do the signal processing, or install an RF transmitter, to send the signal and process it remotely.

Referring to the application, if we want to design a circuit specifically for a determined application it is convenient, first, to know the specifications, specially the frequency and desired gain. Once we know that, we need to adapt our circuit parameters, and choose an appropriate sensor. Also, we can add a low pass filter in the charge amplifier design, to reduce the SNR. If we use the low pass filter on the final stage, as we have done on this project, we have a worst SNR, but on the other hand we have more flexibility for doing changes. That is the most important advantage of digital signal processing.

Furthermore, the digital signal processing stage is very important to classify impacts, and not only, the frequency or time analysis, but also the correlation analysis for noisy signals. Another final thesis about signal processing could be done, once we had the electronic circuit perfectly tuned for the application.

## CHAPTER 6. ANNEX

### 6.1. Matlab code

Once we had acquired the signal with the DAQ we need work with that data. So we saved that as a txt file, as we will see on the next annex, and we used matlab to plot it.

With matlab we made four things in order to plot and filter the signal. The first thing was to plot the signal in the time domain. Then, calculate the FFT in order to plot the same signal but in the frequency domain. The third step is to create a digital filter to cancel the noise. And the last step is to plot in both time and frequency domain the filtered signal.

#### 6.1.1. Plotting the signal time domain

First we need to open the signal txt file and load its data into the matlab workspace. Once we have the data loaded, we need to create a time vector taking into account the DAQ sampling frequency. Finally, we plot the graph, the signal amplitude values and the time of each sample.

```
%filename
n_fichero = signal.txt';
%sampling frequency
freq = 200000;
%load the file to the matlab workspace
muestras = load (n_fichero);
%time vector considering the sampling f
vtemp = ((1/freq):(1/freq):(1/freq)*length(muestras));
%plot the signal time domain
plot(vtemp, muestras)
ylabel('Amplitud V');
xlabel('Tiempo s');
title ('Señal sin filtrar');
```

#### 6.1.2. Calculating the FFT

The FFT (Fast Fourier Transform) is a faster version of the DFT (Discrete Fourier Transform), which utilizes clever algorithms to do the same thing that the DFT but in less time. The FFT shows the power spectral density of the signal. The frequencies go from 0 to  $f_s$ , but the fft is symmetric at  $f_s/2$ , so we can just plot the signal from 0 to  $f_s/2$ . That is because the Nyquist theorem which says the sampling frequency must be at least the half of the signal bandwidth.

```

%zero padding
v_zeros=zeros(2^multiplo_fft(length(muestras)),1);
v_zeros(1:length(muestras))=muestras;
%calculate the FFT
fft_muestras=abs(fft(v_zeros));
%frequency axe from 0 to fs
vfreq=(freq/length(v_zeros):(freq/length(v_zeros)):freq);
%Plot the FFT
plot (vfreq,fft_muestras/length(muestras));
XLim ([0,freq/2])
xlabel('Frecuencia Hz');
ylabel('Potencia W');
title ('FFT de la señal original');

```

Due to the nature of the FFT algorithms, our signal must have a power of two samples number. To achieve that we created a function that calculates the power of two to do a zero padding of our original signal, and achieve a total power of two signal length.

```

function [ m ] = multiplo_fft( length )
aux = log2(length);
if (rem(aux,1)==0)
    m=aux;
    return
else
m=floor(aux+1);
return
end

```

### 6.1.3. Filtering the signal

As we said on chapter 3 we decided to do the filter digitally, after acquiring the signal. We made a FIR filter which we can easily tune up with matlab. The following code shows the function to generate our filter according to our parameters.

```

clear
rp = 3;                % Passband ripple
rs = 40;               % Stopband ripple
fs = 200000;           % Sampling frequency
f = [12000 13000];     % Cutoff frequencies
a = [1 0];             % Desired amplitudes
% Compute deviations
dev = [(10^(rp/20)-1)/(10^(rp/20)+1)  10^(-rs/20)];
[n,fo,ao,w] = firpmord(f,a,dev,fs);
b = firpm(n,fo,ao,w);
save ('filtro.mat')
%Filter response plot
freqz(b,1,1024,fs);
title('Lowpass Filter Designed to Specifications')

```

#### 6.1.4. Plot the filtered signal

Once we have the filtered saved, the next step is to load it into the matlab workspace, filter the signal, and plot both the time domain and frequency domain of the filtered signal.

```

%Load the filter
load ('filtro.mat')
%filter the signal
vfilt = fftfilt (b,v_zeros);
%time vector considering the sampling f
vtempfilt = ((1/freq):(1/freq):(1/freq)*length(vfilt));
%filtered signal fft
fft_filt=abs(fft(vfilt));
%time domain plot
plot(vtempfilt, vfilt)
ylabel('Amplitud V');
xlabel('Tiempo s');
title ('Señal filtrada');
%Frequency domain plot
plot (vfreq,fft_filt/length(muestras));
XLim ([0,freq/2])
xlabel('Frecuencia Hz');
ylabel('Potencia W');
title ('FFT de la señal filtrada');

```



## 6.2. Labview code

We used labview to configure the DAQ, capture the signal from our circuit and save the data into a txt computer file. The program we created to capture the signal needs to know the sampling frequency, and the number of desired samples. Then we hit “run” and the DAQ samples the signal and saves it into the computer.

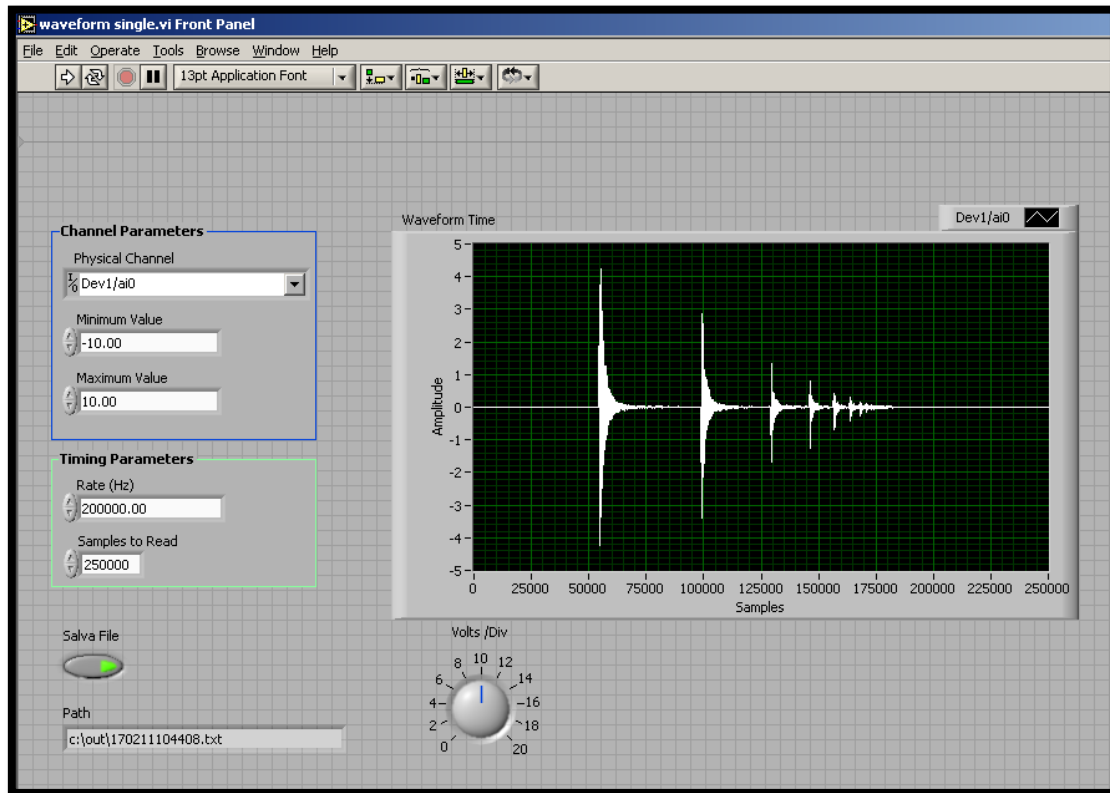


Fig. 6.1 Labview interface for our program.

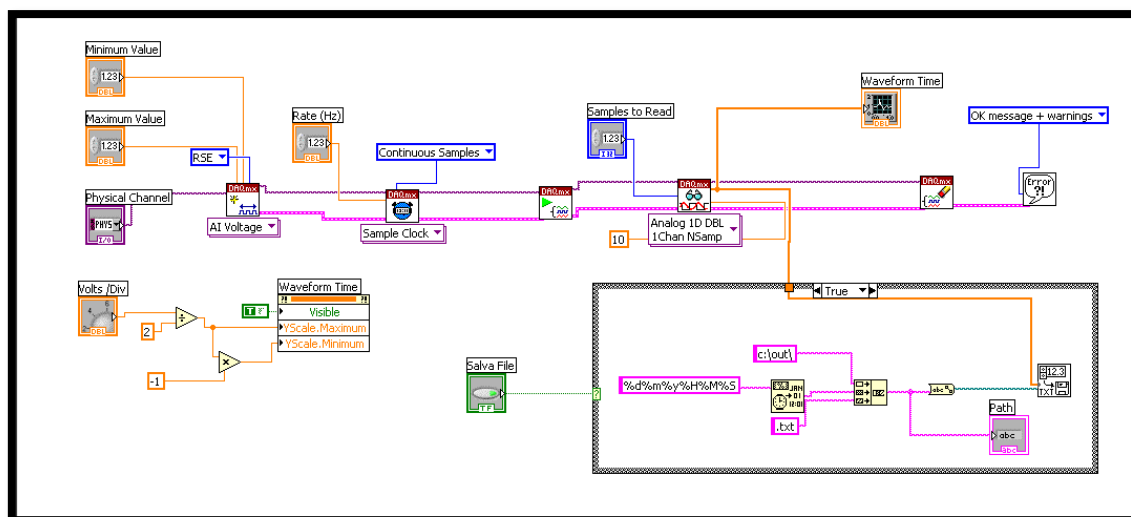
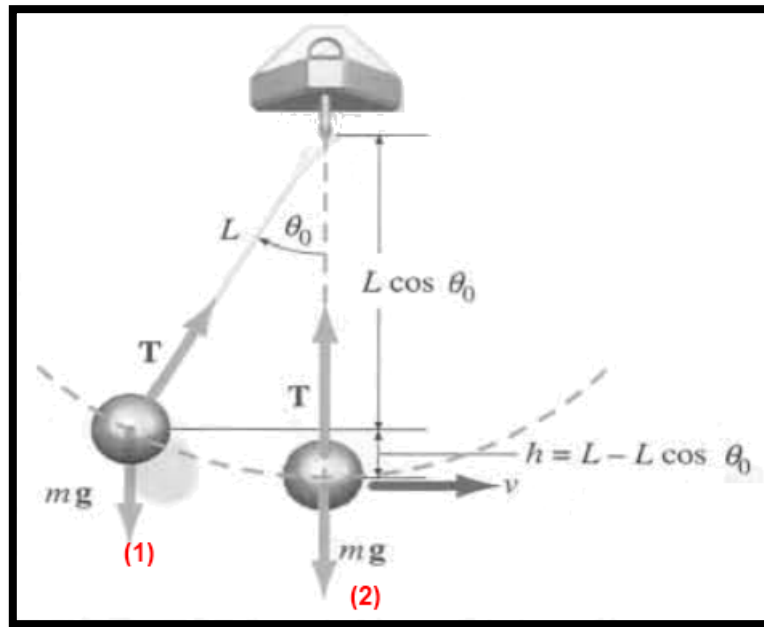


Fig. 6.2 Labview code of our program

### 6.3. The pendulum experiment calculations

On section 4.1 we said that knowing the height of the pendulum we obtained the angle, impact velocity, acceleration and impact force. Now we are going to explain the calculations to obtain those parameters.

On the following picture we can see a model for the pendulum system.



**Fig. 6.3** Pendulum system model

On (1) we have the pendulum elevated some high  $h$  and with a certain angle  $\theta_0$ . On (2) we have the pendulum totally vertically and in that position is where we put the mass with the piezoelectric sensor. Using the potential energy equation and the energy conservation we have:

$$\frac{1}{2}mv_f^2 = mgh \quad (6.1)$$

$$v_f = \sqrt{2gh} \quad (6.2)$$

To calculate the  $h$  we are going to do some trigonometry. We know the length of the pendulum rope,  $L$ , so the pendulum height at (1) is  $L \cdot \cos \theta_0$  and the height at two is  $L$ . So  $h$  would be the height difference:

$$h = L - (L \cdot \cos \theta_0) = L (1 - \cos \theta_0) \quad (6.3)$$

$$v_f = \sqrt{2gL (1 - \cos \theta_0)} \quad (6.4)$$

To calculate the impact force we apply the summation of the forces that act on the pendulum at (2).

$$\sum F = ma \quad (6.5)$$

$$T - mg = ma \quad (6.6)$$

$$T = m(a + g) \quad (6.7)$$

$$a = \frac{v_f^2}{L} = \frac{2gL(1 - \cos \theta_0)}{L} = 2g(1 - \cos \theta_0) \quad (6.8)$$

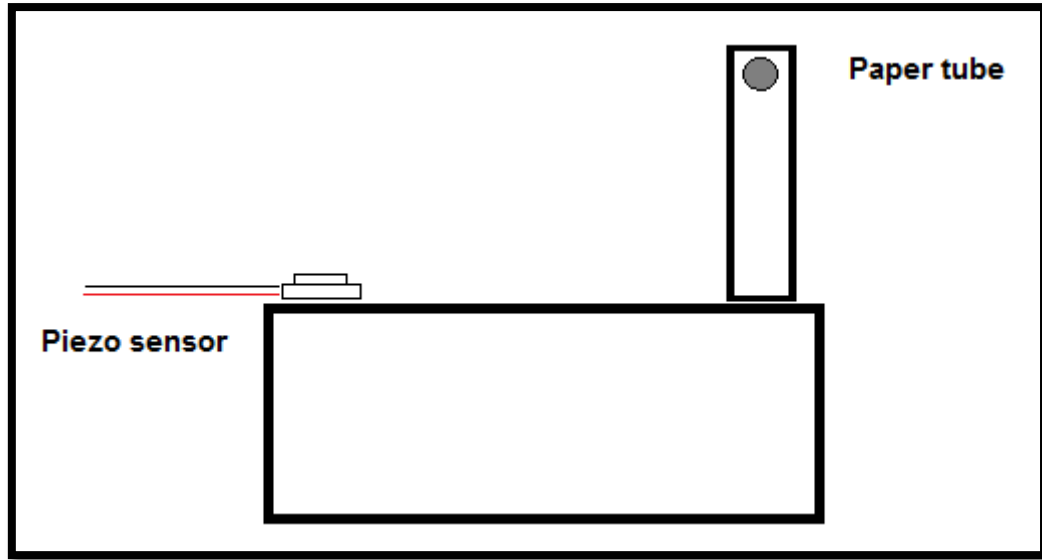
$$T = m[g + 2g(1 - \cos \theta_0)] = (3 - 2\cos \theta_0)mg \quad (6.9)$$

We can see that the mass of the impact body is not necessary to do the calculations as it always gets cancelled.

#### 6.4. The coin experiment calculations

The aim of this experiment is to view the impact of a coin from a determinate height. To do that we made a tube by folding a sheet of paper, that always has the same height, and then we let the coin fall down.

We know that a standard A4 sheet has 21cm width, so our system height would be 21cm.



**Fig. 6.4** Coin experiment diagram

In that case, using the same equations we used for the pendulum calculations, we obtain that:

$$\frac{1}{2}mv_f^2 = mgh \quad (6.10)$$

$$v_f = \sqrt{2gh} \quad (6.11)$$

Considering that we let the coin fall, the acceleration is just  $g$  so the impact force would be:

$$F = m \cdot g \quad (6.12)$$

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