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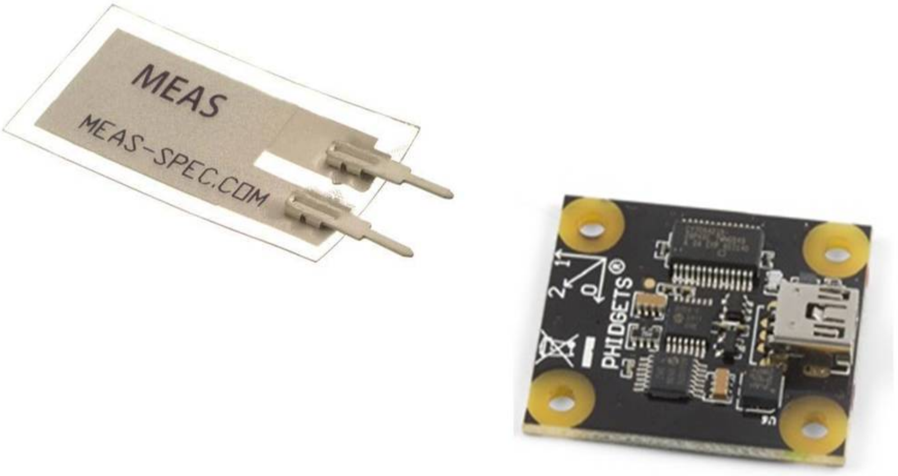

Low-Cost Vibration Sensors: Tendencies and Applications in Condition Monitoring of Machines and Structures

FÁBIO ROBERTO DE CARVALHO ALVES
(Licenciado em Engenharia Mecânica)

Trabalho Final de Mestrado para obtenção do grau de Mestre
em Engenharia Mecânica

Orientadores:
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Professor Doutor Rui Pedro Chedas Sampaio

Júri:
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Dezembro 2015

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Resumo

Atualmente em qualquer indústria, a manutenção assumiu uma grande importância para todas as empresas, e a manutenção preventiva tornou-se uma maneira muito eficaz de prevenir defeitos ou falhas que possam levar à perda de vidas humanas, perdas de dinheiro ou tempos de inatividade. Por isso, o controlo de condição tem vindo a assumir um papel preponderante nos planos de manutenção preventiva, e nos dias de hoje a forma mais utilizada de controlo de condição é a análise de vibrações (Guimarães, 2011). Tendo isso em mente, é importante perceber qual o impacto das escolhas das empresas em relação à tecnologia dos sensores que são usados. Como tal, o objetivo deste trabalho é a comparação teórica e experimental de sensores de vibrações *low-cost* com o sensor piezoelétrico, na sua aplicação no controlo de condição de máquinas e estruturas.

Este documento é o resultado do trabalho realizado ao longo desta dissertação de mestrado. O trabalho consiste no estudo teórico de conceitos relacionados com vibrações, controlo de condição, análise de vibrações, princípios e características dos sensores mais utilizados em análise de vibrações tal como conceitos relacionados com análise de vibrações que são importantes, como o condicionamento de sinal, aquisição de sinal e processamento de sinal.

Nesse documento também é apresentada toda a informação relacionada com os testes experimentais de três tipos diferentes de sensores de vibrações, incluindo o sensor piezoelétrico, a caracterização de cada análise efetuada, bem como os *softwares* utilizados para o processamento de dados, que neste caso foram LABVIEW®, PULSE® e Microsoft Excel®.

A principal conclusão deste trabalho é que os sensores MEMS são o futuro da análise de vibrações, pois são muito mais baratos e produzem resultados muito semelhantes ao sensor piezoelétrico e à sua versão *low-cost*, a lâmina piezoelétrica.

Palavras Chave

Acelerómetro; Vibração; Testes Experimentais; Controlo de Condição de Máquinas; Controlo de Condição de Estruturas.

Abstract

In today's industries, maintenance has assumed a great importance to all companies, and preventive maintenance has become a very effective way of preventing faults or failures that could lead to the loss of human lives, loss of money and inactivity times. Because of this, condition monitoring and structural health monitoring have been assuming an important role in preventive maintenance plans, and today the most used form of condition monitoring is vibration analysis (Guimarães, 2011). Having this in mind, it is important to understand what is the impact of the companies' choices regarding the technology of the sensors that are used. As such, the objective of this work is the theoretical and experimental comparison of low-cost vibration sensors with the piezoelectric sensor, in their application in condition monitoring and structural health monitoring.

This document is the result of the work done throughout this master thesis. The work consists in the theoretical study of concepts related to vibrations, condition monitoring, structural health monitoring, vibration analysis, the principles and characteristics of the most used sensors in vibration analysis, and concepts related to vibration analysis that are important, such as signal conditioning, signal acquisition and signal processing.

In this document it is also presented all the information related to the experimental analysis of three different kinds of vibration sensors, including the piezoelectric sensor, characterising every analysis made, as well as the software used for data processing, which in this case was LABVIEW®, PULSE® and Microsoft Excel®.

The main conclusion of this work is that MEMS based sensors are the future of vibration analysis, as they are much cheaper and produce very similar results to the piezoelectric sensor and its cheaper counterpart, the piezoelectric film.

Keywords

Accelerometer; Vibration; Experimental Tests; Condition Monitoring; Structural Health Monitoring.

Resumo Alargado

Nos dias de hoje a manutenção assume um papel importantíssimo em várias empresas, qualquer que seja a atividade em que está envolvida, e cada vez mais as empresas apostam na manutenção preventiva condicionada devido à sua eficácia na prevenção da falha que possa envolver perda de vidas humanas, custos ou tempos de inatividade. O controlo de condição assume, cada vez mais, um papel preponderante nos planos de manutenção definidos pelas empresas e, dentro do controlo de condição, a análise de vibrações é tecnologia mais utilizada (Guimarães, 2011). Assim, é importante perceber qual o impacto que as escolhas realizadas, ao nível da tecnologia dos sensores, têm nos resultados obtidos.

O objetivo principal deste trabalho foi a comparação teórica e experimental de sensores de vibrações de baixo custo com sensores piezoelétricos, no âmbito da sua aplicação no controlo de condição de máquinas e estruturas. O trabalho desenvolvido ao longo desta dissertação de mestrado englobou uma análise de vários conceitos relacionados com a definição de vibração, que pode ser definida como a movimentação de uma partícula em relação a uma posição de referência, analisando também as principais diferenças entre tipos de vibrações como a vibração periódica, que se repete ao longo do tempo, ou a vibração não periódica, vibração livre ou forçada, vibração linear ou não linear, vibração amortecida ou não amortecida, analisando também o conceito de frequência natural (que se pode definir como a característica das estruturas que indica a frequência à qual a estrutura irá vibrar em vibração livre, sem qualquer força externa a forçar a manutenção do movimento). Este trabalho também aborda o conceito de ressonância, que ocorre quando uma estrutura é forçada a vibrar a uma das suas frequências naturais por uma excitação externa. Ao mesmo tempo, este trabalho englobou uma análise de vários conceitos relacionados com manutenção (que segundo a NP EN 13306:2007 é o conjunto de ações realizadas durante o ciclo de vida de um equipamento de modo a que este se mantenha num estado em que possa realizar a ação desejada), focando o estudo dos conceitos de manutenção na área da manutenção preventiva e mais concretamente na manutenção baseada na condição (conjunto de tarefas e monitorizações de manutenção tendo em conta a condição do sistema) e no controlo de condição (monitorização da condição de máquinas ou estruturas). Neste documento encontram-se também alguns conceitos importantes e a ter em conta quando é realizada uma análise

de vibrações, tal como as ferramentas que são usadas em análise de vibrações, como a Fast Fourier Transform, um algoritmo matemático usado para facilitar a obtenção de espetros de frequência de determinada vibração (McLauchlan, 2006).

O trabalho envolveu também o estudo teórico comparativo dos principais tipos de transdutores (dispositivos que transformam um tipo de energia de entrada noutro tipo de energia de saída) incluindo os de baixo custo utilizados em análises de vibrações, caracterizando os mesmos, os conceitos envolvidos na sua construção, descrevendo com algum pormenor o seu princípio de funcionamento, o seu modo de atuação, as suas principais características e áreas de aplicação. O principal tipo de sensor utilizado para a análise de vibrações é o acelerómetro, e como tal, o levantamento dos principais tipos de sensores usados centrou-se nos vários tipos de acelerómetros. Dentro dos acelerómetros estudados encontram-se os acelerómetros piezoelétricos, que apesar não poderem ser considerados de baixo custo, são os mais utilizados em análises de vibrações e que são baseados na produção de tensão elétrica por parte de certos materiais quando estes são sujeitos a uma deformação (efeito piezoelétrico), os acelerómetros piezoresistivos, baseados num princípio semelhante aos piezoelétricos mas sendo que neste caso existem alterações na resistência dos materiais quando estes são sujeitos a deformações, os acelerómetros capacitivos, acelerómetros que se baseiam na diferença de capacitância (capacidade de armazenar energia) a que a estrutura do acelerómetro é sujeita quando é sujeita a aceleração, os acelerómetros de efeito de hall e magnetoresisitivos que são baseados no efeito de hall (alteração de corrente a atravessar um material condutor provocado pela alteração de campo magnético), os acelerómetros de transferência de calor (baseados no movimento de uma fonte de calor e deteção desse mesmo movimento), os sensores MEMS (Micro Electrical Mechanical Systems), cuja construção é baseada na tecnologia MEMS, ou seja, micro-fabricação de dimensões muito reduzidas e os filmes (ou lâminas) piezoelétricos ou piezoresistivos, sensores de baixo custo que aproveitam as capacidades piezoelétricas ou piezoresisitivas de determinados materiais. Foram também estudados os transdutores de deslocamento, que analisam a variação de posição, e os transdutores de velocidade, que analisam a variação de velocidade. Ao mesmo tempo, neste trabalho encontra-se a descrição e enumeração das principais características dos sensores que são importantes a ter em conta quando se realiza uma análise de vibrações, como a sensibilidade (a relação entre a entrada e a saída), gama de amplitude, gama de frequência, o ruído, linearidade, frequência de ressonância, o peso, a massa, o tipo de montagem e os eixos de medição.

Além do estudo relacionado acerca dos tipos de sensores mais usados em análise de vibrações, foi também realizada uma pesquisa sobre todas as ações que devem ser tidas em conta quando se realiza este tipo de análise, nomeadamente conceitos relacionados com condicionamento de sinal, ou seja, circuitos elétricos desenhados para realizar o tratamento de sinal vindo dos sensores (tratamento esse que pode estar relacionado com amplificação de sinal ou diminuição de ruído, entre outros), aquisição de sinal, ou seja, ações relacionadas com as condições de amostragem mas também com a transformação de sinal analógico para digital, e processamento de sinal, o tratamento dos dados adquiridos usando um programa computacional.

O trabalho descrito neste documento envolve também a análise experimental de três sensores usados em análises de vibrações, com o intuito de comparar esses sensores e perceber quais as diferenças não só nos resultados proporcionados pelos sensores, mas também as diferenças na sua utilização, montagem e nos cuidados a ter quando se utiliza cada um deles. Esta análise experimental envolveu todo um planeamento essencial para a correta realização dos ensaios. Apesar de não se poder considerar um sensor de baixo custo, os sensores piezoelétricos são aqueles que mais são usados em análise de vibrações, e por isso, neste trabalho foi analisado e ensaiado um sensor piezoelétrico, servindo como base de comparação para os restantes sensores de baixo custo analisados. Assim nestes ensaios estiveram envolvidos um sensor piezoelétrico modelo *Kistler* 8640A50, um sensor de construção MEMS modelo *Phidgets* 1041-PhidgetSpatial 0/0/3 Basic e uma lâmina piezoelétrica modelo *Measurement Specialties* LDT0-028K. Esta lâmina piezoelétrica, apesar de não ser produzida para análise de vibrações, pode ser usada para esse fim como alternativa de baixo custo a sensores piezoelétricos. Ao longo do documento encontra-se a descrição e explicação de todos os pormenores relacionados com os ensaios como a descrição das estruturas usadas para a análise de vibrações, a descrição e caracterização dos três sensores previamente mencionados, a montagem e planeamento dos quatro ensaios realizados, os materiais usados, os instrumentos criados e os usados, os aparelhos utilizados, a calibração dos sensores usados, mas também os *software* usados para o processamento do sinal emitido pelos sensores, neste caso um algoritmo realizado pelo autor do trabalho usando o *software* de programação por linguagem gráfica LABVIEW®, o *software* PULSE® da

Bruel & Kjaer e o Microsoft Excel®. Os quatro ensaios realizados consistiram num ensaio de sinal conhecido usando um shaker Bruel & Kjaer, onde vários sinais com várias frequências foram simulados e os espetros de frequências adquiridos foram depois juntos num só espetro com os resultados comparados entre si, um ensaio de sinal aleatório usando também o shaker Bruel & Kjaer forçando uma vibração numa viga de aço inoxidável usada de modo a que os níveis de ruído e a precisão fossem testados, uma análise de frequência (tentando descobrir as frequências de ressonância) de uma placa de aço galvanizado comparando os resultados obtidos e um ensaio de baixa frequência e baixa amplitude utilizando como estrutura um Pêndulo de Newton.

A principal conclusão deste trabalho é a de que, tal como na bibliografia consultada, os sensores MEMS são de facto uma opção bastante credível aos muito mais caros e muito mais difíceis de utilizar sensores piezoelétricos, proporcionando resultados semelhantes e que, sendo utilizados de forma correta, poderão constituir uma alternativa muito mais acessível em relação não só aos sensores piezoelétricos mas também às suas versões mais baratas e acessíveis, as lâminas piezoelétricas.

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Abbreviation List

AC – Alternating Current

BNC – Bayonet Neill–Concelman

DAQ – Data Acquisition System

DC – Direct Current

EFNMS – European Federation of National Maintenance Societies

FET – Field Effect Transistor

FFT – Fast Fourier Transform

FMEA – Failure Modes and Effects Analysis

GPS – Global Positioning System

IEPE – Integrated Electronic PiezoElectric

LAN – Local Area Network

LED – Light Emitting Diode

MEMS – Micro Electrical Mechanical Systems

OpAmp – Operational Amplifier

PLC – Programmable Logical Controller

PVDF – Polyvinylidene Fluoride

RMS – Root Mean Square

SHM – Structural Health Monitoring

USB – Universal Serial Bus

VRMS – Volt Root Mean Square

Symbol List

a – acceleration

A – amplitude of wave

C – capacitor

$Q(s)$ – charge Laplace Transform

c_c – critical damping

ω_n – damped natural frequency

c – damping

ξ – damping ratio

x_i – data of vibration

Δx – displacement

q – electric charge

$I(s)$ – electric current

ω_d – first damped natural frequency

F – force

f – frequency [Hz]

ω – frequency [rad/s]

$x(0)$ – initial point wave

V_{in} – input voltage of board

s – Laplace variable

m – mass

ω_n – natural frequency

N – number of points

τ – piezoelectric time constant

φ – phase

k_q – proportionality constant

R3 – resistance 3

R4 – resistance 4

R – resistor

k - stiffness

t – time

1. Introduction

Chapter one contains an introduction to both this document and the work made along the last academic year, including the motivation for this work, the main purpose of it, the context in which the work was performed and the structure of the document.

1.1 Motivation

As a major area of interest, and as an area that always creates a wide amount of questions, it was quite easy to select a theme based in maintenance, more specifically in vibration analysis. In a relatively new area dating back to only the 1970's (Fanning, 2004), it is always a challenge to immerse in a study that allows the analyser to obtain completely new information about systems and other parts, information that is not obtainable by simply looking at a part and recovering information as seen.

Nowadays, in any industrial company that works with any kind of machines or in companies that work with bigger structures, maintenance assumes an important role in everyday activities. Companies have dedicated staff to maintenance, with the responsibility of planning and performing different types of maintenance.

Condition monitoring, structural health monitoring and condition based maintenance are parts of preventive maintenance that are more and more used as a tool to reduce the loss of human lives, catastrophic faults and loss of active time. In most companies that have a preventive maintenance plan, condition monitoring is an important part of it because of its advantages, and vibration analysis is the most used form of condition monitoring in the world (Guimarães, 2011). This means that a correct vibration analysis integrated in the condition monitoring or structural health monitoring (SHM) program, coupled with a correct choice of instruments and tools, is indispensable for obtaining good results and making good choices maintenance-wise.

Due to the fact that many companies now choose to use vibration analysis, more and more new technologies are now being used in detriment of other technologies that had become established in previous decades. One example of this is the substitution of piezoelectric accelerometers for the new, more affordable and more compact MEMS (Micro Electrical Mechanical System) based accelerometers. This substitution changes the way that companies view maintenance and also changes the way of how is made the application of these techniques, for example in terms of measurements, periodicity of measurements, etc. With this, it is very important to understand the differences in the approaches, mostly in the kind of sensors used and the consequences of the choices made, in terms of tools utilized, have in the results and the conclusions taken from the vibration analysis.

Today, with the technological evolution, the study of vibrations in any kind of system is an important part of a monitoring program for every company in which this kind of approach is applicable. It is almost inconceivable, in modern times, that a monitoring program does not include any kind of vibration analysis, even if it is as simple as one sensor applied in the system. The simplicity of the instruments used today, and the accessibility of the parts involved in those systems is enormous, compared to the beginning of the employment of vibration analysis. Today, it is fairly easy to acquire all the tools required to have a complete vibration analysis, i.e., every company can buy the sensors, software and instrumentation necessary for a complete analysis, and obtain complete conclusions about the state of any system during the functioning period of it.

1.2 Objectives

The work done throughout this master thesis was done with the main purpose of analysing and characterising the most used sensors in vibration analysis, including the low-cost vibration sensors that exist in the market, demonstrating their properties, applications, advantages, disadvantages, the tendencies of the new technologies in vibration analysis and comparing them with the most used sensor in vibration analysis, the piezoelectric sensor.

The objectives of this work were obtained by doing an extensive study of the most common vibration sensors used, and characterising them, not only in terms of properties and characteristics but also in terms of all the actions that should be taken into account when using them (signal conditioning, signal processing, etc.). This study also involves an introduction to the vibration, a brief description of maintenance techniques and the application of vibration analysis in condition monitoring and SHM.

After the study of the most common vibration sensors, a practical application was studied, through four different experimental tests, using three different sensors. This allows a more complete understanding of how a vibration analysis is made, what is involved, the practical application of this study in the state analysis of a structure or machine, and the way that different sensors provide different results, and possibly, different conclusions.

It is important to remain clear that the goal of this work is a comparison between the sensors described and used, not a vibration analysis of a system itself. In the end, the reader should have a clear view of the operation of the sensors used, a clear idea of the applicability of each one of the sensors and the results acquired compared to other sensors.

1.3 Context

The work described in this document was made mostly in the Instituto Superior Técnico (IST) facilities, in the Laboratory of Vibrations, using structures provided by the IST, and using sensors, in which the comparing analysis was based, provided by the Instituto Superior de Engenharia de Lisboa (ISEL). The research made and described in this document was based in the IST and ISEL facilities, with the help of employees and others students, recognized in the acknowledgments section.

1.4 Document Structure

The present document is arranged as such:

Chapter 1: An introduction to the document as well the work done throughout the last academic year.

Chapter 2: A brief description of condition monitoring and SHM, the role of vibration analysis and its applications.

Chapter 3: A context of the most used vibration sensors, namely the low-cost ones, a description of their properties and the importance of the instrumentation used and its influence in the results.

Chapter 4: In this chapter, the experimental studies are presented and all the installations are described. The experimental results are also described in this chapter and interpreted.

Chapter 5: All the conclusions made are presented in this chapter, as well as the future works that can be made with this document as basis.

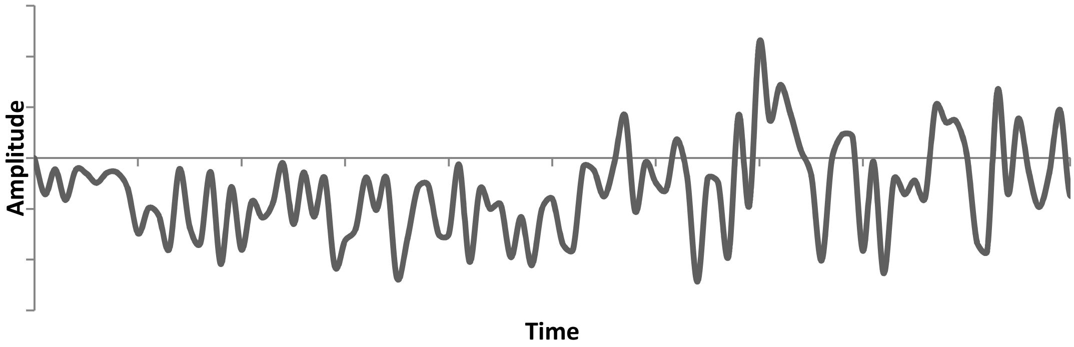
To complement all the information previously described and present in the document, at the end of it there are a few appendixes relevant to understand the work.

2. Vibration Condition Monitoring and Structural Health Monitoring

The understanding of vibrations and the usage of that knowledge is, in modern industries, a fundamental part of any maintenance program, being at the same time a fairly low investment that can bring important results. For that reason, companies are investing more and more in vibration analysis. In chapter two some important concepts are presented that are key points to understand the rest of the work.

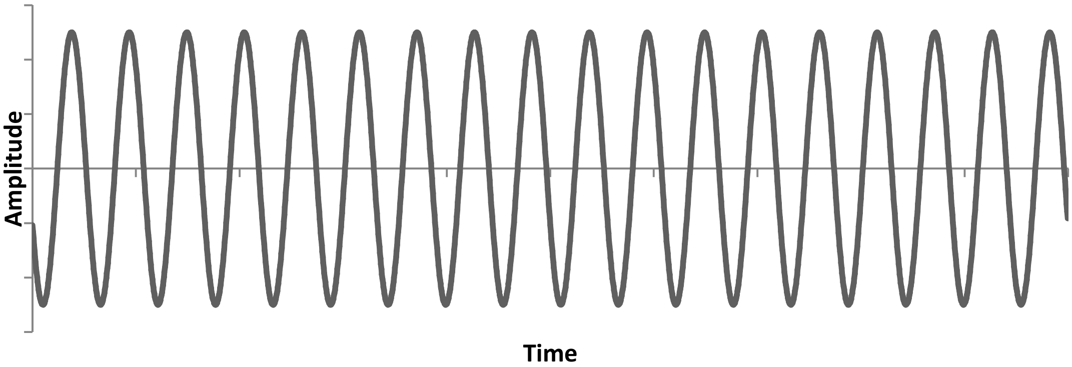
2.1 Important Concepts

To understand the full extent of vibration analysis it is important to have acquaintance with some concepts. A vibration is the movement of a certain point (or set of points) in relation to a reference axle or position, as it can be seen in Graphic 2.1, and that can be given in various units. In vibration analysis, it is usual that the vibration is given in units of acceleration, as it easier to conclude and to obtain information, but the measurement to use is adapted to the application (sometimes it is easier to use displacement or velocity). As such, the main unit of vibration is meters/second^2 (m/s^2) or gravities (other used unit is in/s^2).



Graphic 2.1 – Vibration

A vibration can be described according to its properties. For example, a certain vibration can be considered free or forced. A free vibration is a vibration without any external forces obliging the system to sustain the motion (after the system is set in motion by any kind of force). A forced vibration usually corresponds to the vibration of a system forced and sustained by an external force or moment. Also, a vibration can be damped, i.e., the system can have some sort of damper, or the vibration can be undamped (theoretical, as all systems have some sort of damper). Certain vibrations repeat their behaviour across the spectrum of time. This is called a periodic vibration, displayed in Graphic 2.2.



Graphic 2.2 – Periodic Vibration

In reality many vibrations encountered are not a simple periodic vibration, but rather a random vibration, i.e., a vibration that changes its behaviour in its time range. A vibration can also be linear, where the principle of superposition is applicable (for this principle to be applicable, all the different forces applied to a certain system have to be considered), i.e., when the sum of the system’s responses to each one of the forces applied (considering each excitation force separately) is equal to the system’s response to all the exciting forces together. If that does not happen, the principle of superposition is not applicable and because of that the vibration is not linear.

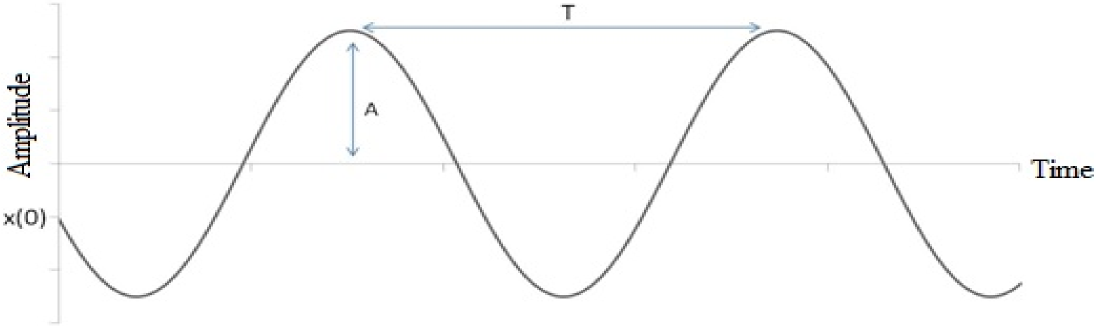
The simplest form of vibration that exists is the harmonic vibration. To describe a harmonic vibration, it requires the knowledge of a set of characteristics. The first characteristic is the frequency (f), i.e., the number of times that a vibration repeats itself in one unit of time. It is usually given in Hertz (Hz), meaning the number of times that the wave repeats itself in one second, but can also be given in radians per second (rad/s), by multiplying the value in Hz by two and π. Frequency can be calculated using the period (T) of the vibration, i.e., the time that a wave takes to start to repeat its behaviour. The inverse of the period (in seconds) is the frequency in Hz. It is also necessary to know the wave’s amplitude (A), i.e., the distance between the minimum and maximum point, divided by two. When a certain wave does not have the same amplitude throughout its time range, it is usual to analyse not the amplitude, but the Root Mean Square (RMS), a measurement that takes into account the differences in amplitude in which N is the number of points analysed, and x is each point of the wave. The RMS formulation can be seen in (2.1):

$$RMS = \sqrt{\sum_{i=0}^{N-1} \frac{{x_i}^2}{N}} \tag{2.1}$$

The last important characteristic that is fundamental to define a harmonic vibration is the phase, the initial point of the vibration, usually given in radians and calculated using (2.2):

$$\varphi = \pm cos^{-1}\left(\frac{x(0)}{A}\right) \tag{2.2}$$

The harmonic wave characteristics can be seen graphically in Graphic 2.3.



Graphic 2.3 – Characteristics harmonic wave

With this set of information, it is possible to describe the simplest vibration in existence, the harmonic vibration. All other forms of vibration are a sum of two or more harmonic vibrations. The harmonic vibration position is given by (2.3):

$$x(t) = A\cos\left(2\pi f t + \varphi\right) \tag{2.3}$$

The velocity and the acceleration of the vibration are obtained by deriving one time (velocity) and two times (acceleration) the expression for the position in order of time. The user chooses the units to use according to the application.

When analysing the vibration of a system, being it desirable or not, all the characteristics and concepts mentioned previously are important and applicable. But an important characteristic of a certain system is the natural frequency, frequency at which a system vibrates when in free vibration without any kind of external exciter maintaining the movement. This is a system's characteristic that depends on the material, more specifically the mass (m), stiffness (k) and damping ratio (ξ). Usually, the mass is measured in grams (g) or kilograms (kg) and the stiffness in Newton/meters

(N/m). The damping ratio (ξ), that is dimensionless and always larger than zero, depends on the system's damping constant (c) and critical damping (c_c), both usually given in Newton second/meter (N.s/m). The damping ratio is calculated using the relation in (2.4).

$$\xi = \frac{\text{damping (c)}}{\text{critical damping } (c_c)} \tag{2.4}$$

The critical damping of a system is calculated using the properties of it, as in (2.5) (McLauchlan, 2006).

$$\text{critical damping} = 2\sqrt{km} \tag{2.5}$$

A system with ξ smaller than one is an under damped system, a system with ξ larger than one is an over damped system and a system with ξ equal to one is a critically damped system (system returns to rest almost immediately).

The easiest way to understand the natural frequency concept is the analogy to a simple mass + spring system. This is called a one degree of freedom representation, as the mass is only allowed to move according to one axis. The system's total mass and the system's total stiffness is used to create this model. An example of this can be seen in Figure 2.1.

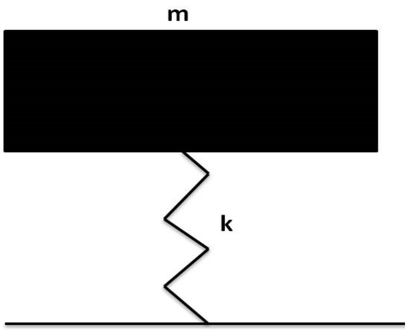


Figure 2.1 – Mass + Spring System

This model allows the calculation of the first natural frequency using the mass (m) and the stiffness (k). It is determined by the expression in (2.6) in units of radians per second.

$$\omega_n = \sqrt{\frac{k}{m}} \tag{2.6}$$

However, all systems have damping and therefore it should be accounted for when calculating the natural frequency, i.e., the calculation has to account the system's global damping. The example of a representation of a mass (m) + spring (k) + damper (c) system can be seen in Figure 2.2.

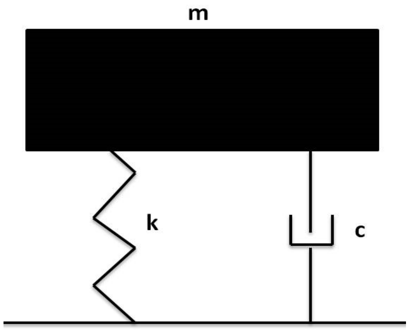


Figure 2.2 – Mass + Spring + Damper System

The first damped natural frequency, in radians per second, of a system converted into a one degree of freedom model is given by the expression in (2.7).

$$\omega_d = \sqrt{\frac{k}{m}}\sqrt{1-\xi^2} \tag{2.7}$$

Any system has more than one natural frequency meaning that the representation into a one degree of freedom model is not the most appropriate in a real situation. When the system is forced to vibrate at one of its natural frequencies, by an external exciting force, it tends to enter in resonance, i.e., it tends to vibrate at the maximum amplitude of movement possible by the system. This is undesirable, as this motion will damage the system and sometimes even destroy it. As such, it is fundamental to know all natural frequencies, or, if not all, the lower natural frequencies that are easier to be reached. In some cases, it is only necessary to know the lowest natural frequency, called fundamental frequency, because it is the easier to reach by external vibrations, as it requires fewer repetitions per second. Every natural frequency has its vibration mode, i.e., the way that the system will tend to vibrate and the aspect that it will display whilst vibrating at the natural frequency.

Undesirable vibrations can cause or indicate problems. Most of the problems are system related, i.e., unwanted vibration can indicate damage to the system itself that can have a lot of origins. One of the most problematic situations is fatigue (McLauchlan, 2006), a process in which the system will fail at a considerably lower stress than the static breaking strength, due to repeated cycles throughout a time span (Beer et al, 2012). This kind of failure usually starts with the development of small cracks into larger cracks appearing at an unstable rhythm, evolving into ruptures of the system and ultimately fatigue failure.

2.2 Condition Monitoring and Structural Health Monitoring

According to NP EN 13306:2007, maintenance is defined as the set of technical, administrative and management actions, during the life cycle of a certain equipment, destined to keep it or restore it to a state in which it performs the desired function. As such, several approaches and views of maintenance exist in industry, according to demands, as the Figure 2.3 shows. For this work, the important approach of maintenance is the preventive maintenance, that bases its principle in acting before a machine or structure fails, trying to avoiding faults.

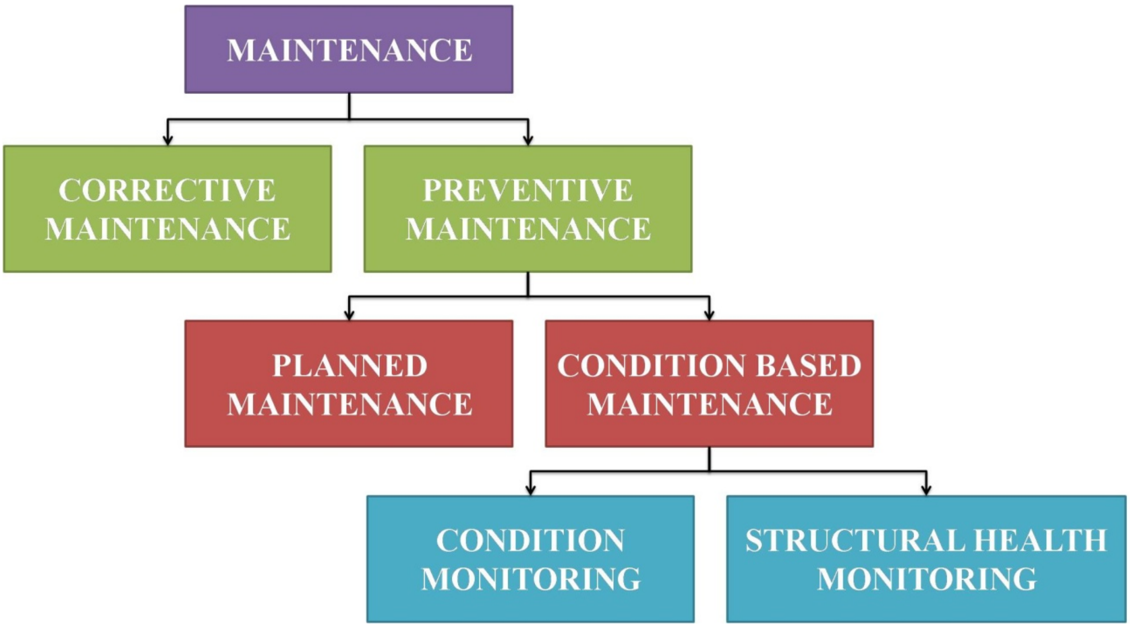


Figure 2.3 – Types of Maintenance

Despite many authors considering that condition monitoring, SHM and condition based maintenance are exactly the same activity(ies), the European Federation of National Maintenance Societies (EFNMS) distinguishes the concepts, considering that condition monitoring involves acts of inspection and condition based maintenance involves acts of maintenance and inspection including actions made to machinery such as repairs or substitutions (The European Federation of National Maintenance Societies, 1993). This difference is also present in the ISO Standard 17359:2011, where all the information needed for the implementation of a condition monitoring program and the implementation of actions designed to keep the system in a functional state are present (Mills, 2011). Condition monitoring and SHM are two maintenance approaches that are related, but are applied in different areas. Both consist in a series of non-destructive tests and analyses of the recovered data, comparing it to previous results or standards, in order to make predictions of remaining functioning time, planned repairs, status, etc, but applied to different areas. Condition monitoring is applied to machines, more noticeably to rotating machines and alternating machines, whilst SHM is applied to structures such as bridges, buildings, dams, etc. As such, one can conclude that condition monitoring and SHM are a tool of condition based maintenance and therefore preventive maintenance.

Despite the fact that in the last few decades' condition monitoring has become almost widespread, it has not been that way forever. In the industrial era's beginning, in the first few years of the 20th century, machines were very simple and had very few parts. This made repairing said machines much simpler and more practical, and for that reason companies had only two approaches. Or either repair a broken machine, or simply substitute it with a new one. With the industries' evolution came the evolution of the machines. That meant that repairing those machines took much more time and money, what lead to an effort by companies to understand the machines that they used, and try to understand everything about them, in order to prevent losing time repairing them and, with that, save much more money. Nowadays, companies view condition monitoring as paramount and try to implement that approach in every way they can. In the last three decades, condition monitoring and condition based maintenance have really developed and have been established as a vital part of various industries (Dunn, 2009). Modern companies have entire departments responsible for its design and implementation. Condition monitoring is also an important part of every company's goal of continuous improvement of manufacturing processes or functioning processes. There are several standards that define condition monitoring guidelines and strategies, and one of the most used in Europe is the ISO 17359:2011. This is used with the primary role of avoiding any situation that can put into danger human lives, as it is vital for every company to ensure the safety and well being of their working force. With this also comes the reduced occurrence of catastrophic faults (if planned and applied correctly), implying smaller costs and smaller amounts of time lost without fabricating or functioning. Condition monitoring is a process involved in the maintenance of entire machines, and it has an important economic side to it (Rao, 1996). It also encompasses various areas of expertise, and includes several analyses such as vibration measurement, infrared thermography, oil analysis and various other areas (Dunn, 2009).

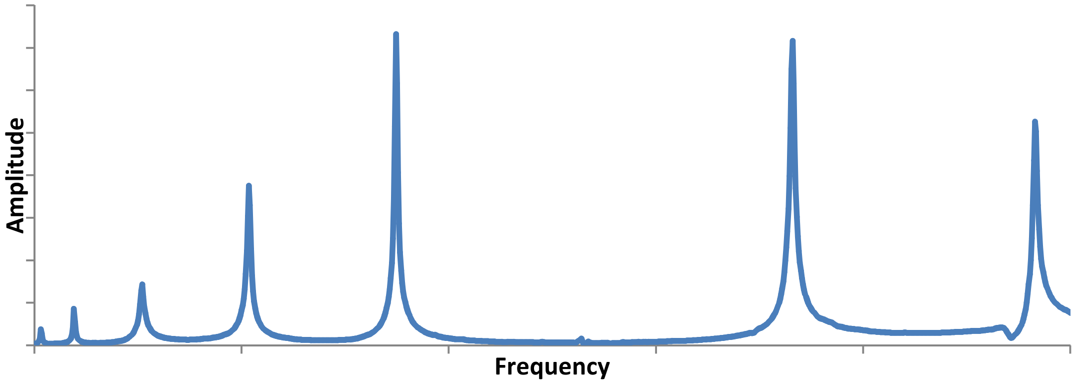
Structural health monitoring is a technique applied to larger structures and focuses the analyses in understanding the structure's status regarding problems like fatigue, resonance, connections, etc. The detection of problems in structures is more complicated than in machines because of the larger scale of the equipments in question, but also because of the fact that structures do not make any noise (many problems are detected by analysing the noise performed whilst in function). In many cases the structure's problem is located, but the problem's detection is complicated because the analyser has difficulties in selecting the exact position to evaluate and because of that, sometimes the problem goes undetected in the structure's global analysis (Haghighi, 2010). In this case, the analysis of the structure is focussed on the characteristics of it such has geometry, weight, etc. Forms of SHM applied to various structures, like bridges or dams, have always been applied but for example, in the 2000's, the development of new methods that can detect damages in bridges and can assess the stability of them has been pursued (Haghighi, 2010).

2.3 Condition Monitoring and Structural Health Monitoring - Vibration Analysis

Vibration analysis applied to SHM is ever growing, with the development of new techniques and new equipments, but is limited because of the difficulties caused by the larger scale of the structures in question. However, in today's industries, vibration condition monitoring is one the most used techniques of condition based maintenance applied to machines. Almost 80 % of the studies related to condition monitoring are vibration based (Mahmood, 2011). These studies are based on the knowledge that every structure or machine that is not balanced, is damaged, or is working outside of its intended parameters, will vibrate more than it should or in incorrect way. With this knowledge, it is possible to detect a system's malfunction. That usually implies a previous knowledge of the condition of said system. An organized condition monitoring or SHM plan has a schedule of tests, and the periodicity of those tests, as well as an historic of results.

Usually, vibration analysis is made in a time basis, i.e., usually the test results are given in a certain time range. As previously explained, the most problematic issue of a vibrating structure or machine is the fact that, when the exciting vibration has the same frequency as the system's natural frequency, it will enter resonance. As such, when doing a vibration analysis, one of the goals is to determine the frequencies present in the vibration, and determine if there is no problem in terms of resonance or if there is any change to the natural frequencies of the system, as this can indicate damage to the system (alteration of the characteristics of the system such as weight, rigidity or damping). In this way condition monitoring or SHM implies two phases. The detection phase, in which every company has its procedure and list of steps that should be followed, and the diagnosis phase in which the data will be analysed and conclusions will be made about the condition of the machine or structure. With the technological advances of today's age, most data obtained during the tests made is computerized and worked through software (commercial or company made) saving a lot of time and effort. It is usually this software that has the alarms and compares the data recovered to pre-established values. If any values are above the limits defined in the software or outside the intended parameters, the computer will send an alarm, either of risk or of complete shutdown. These limits are normally present in international standards.

Determining the natural frequencies is essential, in order to avoid exciting forces applied in the system that have the same frequency as one of the system's natural frequencies. To determine the frequencies present in a signal, whether it is a structure vibrating freely (meaning that the frequencies detected are the natural frequencies) or any other kind of vibration, many methods are used and for most of them it is necessary to do a transformation in order to obtain not a displacement, velocity or acceleration analysis, but a frequency analysis. This was impossible until the works of several researchers obtained new techniques. The most used technique is a algorithm called Fast Fourier Transform (FFT), which is based mostly on the works of Gauss in 1805 in his research of orbital measurements of asteroids (Anand, n.d; Worner, n.d.), but is also influenced by the works published in 1822 by Joseph Fourier (Worner, n.d.). In 1965, Cooley and Tukey invented the FFT algorithm that is used to this day (Worner, n.d.). Subjecting the data recovered to the FFT algorithm transforms the data into a frequency spectrum, seen in Graphic 2.4, in which the dominant frequencies of the signal are made visible and perceptible in the form of peaks in amplitude. The amplitude correspondent to the respective frequency corresponds to the amplitude of that specific harmonic dominant in the signal. The spectrum also contains spread spectrum content, located in the frequencies that are not dominant in the signal. There are numerous ways to visualize a frequency spectrum, with possibilities in units, frequency range, etc. Nowadays, any software dedicated to vibration analysis, and even other commercial software, allows the user to perform a FFT analysis of the input data. Doing this process at various moments of the system's functioning period allows, for example, the analyser to conclude if there are any changes to the natural frequencies, and therefore, any changes to the system's characteristics.



Graphic 2.4 – Frequency Spectrum

As it is a numerical algorithm, FFT has some problems in its implementation. One of the problems implementing FFT is aliasing, i.e., mistaking a higher frequency for a smaller frequency. This happens when the sampling frequency is smaller than the maximum frequency that the user wants to analyse. This problem has been solved by the works of Claude Shannon and Harry Nyquist, which proved that if the number of points read divided by the sampling period is superior to two times the signal's maximum frequency, aliasing no longer becomes an issue (Olshausen, 2000). Two times the maximum frequency is then called Nyquist frequency. Nowadays, it is customary to use not two times the maximum frequency, but 2.56 times the maximum frequency, to allow the roll-off associated with the filters used in signal acquisition (Agilent Technologies, 2002). The roll-off is a problem of filters that shows itself in the form of a transition region after the cut frequency in which the signal is still coming through, but has amplitude attenuated. Another problem of the implementation of FFT is the leakage that occurs when the sampling period does not end in a complete wave(s) cycle, demonstrating itself in the form of smaller amplitudes close to the dominant frequency's amplitude in the spectrum. To solve this problem, several types of windows are used, i.e., reductions of the time of analysis according to the situation in case (Lyon, 2009). The last major problem of FFT is the picket fence effect, occurring when the dominant frequency of the signal does not have correspondence in the frequency spectrum. When this happens, the dominant frequency will be represented in the closest frequency to the real dominant frequency. Increasing the sampling time helps reducing this.

Every vibration analysis has to be made in accordance with the characteristics of the structure or machine to be analysed, but it also has to take into account certain aspects that a correct analysis has to have, of which examples are given. For instance, a correct analysis of a system should involve measurements in different locations. In every location, sensors (or the same sensor at different times) should be positioned in three different orientations (x, y and z) in order to collect data from all directions. This is important as some issues are only detectable according to one or two directions (Yung, n.d.). In all systems there should be a special care in the sensor's positioning, as well as in the mounting of the sensor itself. There should be an anticipation of the points where the vibration will be most felt, and the analyser should place the sensors in those positions, trying to maximize the results obtained (Rao, 1996). For example, in rotating machines, the analysis should be made in the bearings.

One important aspect to consider when planning a vibration analysis is the sensor used. The sensor's resonant frequency should be much superior to the maximum frequency of interest (Rao, 1996). This guarantees that the sensor will not enter in resonance, and therefore it will not amplify the measured amplitudes. There should also be attention to certain parts that could be present in the system to analyse, as certain elements have a shorter life span than other components, and therefore the monitoring plan should have shorter maintenance intervals for them.

An experienced analyser can detect certain problems by looking at the system's vibration and/or hearing the noise that it makes whilst functioning. This is the usual approach on most cases, but not the correct one. According to the system being analysed, there are standard tables that relate the vibration, the type of vibration, the vibration's characteristics or even the noise emitted by a machine whilst functioning, and the possible cause of failure. This facilitates the analysis, as it provides a direct searching point after the data is collected. For example, for rotating machines, an undesired vibration with a frequency of one time the machine’s rotations per minute can indicate problems of unbalance, misalignment, looseness or electrical resonance caused by the motor (Rao, 1996). Some organizations have data interpretation standards that define certain parameters of functioning for specific functions. For example, ISO 16587:2004 defines performance parameters for condition monitoring of stationary structures in terms of mechanical vibration and shock.

3. Vibration Sensors

In chapter three several explanations, related to vibration sensors, as well as a study of the most common low-cost sensors utilized in vibration analysis applied to condition monitoring and SHM will be presented.

Vibration sensors are transducers, i.e., they transform a certain type of energy into a different type of energy, for purposes of data analysis or to facilitate the acquisition of a certain signal. As the sensors that have the best characteristics for vibration analysis perform acceleration measurements (Mathas, 2012), this is the unit most used for vibration analysis.

3.1 Data Acquisition and Processing Chain

Data (or signal) acquisition is the process of measuring any kind of physical or electrical phenomenon and recording it using a computer (National Instruments, n.d). Before the introduction of computers into the market, this data acquisition was made using specific storage systems or a programmable logical controller (PLC) (Serrano et al, n.d.). Even today, many companies use PLC's to perform these actions. However a signal acquisition and processing system is not only that. Nowadays, this system involves all the instruments used for data acquisition, as the sensors, the instruments used for signal conditioning and for signal acquisition, the computer (or PLC's) and even all the cables and wires that connect all those parts. This can be seen in Figure 3.1.

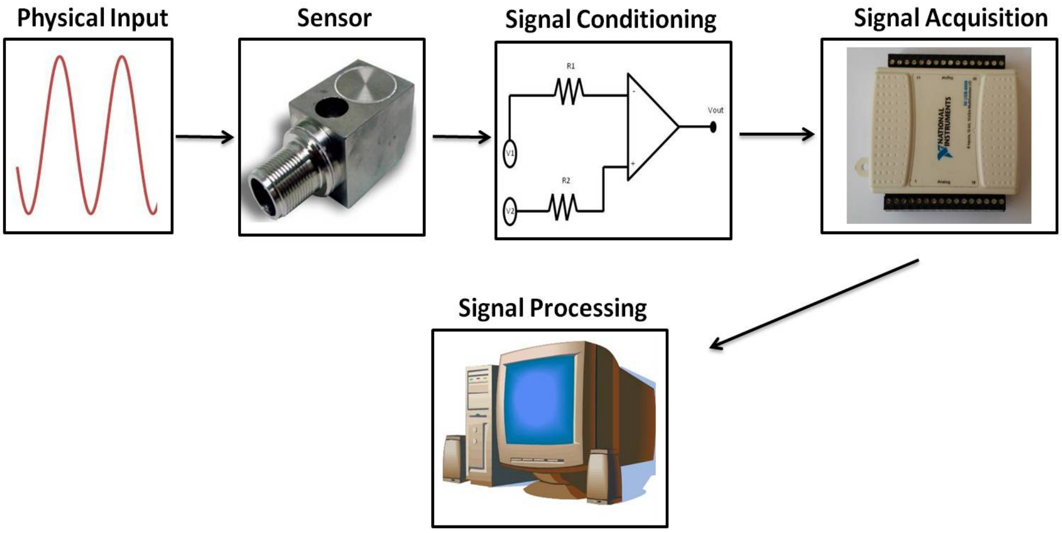


Figure 3.1 – Data Acquisition and Processing Chain

Sensors are used for the physical phenomenon's detection and to detect any changes on input magnitude, signal conditioning transforms the signal measured by the sensor in a similar signal to the one detected but with different characteristics, signal acquisition defines the sampling conditions and transforms the signal from analog to digital, the computer or PLC allows the signal's storage after conditioning and the software installed in the computer allows the analyser to view, save and interpret the values recorded in the whole process.

3.2 Main characteristics of Sensors

In order to select the most adequate sensor to a certain application, it is fundamental to have a clear view of the sensor's characteristics.

3.2.1 Power Source

There are two different kinds of sensors in terms of power source. There are active sensors, that require an outer power source in order to work, and there are passive sensors who do not need an external power source in order to work. This characteristic is related to the sensor's signal conditioning and not the sensor itself. If a sensor is active, the power source should be present in the signal conditioning

3.2.2 Sensitivity

Sensitivity refers to the relation between input and output, i.e., the output signal's modification with the input signal. In simpler terms, it is the electrical output's ratio in relation to the physical input. It is usually specified in units of output voltage per unit of displacement (Albarbar et al, 2008). In the case of accelerometers, it is the ability to provide a change in voltage or resistance when in the presence of acceleration. For example, if a sensor has a sensitivity of 50 mV/g and it is subjected to 1 g of acceleration, its output will be of 50 mV.

3.2.3 Amplitude Range

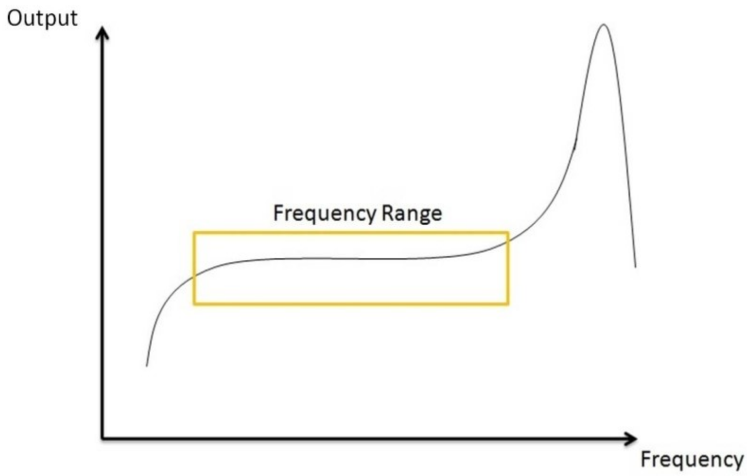
Range is usually the array of motion that a sensor can detect. In theory, a sensor can detect acceleration larger than its range, but it will start to distort the signal and the output will have added error (every sensor has internal error, even when it is new). In the case of accelerometers or other sensors used in vibration analysis, range is usually given in the same units as the ones the sensor captures.

3.2.4 Resonant Frequency

Like all systems, sensors have a resonant frequency meaning that at a certain frequency (or frequencies) determined by the sensor's characteristics (mass, rigidity, dampening), the sensor will enter in resonance, and the amplitude of movement will increase uncontrollably. This means that close to and at resonant frequency, any measurement made with the sensor will be invalid, because it is influenced by the behaviour of it. This is one of the most important characteristics to have into account when choosing a sensor for vibration analysis, as it is preferable that the sensor's resonant frequency is higher than the maximum frequency to measure.

3.2.5 Frequency Range

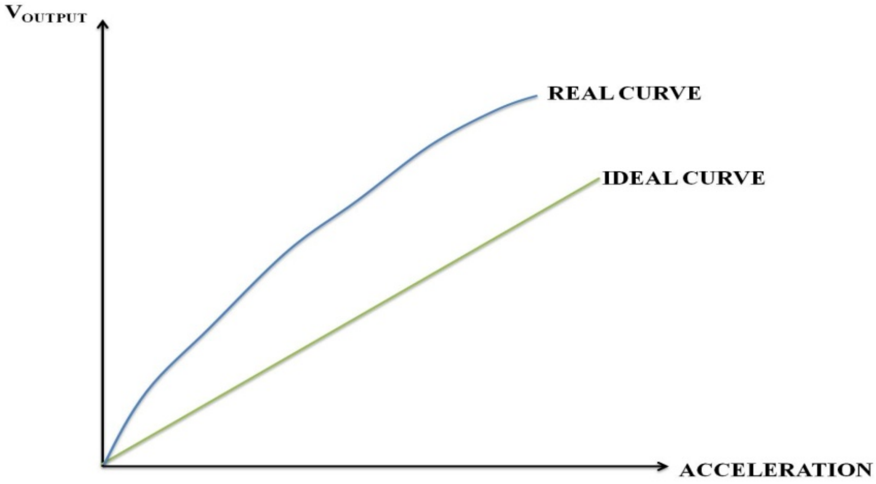
As the name suggests, this is the range of frequencies in which the sensor will detect motion, or in the case of most vibration sensors, acceleration. It is important to know that the frequency response of a certain sensor will be limited to its range (it will only capture frequencies inside of the frequency range). After a vibration analysis is complete, it does not mean that, for example, the dominant frequencies are limited to the ones recorded, but it means that, in the sensors range, those are the signal's dominant frequencies. This characteristic is easily demonstrated using graphic analysis, as present in Graphic 3.1.



Graphic 3.1 – Frequency Range

3.2.6 Linearity

Linearity is the characteristic related to the sensors's acuracy, i.e., the degree of acuracy that the sensor has in its frequency range. This means that the sensor's behaviour, when subjected to a linear input (acceleration) should produce a linear output (voltage or other electrical measurement), i.e., when excited through the frequency range with a linear input, the response should also be linear as shown in Graphic 3.2 (Albarbar et al, 2008).



Graphic 3.2 – Linearity

3.2.7 Noise

Noise is any change in the output signal's parameters derived from sudden changes, noticeable for example, in changes in amplitude or phase (Tuzlukov, 2002). This can generate the creation of false information in the signal, depending on the type of noise (Tuzlukov, 2002). Usually, as the signal's frequency increases, the noise will decrease (Huan, Jafaar and Yunus, n.d.), meaning that noise is usually encountered in the smaller frequencies. This means that it is crucial, for low frequency applications, to select a sensor with a small amount of noise. Noise is usually measured in μg/$\sqrt{Hz}$.

3.2.8 Axis

Most of today's vibration sensors have the ability to record acceleration in all three Cartesian axles. This is an important characteristic of the sensor, which gives the degrees of freedom in which a certain sensor can detect the system's acceleration.

3.2.9 Size

Size is a very important characteristic, as it should be suitable for the system in analysis. For example, a small sensor should be used in a small system in order to not influence the system's geometric format or when there is a small space available. In larger systems or in larger areas, larger sensors can be used without deficit.

3.2.10 Mass

As certain properties of the system depend on the mass of it, it is important to select a sensor that does not influence the mass of system, or at the minimum, does not impact the total weight.

3.2.11 Mounting

The sensor's positioning or mounting is also an important characteristic. There are sensors that have a mounting system pre-defined, whether through screws or studs, and there are others that have to be mounted using adhesives or even welded to the system. There are also sensors that do not need to be positioned in the system to measure, and in that case it is important to define a good positioning for the sensor in order to obtain accurate results.

3.2.12 Calibration

This is not a direct characteristic of a sensor, but it is an integral part of the sensor. To correctly measure a signal using any sensor, it is important to determine if the sensor is calibrated, i.e., if the response signal given by the sensor is correspondent to the input signal in the sensor. If this is not the case, a calibration is required. Calibration of a sensor is fundamental to any analysis and, when starting this analysis, it is essential to guarantee that the sensor is calibrated. The user should guarantee that the calibration was made using the correct methods and instruments.

3.3 Main Types of Vibration Sensors Used

The most used sensor for vibration detection is the accelerometer (Mathas, 2012) in various formats, but there are also several other sensors that use other measurements and that are used in vibration analysis.

3.3.1 Accelerometer

Accelerometers are transducers that transform an input into electric output, with the goal of calculating the acceleration that the accelerometer and the system in which the accelerometer is placed are subjected. They are used in a multitude of applications, but this work focuses on their use in vibration analysis.

Nowadays, there are accelerometers that can detect acceleration in the three coordinates of the Cartesian 3D referential (x, y and z), but there are also accelerometers destined to detect acceleration in one or two axis. Accelerometers usually display the output in g acceleration, i.e., if the vibration's magnitude is 2 g, it means that the system is subjected to two times 9.81 m/s^2.

All accelerometers are based in a mass-spring system. When the accelerometer (and the system in which the accelerometer is attached) is under some kind of movement that creates acceleration, the mass will move (Marsh, 2007). Knowing the spring's elasticity, the acceleration (a) in question and knowing the mass (m), or knowing the stiffness (k) and the displacement (Δx), it is possible to calculate the restoring force created by the spring and the acceleration, based on Newton's second law (3.1) (Policarpo et al, n.d.).

$$\mathrm{F} = \mathrm{ma} = \mathrm{k\Delta x} \; <=> \mathrm{a} = \frac{\mathrm{k\Delta x}}{\mathrm{m}} \tag{3.1}$$

One of the downsides of accelerometers is their resonant frequency. Every accelerometer has a resonant frequency, in which it will enter resonance. This is highly problematic and should be avoided. On the other hand, this kind of sensor is simple to work with and accessible to use, which makes it the most used sensor for vibration analysis, in its piezoelectric version (Rao, 1996).

Accelerometers are used in a variety of applications and industries such as moving vehicles, all kinds of plants or facilities with rotating machinery, aircrafts and structures (Judd, 2008). Of course, each one of the industries has its own characteristics, and for each, a certain kind of accelerometer is applicable. For vibration analysis, this sensor is used to determine if the system in analysis has acceleration in a/or several axes. If this is the case, it should be monitored to see if that movement (vibration) is under certain standards that do not harm the machine or part. When selecting the appropriate accelerometer for a certain application, there are a number of questions that should be answered, and by doing so, the user is doing the accelerometer's selection. The most important questions that should be answered are related to how precise should the accelerometer be, the acceleration's shape (prolonged acceleration or instantaneous acceleration), the range of frequencies that should be considered and the application of the accelerometer itself (Phidgets Inc, 2014). The user should also consider the budget that is available to perform the desired measurements, and any other aspect that is considered relevant to the choice. Choosing the accelerometer implies the selection from several types of accelerometers.

3.3.1.1 Piezoelectric Accelerometer

The piezoelectric accelerometer is based in the principle of piezoelectricity (piezo is the Greek word for pressure). This effect was discovered by the Curie Brothers in the 1880's, when during their research discovered that quartz, when subjected to a change in electric field, deformed (Measurement Specialties, 1999). After this, it was discovered that the same material, when subjected to a deformation in its shape, created a variation in voltage. Various researchers and companies started to use this principle and started various programs in order to encounter other materials that provided the same effect. Today, there are several natural piezoelectric materials that are used in several sensors, such as quartz, apatite, barium titanate and several ceramic and polymeric materials designed by the human being.

The piezoelectric accelerometer is usually constituted by a seismic mass, a piezoelectric material and a pin or stud connecting the two, as seen in Figure 3.2. When the accelerometer is subjected to acceleration, it provokes a movement in the seismic mass, which will provoke a change in the piezoelectric material's shape. With this, the change in voltage will occur, and the instrumentation of the accelerometer itself, combined with the installation's instrumentation, records that change in voltage, as little as it may be. This is based in Newton's second law, as the force exerted by the mass on the piezoelectric material whilst on acceleration will kick-start the deformation of the material. The way that the mass deforms can be enforced by a bending force, if the force is applied in both sides of the piezoelectric material, or by a compression force, if the force is applied on one of the sides of the piezoelectric material whilst the other side is completely fixed. There are two main types of piezoelectric accelerometers. There are compression type piezoelectric accelerometers that, as the name suggests, places the piezoelectric material in a position in which it will be compressed under acceleration, and shear mode piezoelectric accelerometers in which the piezoelectric material is located in a position in which it will be sheared when the sensor is placed under acceleration (Judd, 2008).

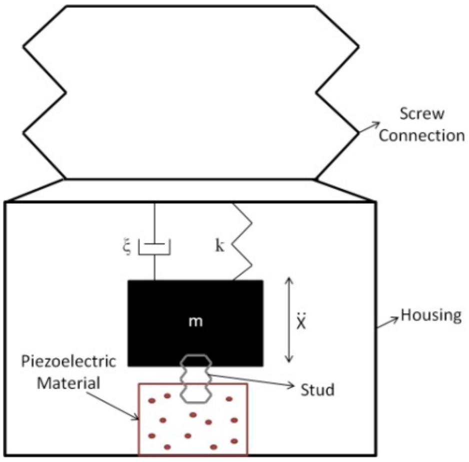


Figure 3.2 – Schematic Piezoelectric Sensor

The acceleration's calculation through the use of the piezoelectric effect is made using a series of formulations. The first formulation is the electric charge (q), that takes into account the proportionality constant (k_q) and the displacement (Δx), shown in (3.2) (Policarpo et al, n.d.).

$$q = k_q \Delta x \tag{3.2}$$

Using the analogy to a electric circuit, it can be considered that the piezoelectric material is a current source placed in parallel to a Resistor (R) and a Capacitor (C), also assuming that the electric current I(s) is the time derivative of charge. Using the charge Laplace transform Q(s), and using the Laplace variable s=ωj, where ω is the frequency and j=$\sqrt{-1}$, the Laplace transform of the output voltage $V_x(s)$ can be obtained using (3.3) (Policarpo et al, n.d.).

$$V_x(s) = \frac{RI(s)}{(RCs + 1)} = \frac{RsQ(s)}{(RCs + 1)} \tag{3.3}$$

Applying (3.3) into (3.2), it is possible to obtain the transfer function (designated by piezoelectric characteristic) that relates the output voltage $V_x(s)$ and the piezoelectric material's displacement $X_i(s)$, as shown in (3.4), where τ is the piezoelectric time constant (Policarpo et al, n.d.).

$$\frac{V_x(s)}{X_i(s)} = \frac{Rk_q s}{RCs + 1} = \frac{k_q s}{\tau s + 1} \tag{3.4}$$

It is possible to obtain the transfer function between the displacement $X_i(s)$ and the acceleration $\ddot{X}_i(s)$ of a system that follows Newton's second law, using the damping ratio (ξ) and the natural frequency (ω_d) (3.5) (Policarpo et al, n.d.).

$$\frac{X_i(s)}{\ddot{X}_i(s)} = \frac{1}{s^2 + 2\xi\omega_d s + \omega_d{}^2} \tag{3.5}$$

Finally, substituting (3.5) into (3.4), the acceleration $\ddot{X}_i(s)$ as a function of the output voltage $V_x(s)$ can be obtained as seen in (3.6) (Policarpo et al, n.d.).

$$\ddot{X}_i(s) = \left(\frac{(\tau s + 1)(s^2 + 2\xi\omega_d + \omega_d{}^2)}{k_q s}\right) V_x(s) \tag{3.6}$$

Piezoelectric material can be a natural resource, like quartz, which is the most used material in this kind of sensors, because it is a natural mineral and never loses piezoelectric properties (Meggit, 2009), it can be a ceramic material, or even a combination of both, so that some of the sensor's characteristics are multiplied in order to upgrade it. Sensors using quartz crystals provide higher temperature range but are also more expensive and provide low output sensitivity (Judd, 2008). Ceramic based accelerometers are cheaper, provide higher output sensitivity, but have a smaller temperature range and the disadvantage of losing piezoelectric properties with time and with higher temperatures of operation (Judd, 2008). This kind of accelerometer has a damping system connected to the seismic mass, to help create linearity in the application of the force from the mass to the piezoelectric material. This damping system can be a simple spring, or a spring-damper set.

Normally, this kind of accelerometer provides a wide frequency range, up to 20 thousand Hz in some cases (Walter, n.d.), as well as an ability to function on high temperature environments, related to the characteristics of the piezoelectric materials used, because at a certain temperature those materials will start to lose their characteristics (Judd, 2008). There are also various types of mounting systems between the piezoelectric accelerometer and the system to analyse. This mounting system depends on the characteristics of the accelerometer itself, as it is recommended that the mounting should not interfere with the measurement. Some examples of mounting types are the screw mounting, stud mounting or magnetic mounting (PCB Piezotronics, n.d.). Despite being the most used type of accelerometers for all kinds of applications, piezoelectric accelerometers can be quite expensive, being considered by many as a long term investment.

As most sensors used in modern days, some piezoelectric accelerometers already have integrated electronics, in the form of a pre-amplifier, with the ultimate goal of transforming a high impedance signal into a low impedance signal that can travel longer distances (Wagner & Burgemeister, 2012). These are known as IEPE (Integrated electronic PiezoElectric) accelerometers.

3.3.1.2 Piezoresistive Accelerometer

Piezoresistive accelerometers, despite the similarity in name, are different from piezoelectric accelerometers. In this case, piezoresistive accelerometers contain materials that, under a certain type of strain, provoke a change in electrical resistance. This piezoresistive effect was first discovered and documented by William Thompson, by then known as Lord Kelvin, based on his work with iron and copper. Lord Kelvin devised an experiment where he used two same length wires, one of copper and one of iron, and stretched them with a weight. Since they were exactly the same length, and the weight was the same, Kelvin used a modified Wheatstone bridge to measure the difference in resistance, and therefore conclude that each material had its own conductivity. Based on Lord Kelvin's works, and after many years of work, it was able to apply this principle into the usage of accelerometers and other sensors. The usage of semi-conductor materials for the same principle, as well as doped materials, is ever growing, with the development of more semi-conductor materials applicable to piezoresistive accelerometers (Barlian et al, 2009).

Nowadays, this kind of behaviour is used to construct various types of sensors and transducers (Dirjish, 2012). These devices are basically strain gauge accelerometers. When a certain system to which the device is connected is subjected to acceleration, the accelerometer's material will deform, provoking the change in resistance.

Most of the piezoresistive sensors come, in factory spec, with amplification devices and systems, as the difference of resistance is present, but almost unnoticeable. Nowadays, this kind of accelerometer is one of most used, mostly because of size, three axis sensing capability, availability (Barlian et al, 2009) and also because of the higher sensitivity created by modern piezoresistive accelerometers compared to older models of the same accelerometer (Bao, 2005). It is also one of most mass produced by the industry since the 1980's, as great strides have been made in the characteristics of this type of sensor, mostly in damping control (Bao, 2005) which allows this sensor to be used in high shock applications. Many of the piezoresistive accelerometers that exist today use the functionalities of MEMS construction (Jain, n.d.). An example of piezoresistive accelerometer can be seen in Figure 3.3.

Figure 3.3 – Piezoresistive Accelerometer (Meggit Sensing Systems, n.d.)

3.3.1.3 Capacitive Accelerometer

The principle of capacitors is also used as basis of accelerometers. The capacitive accelerometer is based on the concept of capacitance, i.e., the capability of a certain set of bodies to store electric energy, and the capacitor, i.e., a set of bodies designed to maintain a certain electrical charge. The amount of charge that capacitors can store is dependent on many characteristics, like the materials' properties, the distance between them, etc.

A capacitor accelerometer consists, in its simplest form, of a mass, to which movable plates are connected, and various fixed outer plates. The distance between the movable plates and the fixed ones is known, and is stable when the accelerometer is stopped, as seen in Figure 3.4.

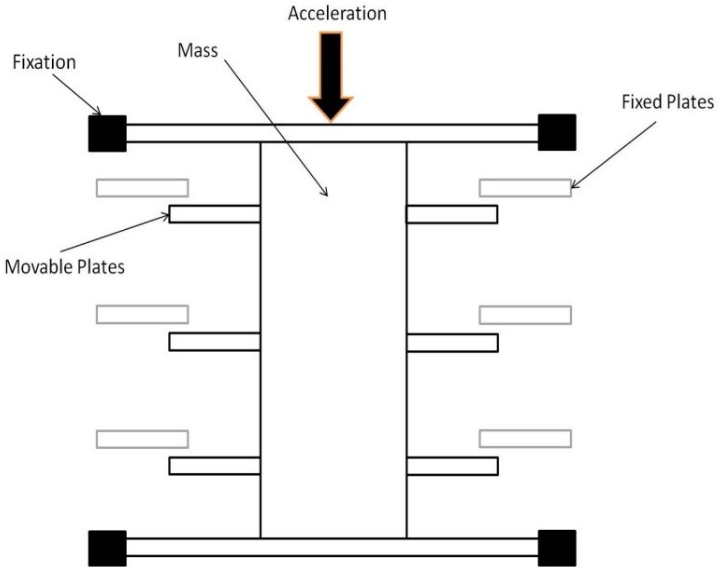


Figure 3.4 – Capacitive Accelerometer Principle

When the accelerometer is working, an input voltage is applied in the fixed plates. When the system is subjected to acceleration, the mass will move (small displacement), and the movable plates will also move. This will create a variation in charge stored in the capacitor, i.e., a change in capacitance, which will influence the sensor's output voltage. Because of its construction, this type of sensor is mostly applied in small movements (Andrejasic, 2008).

Nowadays, this kind of accelerometers is constructed using MEMS technology, allowing much more advantages and flexibilities, such as high resolution or low cost mass production. This presents as an advantage compared to older models (Bao, 2005). This kind of accelerometer, despite the advantages that provides in terms of MEMS construction, carries some problems from the non MEMS accelerometer. Capacitive accelerometers have usually a limited frequency range and limited amplitude range (Jain, n.d.).

3.3.1.4 Hall Effect and Magneto Resistive Accelerometer

Hall effect accelerometers are transducers based on the hall effect. This effect was discovered by Edwin Hall in 1879 (Popovic, 2003) and it can be described as a change in voltage caused by a magnetic field of a certain electrical conductor material crossed by an electrical current (Jain, n.d.). They are used to detect the presence of a magnetic field. The hall effect accelerometer consists in a plate of semiconductor material, connected to several electrical contacts. The plate is crossed by an electrical current and the change in magnetic field will cause a change in the sensor's output voltage (Popovic, 2003).

Hall effect accelerometers are basically formed by a hall effect sensor, which is used to detect the presence of the magnetic field, and a magnet (or magnets) connected to the seismic mass that will move under acceleration. This will create the difference in magnetic field, that will be detected by the hall effect sensor and then measured (Jain, n.d). This structure can be seen in Figure 3.5. Another format of this sensor consists in a coil supplied with an input voltage, and another coil parallel to the initial coil, creating a mechanism of electromagnetism, provoking the passage of electric current in the second coil. When the sensor is under acceleration, the coil supplied by the voltage will vibrate, and therefore the relative position between coils will change, creating a difference in the electromagnetic effect between the coils and a difference in the current present in the second coil. This difference is then processed and converted into acceleration (Huan, Jafaar and Yunus, n.d.).

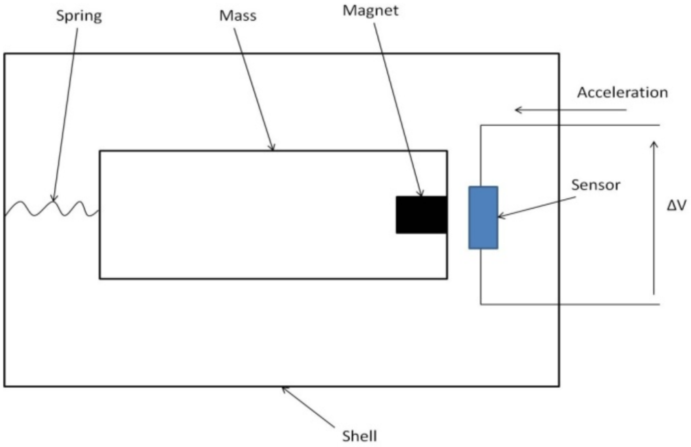


Figure 3.5 – Typical Hall Effect Accelerometer Principle

Magneto resistive transducers are based on the same principle of hall effect accelerometers (Jain, n.d.) and also have the same structure. However, the variable in measurement in this case is the change in resistance of a certain electrical conductor material, similar to the change created in piezoresistive sensors, but in this case caused by a change in magnetic field (Popovic, 2003).

This kind of accelerometers is mostly used for position detection, as the sensor's structure is most applicable to that purpose. Hall effect sensors have the advantage of not being affected by the surrounding conditions; they also have no contact with moving parts, guaranteeing reliability. However, high temperature creates damage to the sensor's elements, posing a threat to the reliability of it, and the presence of external magnetic fields interfere with the results acquired by the sensor (AZO Sensors, 2012). The main problem of magneto resistive accelerometers is the change in the wiring material's resistance provoked by high temperatures, making it unusable for high temperature environments.

3.3.1.5 Heat Transfer Accelerometer

Not very used for vibration analysis, but used in selected applications, is the heat transfer accelerometer. It is based on the change of temperature in a thermistor (or thermo resistor), and the heat gradient caused by that temperature change. The rules of thermodynamics state that when a system is in equilibrium, the heat flow between the system's components is constant (Huan, Jafaar and Yunus, n.d.). However, when there is a change in the state of equilibrium, the heat flow will experience changes. When a thermistor is under a certain change in temperature, it will experience a change in electrical resistance (U.S.Sensor Corp, n.d.). It is this change in resistance that will be measured and converted into the form of acceleration (in the case of accelerometers). The structure of heat transfer accelerometers consists of a heat source centred in the accelerometer (substrate) and suspended in a cavity. When the accelerometer is subjected to acceleration, the heat source will move in relation to the different thermistors located in the corners of the accelerometers approximating the heat source to specified thermistors, and, at the same time, the heat source will be more distant to the rest of the thermistors. This causes the heat gradient and the change in thermistors's resistance that will be measured and converted to acceleration (Jain, n.d.). This behaviour is shown in Figure 3.6.

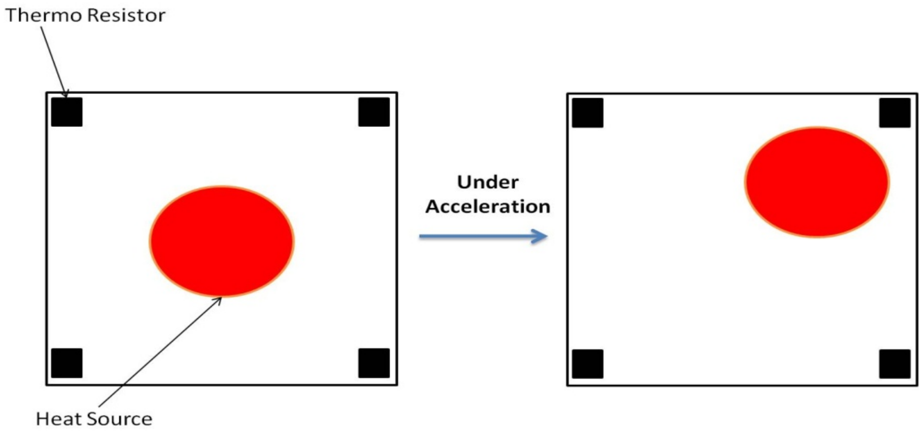


Figure 3.6 – Heat Transfer Accelerometer Principle

The principal application of this kind of sensor is meteorology, but certain companies use this sensor to measure accelerations changes. In modern times, heat transfer accelerometers are not very used when compared to other types of accelerometers, despite the fact that some MEMS accelerometers use this same behaviour but in a very smaller scale. This sensor requires the movement to be planar, i.e., if for example the movement is upwards or downwards, the heat source will not move in relation to the thermistors. This will provoke no change to the output signal, despite the existence of movement.

3.3.1.6 MEMS Accelerometer

MEMS accelerometers are considered by many as the future of vibration analysis, and are by far the more popular and cheapest form of low-cost sensors (Judd, 2008). From aerospace industry, to automotive and even to computer and smartphones construction (Haritos, 2009), MEMS accelerometers are integral parts of the products that these industries construct such as airbag control, mobile phone orientation, GPS (Global Positioning System) orientation, camera stabilization, various systems of aircraft flight control, and many others (Serrano, 2013). MEMS technology was first utilized by a Stanford University research program in 1979, but only in the early 1990’s, all the faculties and advantages of MEMS surpassed the majority of problems encountered during their functioning time (Andrejasic, 2008). The development of MEMS technologies came from the necessity of creating smaller structures in order to simplify all the systems in which sensors are applied.

MEMS is a technology that combines micro-elements (mechanical and electrical), made utilizing methods of micro-fabrication. All the elements constructed by micro-fabrication are very small, with sizes in the micrometer scale, which allows for mounting in very small spaces and in very small systems, and provides a saving in material usage for construction, even if the construction method is more complicated and expensive. Many of the MEMS structures are not solid, i.e., they have all kinds of cavities, which makes them very light (Andrejasic, 2008). MEMS accelerometers have the potential of capturing acceleration changes in all three Cartesian axles (x, y and z). One of the advantages of MEMS based accelerometers is the small size and weight, allowing them to be applied in a multitude of applications.

There are two main types of construction of MEMS accelerometers (Bao, 2005). Bulk micromachining, which consists in the removal of material from a bulk substrate to form the desired sensor (Andrejasic, 2008), and surface micromachining, consisting in the deposition of thin layers of film in a certain order, until the final product is achieved (Andrejasic, 2008). Surface micromachining tends to create smaller sensors, and creates the possibility of integration with electronic systems of signal conditioning (Bao, 2005).

MEMS accelerometers use as basis some of the technologies that are used in other kinds of accelerometers. For example, the most common MEMS accelerometer, as well as the simplest, is the capacitive MEMS accelerometer (Andrejasic, 2008). It consists of a cantilever beam with a seismic mass surrounded by a capacitor in the form of movable plates and a fixed outer frame. Modern MEMS accelerometers use, not a spring-damper system, but a residual gas in order to dampen the seismic mass's movement. When the accelerometer is subjected to acceleration, the seismic mass will move, and the movable plates fixed to the mass will also move. This causes a variation in the free air between the movable plates and the fixed ones, which will cause a difference in capacitance that will be used to calculate the mass's movement and to calculate the acceleration to which the system is subjected. The principle of functioning is the same as the capacitive accelerometer, but in a very smaller scale. However, other technologies are used to create MEMS accelerometers, namely the piezoelectric or piezoresistive properties of certain materials. An example of MEMS based accelerometer is shown in Figure 3.7.

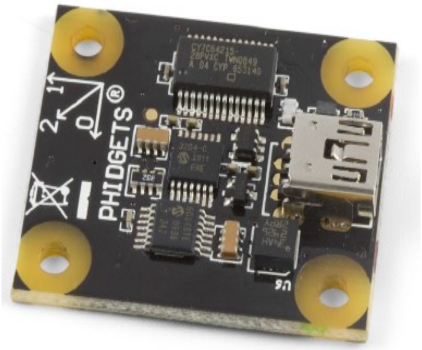


Figure 3.7 – MEMS Accelerometer (Phidgets, 2010)

Most MEMS accelerometers only require a connection to a computer as they have integrated signal conditioning circuits and signal acquisition devices, making them easy to use. In terms of characteristics, Phidgets, one of the most prolific vendors of low cost MEMS accelerometers, provides a range of sensors that measure up to 500 Hz, accelerations of up to 8 g's and very small resolutions (Phidgets Inc, n.d.), guaranteeing a good behaviour to smaller frequencies. Therefore, this type of accelerometer, in its low-cost variety, is not recommended to high frequency applications. The general characteristics of MEMS accelerometers depend mostly on the technology used for its construction. Piezoelectric MEMS accelerometers provide a wide frequency range, wide temperature range, wide amplitude range and are very small in size, providing also very strong resistance (Walter, n.d.). Piezoresistive MEMS accelerometers also provide a wide amplitude range, but are more directed to severe mechanical shocks, what makes them most used in the automotive industry and defence industry, being constructed in large quantities. However, they have a limited temperature range, being highly affected by environments where the temperature is outside of the accelerometer's temperature range (Walter, n.d.). Capacitive MEMS accelerometers usually have a limited amplitude range (comparing to piezoelectric technology) but provide a good operating temperature range and are usually used for the transportation industry (automotive mostly) and aircraft construction (Walter, n.d.). Despite many of the advantages that are announced by the manufacturers, conventional accelerometers such as the piezoelectric accelerometer are still preferred over MEMS accelerometers. Because of this, many resources have been placed in the research and publication regarding the properties of MEMS sensors in the area of vibration detection (Policarpo et al, n.d.).

This kind of system provides many advantages, but also many problems, natural to a technology that is only about 20 years old in commercial application and 40 years old since its invention. Nowadays, the introduction of techniques like FMEA (Failure Modes and Effects Analysis) and other maintenance tactics, as well as a large investment in understanding the properties of the materials involved, has lead to a monumental improvement in reliability of MEMS (Tanner, 2009). One of the major breakthroughs in the last few years is the integration of more recent technologies, such as wireless, in the circuit's of MEMS sensors, providing even more functionalities to the usage of MEMS sensors and accelerometers (Walter, n.d.).

3.3.2 Displacement Transducers

Displacement transducers are used to detect modifications in the position of systems or parts, but can also be used to detect differences in position from one part to the other (such as internal clearances). This allows, for example, the detection of the vibration motion of a shaft rotating inside a bearing. If the shaft has a periodic (or non periodic) movement of approach and go away from the bearing, it can indicate that the shaft is not working properly. This sensor is used for very small displacements, as well as very low frequencies, because the sensor's principle is not indicated for vibration detection (Cole-Parmer, 2006). Nowadays, displacement transducers (or Proximity Probes) are based in changes in magnetic field of the sensor, caused by the change in the position of the part. They are used in a relatively small range of frequencies, usually in pairs and require extra care in the condition of magnetization of the system to analyse (Azima DLI, 2009).

One issue with this sensor is the fact that it detects total movement (Cole-Parmer, 2006), i.e., if a shaft moves five millimetres upwards and six millimetres downwards, the sensor will detect a movement of 11 millimetres. This sensor has almost no wear, meaning that there is continuity in behaviour during the sensor's life span. However, it is complex to install, provides all kinds of noise and requires an external power supply (Huan, Jafaar and Yunus, n.d.). An example of a displacement transducer can be seen in Figure 3.8.

Figure 3.8 – Displacement Transducer Inductive Type (Pruftechnik, n.d.)

3.3.3 Velocity Transducers

Velocity transducers, either inductive, piezoelectric or in any other form, are used for low and medium frequencies as they do not have a large frequency range (Azima DLI, 2009). In this case, the measured variable is the velocity at which a certain system is moving. With this measurement it is possible to capture any change in velocity of a certain system. Like accelerometers, they can be utilized in vibration analysis, but with the development of accelerometers, and especially MEMS accelerometers, the application of velocity transducers to vibrations as become mostly obsolete. Other reasons to the decay of velocity transducers applied to vibration analysis are the sensor's weight, the complexity of it, the price (Azima DLI, 2009) and the fact that, compared to accelerometers, velocity transducers have lower sensitivity to higher frequencies (Cole-Parmer, 2006). Some companies use a type of velocity sensor, mostly based on the piezoelectric effect, for vibration analysis. The components of it are similar to the piezoelectric accelerometer, but before the output signal, an integrator is responsible for the conversion from acceleration into velocity. The whole sensor is called velometer, used because it has the advantages of the accelerometer, without the disadvantages of the velocity sensor (Azima DLI, 2009).

Velocity sensors are used because they allow for an easy installation, have good response in the middle of the frequency range and the fact that they do not need external power supply. However, the fact that they have a low natural frequency, which means that it can easily enter resonance, their high cross axis sensitivity (the sensitivity in the remaining axis that are not being used for measurements) and the fact that they need the use of an external signal conditioning circuit make them not the easiest of sensors to use in vibration analysis (Huan, Jafaar and Yunus, n.d.).

3.3.4 Cantilever Type Film

Also used for vibration detection are cantilever type films. They consist in a thin strip of film, made from some sort of piezoelectric or piezoresistive material connected to an output union that delivers the signal, according to the principle of this kind of material (Kon et al, 2007). Basically it is a piezoelectric material of some sort coated with electrically conductive material, meaning that it has the piezoelectric material's characteristics, such as the linearity and material's durability, but not the characteristics of the sensor, such as the robustness, making it more susceptible to perturbations. As such, they are also known as piezoelectric or piezoresistive film. Also, the characteristics of this sensor make it more susceptible to low resonance frequencies, as the sensor itself is very light and has low rigidity, meaning that it has a small frequency range. This is a sensor that can be used for many applications, such as washing machines, automobiles and body movement detection (Digi-Key Corporation, n.d.) but one of the most used applications is as a vibration sensor ("LDT0 Solid State Switch/Vibration Sensor- Application Note 111398", n.d.). As this sensor is based on the piezoelectric or piezoresistive properties of certain materials, the principles involved are the same as the ones described in Chapters 3.3.1.1 and 3.3.1.2, but in this case, in order for it to work, the sensor should be positioned as an integral part of the system, whether through some kind of adhesive or weld. In Figure 3.9 a piezoelectric film can be seen.

Figure 3.9 – Piezoelectric Film (Digi-Key Corporation, n.d.)

Opposite to other vibration sensors used, this kind of sensor does not have integrated equipment ready to use destined to the signal conditioning of the sensor's output signal. The user has to build its own signal conditioning and acquisition equipment or buy an existing signal conditioning and acquisition equipment, creating an additional source of costs. Together with the MEMS based accelerometers, they are the most common forms of low-cost vibration sensors used.

3.4 Signal Conditioning

Every sensor, as technologically advanced as it can be, has inherent problems. Situations like noise, small output signal or other problems require a solution by the user. For that, it is usual to utilize other electronic instruments, together with the sensor itself, to create the best output signal possible. When there is a output signal modification, through the use of instrumentation, it is called signal conditioning and it consists in the conditioning of the signal given by a certain sensor (or any other device), in order to obtain the most accurate measurement. Nowadays, many sensors have those electronic devices integrated to the sensor itself, thus creating a sensor with the instrumentation bundled. Many actions can be taken when a signal conditioning process is being considered ("Vibration Sensors", n.d.):

- Signal Amplification, which consists in the output signal's amplification (many sensors produce a very small signal as a response to input).
- Signal Attenuation, the contrary of signal amplification.
- Isolation, i.e., transporting the signal from the sensor to the analyser with the existence of a real connection between them.

- Excitation, required in certain sensors that measure differences of a variable that is not measurable (like changes in resistance).
- Grounding, that consists in properly grounding the system to avoid any undesirable vibration of the system ("Vibration Sensors", n.d.).
- Current transformation, because it can happen that a sensor works in alternated or direct current and other instruments work in a different kind of current.
- Filtering, the action of restricting the passage of certain frequencies of a signal (McLauchlan, 2006).

In vibration analysis there are four major types of filters, used whether in the signal conditioning or even in the signal processing software:

- Highpass Filter: attenuates the signal amplitude with frequency lower than the cut frequency defined and does not act on the signal with frequency higher than the cut frequency, as shown in Figure 3.10.

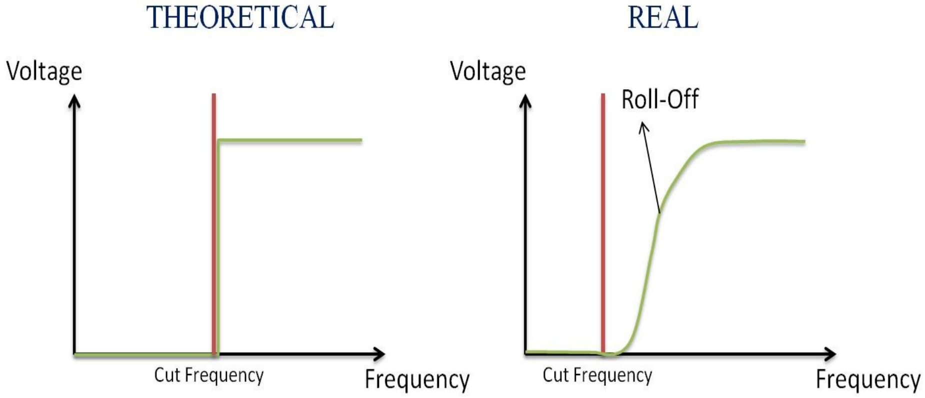


Figure 3.10 – Theoretical vs Real HighPass Filter

- Lowpass filter: attenuates the signal amplitude with higher frequency than the cut frequency defined and does not act on the signal with frequency lower than the cut frequency, as shown in Figure 3.11.

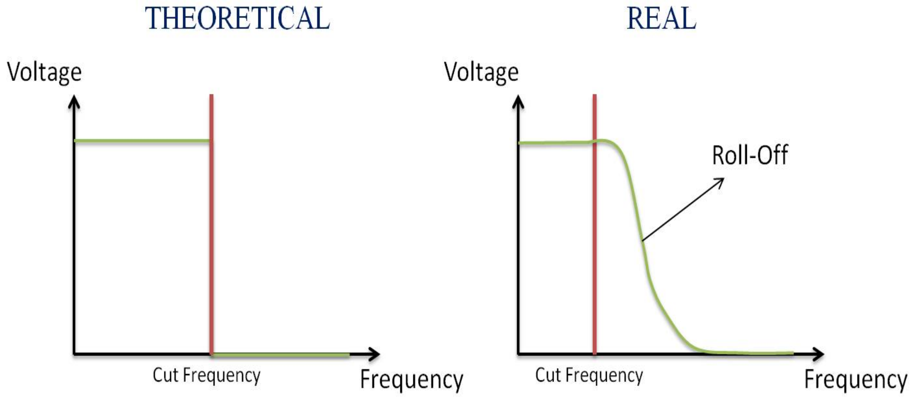


Figure 3.11 – Theoretical vs Real LowPass Filter

- Bandpass filter: attenuates the signal amplitude with frequency outside of the band defined by the cut frequencies, not acting on the signal with frequency inside of the band defined by the cut frequencies, as shown in Figure 3.12.

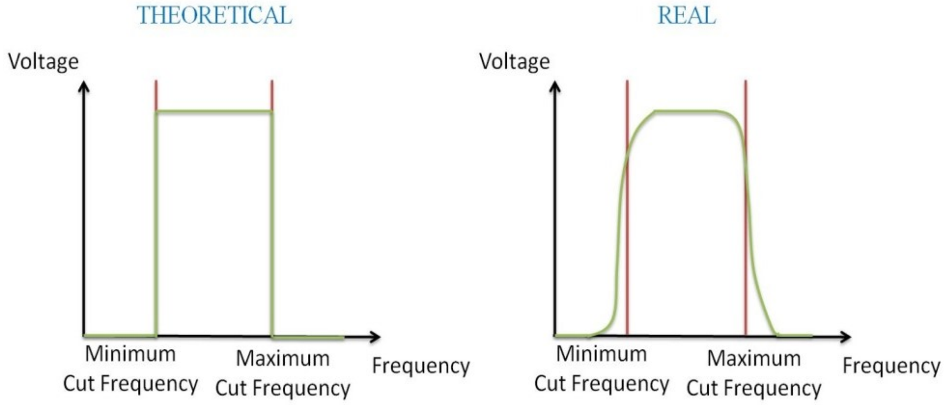


Figure 3.12 – Theoretical vs Real BandPass Filter

- Bandstop filter: attenuates the signal amplitude with frequency inside of the band defined by the cut frequencies, not acting on the signal with frequency inside of the band defined by the cut frequencies, as shown in Figure 3.13.

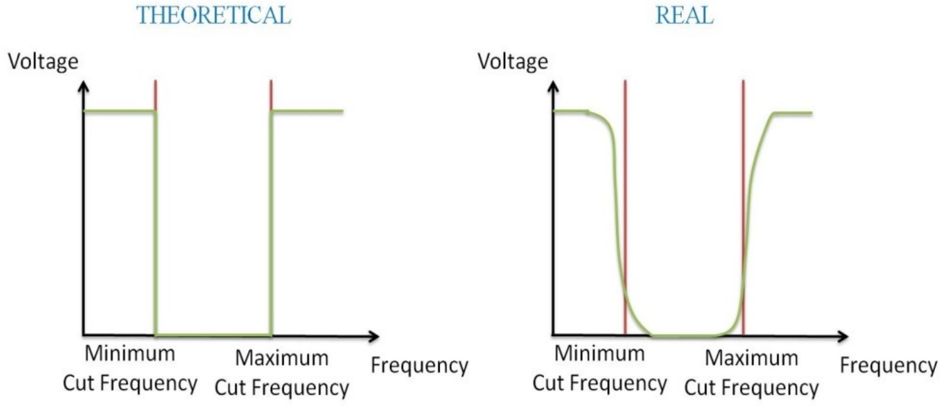


Figure 3.13 – Theoretical vs Real BandStop Filter

A function of the signal conditioning circuits used is the conversion of the sensor's electrical output signal into a signal that can be converted into a digital form, using a signal acquisition device. Signal conditioning can also serve other functions as a power supply to the sensor (when needed), as a calibrating equipment, to perform integrations and to serve as monitoring equipment in order to avoid signal distortion (when the signal conditioning output voltage is higher than the range of the data acquisition device).

3.5 Signal Acquisition

Signal acquisition is an important part of the data acquisition and processing chain and contains the conversion of the analog signal (physical input) into a digital signal, i.e., a set of discrete values understood by computers, through a series of mathematical formulations and transformations. This assumes a fundamental importance in today's industry, as almost all data processing is made using computers that require an input signal in digital format. Therefore, signal acquisition devices contain an analog to digital converter. This transformation occurs after the signal conditioning. It is in this device that characteristics like sampling rate (in samples per second) are defined and that inherent characteristics of the device affect the acquisition of the signal. These devices also perform actions like amplification or filtering, to diminish the effect of errors (like aliasing) have on the results acquired. Sometimes, a series of converters is needed in order to allow the signal to be converted into digital form.

3.6 Signal Processing

Nowadays, almost all signal processing is done through the use of computers that allow the storage, manipulation and visualization of the data coming from the data acquisition device. Multiple software are available to users that give the possibility to perform a multitude of actions (visualize in various units, in time or frequency domain, manipulate the results, etc) destined to the various work objectives in question, but also to store the data recovered allowing the creation of historical records. Sometimes, PLC's are used to store the data recovered and to be processed afterwards.

4. Experimental Tests

In chapter four the experimental tests will be described, as will all the sensors used in the experimental tests, with all their characteristics, instrumentation, software and devices. The analyses' description, as positions of measurement, methods of analysis and results are also presented in this chapter.

4.1 Experimental Work

To perform the comparison between the low-cost sensors and the piezoelectric sensor, it was important to define the characteristics that are important to take into account when analysing vibration sensors. As such, certain characteristics of the sensors were compared, some through experimental works, others through manufacturer information, as there is no other way. They can be found in Table 4.1.

Table 4.1 – Characteristics to analyse and compare

CHARACTERISTICS ANALYSED THROUGH EXPERIMENTAL TESTS	Accuracy
	Linearity
	Noise
	Sensitivity (through comparison)
	Mass and Size (Applications)
	Mounting (Applications)
CHARACTERISTICS ANALYSED THROUGH MANUFACTURER INFORMATION	Frequency Range
	Sensitivity
	Amplitude Range
	Temperature Range
	Resonant Frequency
	Mass and Size

The characteristics to analyse were chosen taking into account their importance in condition monitoring and SHM. Sensitivity translates the ability that the sensor has to react to stimulus, important when in the presence of small amplitude movements, mass, mounting and size are important because not all systems are compatible with large and heavy sensors or with certain mounting schemes, linearity relates to the ability that the sensor has to maintain a accurate behaviour even in the presence of increasing input, accuracy is important so that the results can be precise so that the correct conclusions could be made, ranges are always important to have into account because they define the environment were the sensor can be used and noise is very important so that the signal would not be influenced and therefore the conclusions would not be incorrect.

For the experimental tests described in this chapter, three vibration sensors were used (one MEMS sensor, one piezoelectric film and a piezoelectric accelerometer), with the corresponding measuring chain equipment, three software were used (PULSE®, Microsoft Excel® and LABVIEW®) and several other equipments and structures.

4.2 Measuring Chains

In this work, three sensors were used, and for all sensors, a measuring chain was established, that involved not only the sensor but also all the instruments required for the sensor to work properly. For the MEMS sensor, the measuring chain contains the sensor connected to the computer, as seen in Figure 4.1.

Figure 4.1 – Measuring Chain MEMS sensor

For the piezoelectric film, the measuring chain contains the sensor, the signal conditioning board, the DAQ (Data Acquisition System) and the computer, as seen in Figure 4.2.

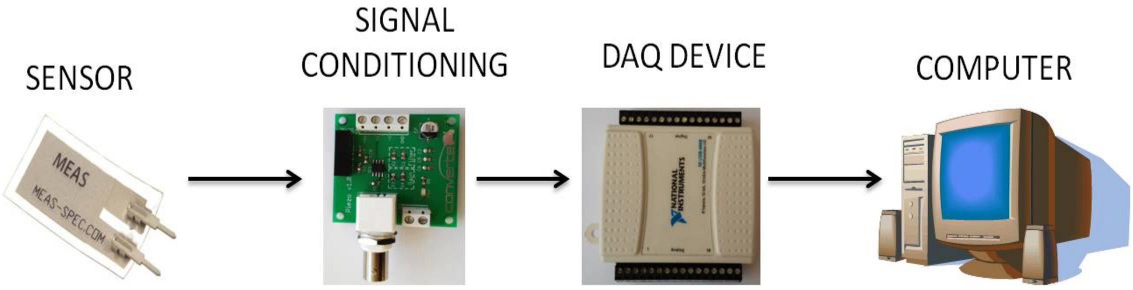


Figure 4.2 – Measuring Chain Piezoelectric Film

For the piezoelectric sensor, the measuring chain contains the sensor, the Local Area Network (LAN) data acquisition device and the computer, as seen in Figure 4.3.

Figure 4.3 – Measuring Chain Piezoelectric Sensor

4.2.1 Sensors Used

All measuring chains start with the sensor. As such, it is important to define the characteristics of each sensor used for this work, their properties and applications

4.2.1.1 Sensor 1- Phidgets 1041-PhidgetSpatial 0/0/3 Basic

The first sensor used was a MEMS sensor, a Phidgets 1041- PhidgetSpatial 0/0/3, which is presented in Figure 4.4.

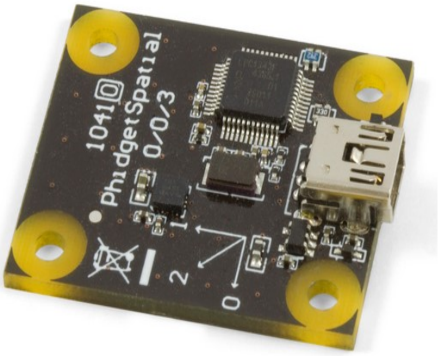


Figure 4.4 – Phidgets 1041-PhidgetSpatial 0/0/3 Basic (Phidgets Inc, n.d.)

This sensor has an accelerometer in its interior and therefore it is recommended to be utilized in vibration analysis. The accelerometer present in this sensor measures any kind of vibration in all three axes if the vibration is limited to 8 g's, i.e., 78.48 m/s^2, with a resolution of 976.7 μg. However, it is more used to detect the presence of vibration, and not the magnitude of it (Phidgets Inc, 2012), meaning that this sensor can be used for vibration analysis, to detect if there is any kind of vibration, but is not recommended to be used when the exact amplitude level is needed. One of the major advantages of this sensor is that it is directly connected to any computer through a USB (Universal Serial Bus) cable, discarding the necessity of any signal conditioning or signal acquisition, as it is already present in the sensor's internal circuits. The sensor has a DAQ integrated, also converting the signal from analog to digital. To be used, it should be mounted or with a specified mounting kit or adapted to the system to be analysed. The manufacturer recommends the use of this sensor to trace the system's movement, determine the movement's direction, find out if there is any moving system in the sensor's proximity and to track the system's orientation in which the sensor is attached to in relation to the earth's gravitational pull (Phidgets Inc, 2012). The simplicity of the recommendations of application made by the manufacturer indicates that this sensor should not be used in any application requiring accuracy and minute control.

4.2.1.2 Sensor 2- Measurement Specialties LDT0-028K

The second sensor used was a piezoelectric film, in this case the model LDT0-028K from Measurement Specialties. Despite the fact that this is not a sensor built particularly for vibration analysis, its characteristics enable it to be used in this kind of analysis. The sensor is shown in Figure 4.5.

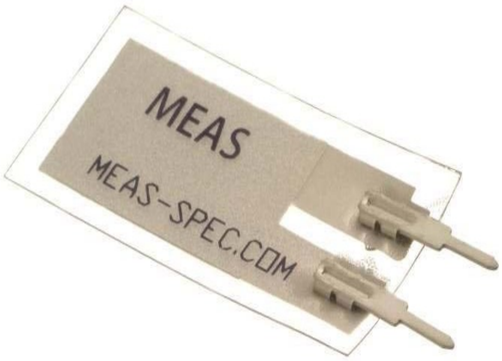


Figure 4.5 – Measurement Specialties LDT0-028K (Radiolocman, 2010)

This piezoelectric film consists in a 28 µm thick PVDF (Polyvinylidene Fluoride) layer, a polymer that has piezoelectric properties, connected to screen printed silver electrodes that allow the transmission of the voltage change. It is also laminated with a 0.125 mm polyester substrate layer for protection, and is equipped with two crimped contacts (LDT0 Solid State Switch/Vibration Sensor- Application Note 111398, n.d.). The technical design of this sensor is present in Figure 4.6.

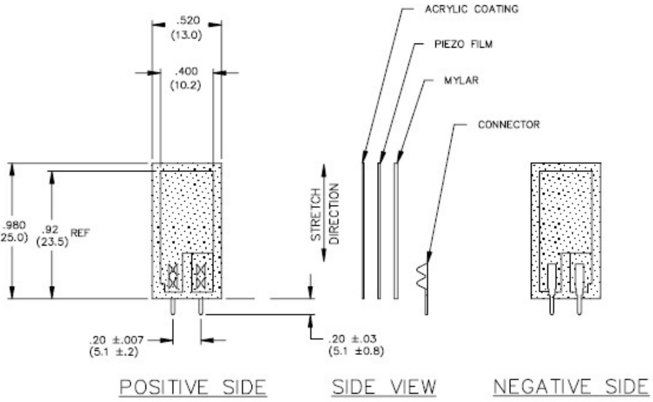


Figure 4.6 – Measurement Specialties LDT0-028K Technical Design (LDT0 Solid State Switch/Vibration Sensor- Application Note 111398, n.d.)

The LDT0-028K is part of a low-cost range of sensors sold by Measurement Specialties, as an alternative to the LDTM-028L, a sensor in all similar to the one used for this work, but that has a mass on the edge of it in order to increase sensitivity. Despite its simplistic design, the LDT0-028K can be very powerful. Tests indicated that, when bended to 90°, it can generate voltages of over 70 Volts. The sensitivity of this piezoelectric film is 50 mV/g, which means that for every g of acceleration that the sensor will be subjected to, the output will be of 0.050 Volts. It has a resonant frequency of 180 Hz, with an output of 1.4 V/g at resonant frequency (LDT0 Solid State Switch/Vibration Sensor- Application Note 111398, n.d.).

The LDT0-028K can be used in several applications such as a displacement sensor, an electrical frequency response sensor or as a vibration sensor. The manufacturer recommends this series of sensor (LDT) for usage in counters (in their Solid State), momentary closure type switches and, most importantly for this work, as vibration sensors when using the beam type format of sensors, to which the LDT0-028K belongs (Digi-Key Corporation, n.d.). The LDT0-028K is recommended for vibration detection in washing machines, car alarms, body movement detection, some types of security systems and low power switches (Digi-Key Corporation, n.d.). For the different applications, different types of mountings are recommended. For this work, the sensor will be used as a vibration sensor and therefore it will be mounted using adhesive tape. In order to use this as a vibration sensor, it is recommended the usage of a circuit of signal conditioning known as a charge amplifier circuit, in order to detect the output signal.

4.2.1.3 Sensor 3- Kistler 8640A50

Sensor 3 is a piezoelectric accelerometer, in this case a Kistler 8640A50. This was the benchmark for the experimental analysis, and the comparison for all other sensors used. This sensor is shown in Figure 4.7.

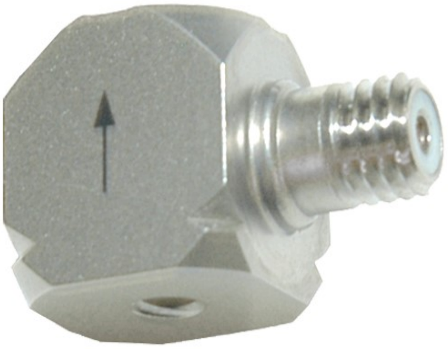


Figure 4.7 – Kistler 8640A50 (Kistler Instrument Corporation, 2011).

This is a single axis accelerometer that is part of the PiezoBEAM® range of accelerometers by Kistler. This sensor consists in the combination of a vibration sensing element and a low noise charge amplifier internally built. The vibration sensing element is a cantilever made from a ceramic material with piezoelectric properties, that when subjected to any kind of vibration will deflect and will output a certain voltage proportional to the amount of deflection. After this, the output voltage goes through the low noise charge amplifier where it will be converted into a proportional high level voltage signal with an impedance of no more than 500 Ω. This means that the signal will be internally converted to a form where it will need less signal conditioning than it would be required without this conversion (Kistler Instrument Corporation, 2011).

This is a lightweight sensor, excellent for applications where there is a small mass involved, in order to not interfere with the system's characteristics, and is recommended for modal analysis (studying the characteristics of systems under the influence of any kind of vibration excitation). It is equipped with a casing, in this case a titanium casing, making it resistant to most kind of external interferences, such as environment, external vibrations, etc, making it a sensor sealed to the outside environment. It can be mounted in a variety of ways, with a stud or even with some sort of adhesive in order to connect it to the system to analyse. Despite its minimalistic design, it is capable of generating easily readable signals, and also has a very good sensitivity, which allows it to be used in cases where the amplitude of movement is small. The measuring range of this sensor is also far superior to other sensors used for this work, allowing it to be used for many other applications other than small accelerations or small displacements (Kistler Instrument Corporation, 2011).

The connection of this sensor to the signal conditioning and acquisition described in Chapter 4.2.3 is a coaxial cable, designed for this kind of sensor. This cable has the connection desired to the sensor at one end, and the other end has a Bayonet Neill–Concelman (BNC) type connection, that allows the linkage between the sensor and the DAQ. According to the manufacturer, the characteristics of this sensor, including the transverse sensitivity in percentage (the percentage displayed should be multiplied by the sensitivity) are the ones present in Table 4.2

Table 4.2 – Characteristics of Kistler 8640A50 (Kistler Instrument Corporation, 2011)

Measuring Range (g)	+/- 50
Measuring Limit (g)	+/- 80
Sensitivity (mV/g)	100,6
Transverse Sensitivity (%)	3
Resonant Frequency (Hz)	25000
Frequency response (Hz)	0.5 to 5000 (+/- 5%)
Temperature Range (˚C)	-40 to 65

Some characteristics, as sensitivity, range and resonant frequency will be used when comparing with the results obtained from the tests made and described in this work. This sensor is recommended for use in small components or subsystems, but can also be used in full vehicle analysis in various industries, such as aerospace and automotive. It can also be used for general test in various other systems (Kistler Instrument Corporation, 2011).

4.2.2 Signal Conditioning Experimental Tests

Only for one of the sensors used in this work (piezoelectric film) there was the need to construct a signal conditioning circuit. The MEMS sensor has an integrated signal conditioning circuit, whilst for the piezoelectric sensor the signal conditioning was integrated in the DAQ device used. As such, only for the piezoelectric film a signal conditioning circuit was constructed in order to transform the signal into a readable signal by the DAQ device.

The first approach to the signal conditioning circuit to be designed was using the sensor's manual, and following the recommended circuit. In order to utilize the sensor as a vibration sensor, the manufacturer recommends the usage of a charge amplifier circuit to amplify the output signal (LDT0 Solid State Switch/Vibration Sensor-Application Note 111398, n.d.). Having the manufacturer's recommendations in mind, the help of Paulo Almeida to complete the circuit required for the experimental analysis was crucial. The circuit was designed on a completely new board, with various components and pieces. The projected board is shown in Figure 4.8.

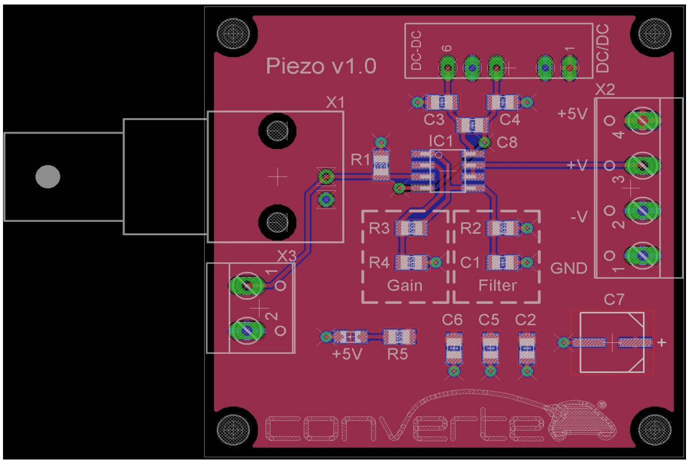


Figure 4.8 – Project of Signal Conditioning Board (Almeida, 2015)

This board was designed having into account a lowpass filter with a cut-off frequency of 100 Hz, frequency chosen having into account the piezoelectric film's relative low resonance frequency. The board created would have a gain of 30.3, meaning that the input signal would be multiplied by 30.3. This gain was used so that the amplitude of the piezoelectric film's results would correspond to the amplitudes recorded by the piezoelectric sensor. However, the value of gain implemented in the board would have to be removed from the signal during the data processing; this action was taken so that the measurements that were detected by the sensor would not be inflated by this gain, as the piezoelectric film had incoherent measurements when compared to the benchmark sensor (in certain experimental tests, the piezoelectric film measures amplitudes higher than the ones measured by the piezoelectric sensor, and in other experimental tests the opposite occurs) . This would be made by removing the gain through the program (not in the hardware). Having this into account, the boards' value of gain is given by the relation present in (4.1).

$$V_{out} = \left(1 + \frac{R3}{R4}\right) V_{in} \tag{4.1}$$

The equation in (4.1) relates the value of output voltage of the board (V_{out}) with the value of input voltage of the board (V_{in}) and the value of resistance 3 (R3) and 4 (R4). The signal coming from the sensor goes into X3. After this, the signal goes through the conditioning circuit and exits through X2 where there is a positive terminal (+V), a negative terminal (-V), a +5 Volts connection and a Ground (GND). The circuit present in this board can be seen in Figure 4.9.

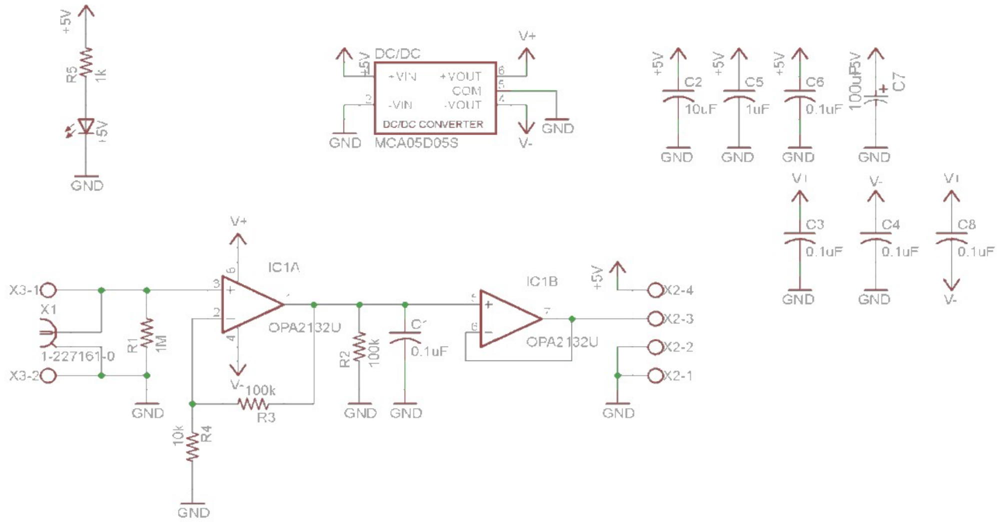


Figure 4.9 – Signal Conditioning Board Electric Circuit and Schematic (Almeida, 2015)

This circuit is divided in two major parts. The filtering through the use of a lowpass filter with a cut frequency of 100 Hz and the amplification part, that has a OpAmp (Operational Amplifier) and a feedback circuit, managing the amplified signal coming from the OpAmp. The OpAmp is a Direct Current electronic device that has the function of amplifying the signal and transforming a differential input (with a positive and negative pole) into a single ended output (in most cases). There are many kinds of OpAmp used in different applications and with different goals. One of the most used kinds of OpAmp is the FET (Field Effect Transistor), which uses an electrical field in the joining parts. The circuit's characteristics are presented in Table 4.3.

Table 4.3 – Signal Conditioning Board Characteristics (Almeida, 2005)

Component	Description	Characteristics
Board	Texas Instruments Board	50 mm x 50 mm
X1	BNC Terminal	-
X2 (X2-1 to X2-4)	Differential Screw Terminal	-
X3 (X3-1 and X3-2)	Differential Screw Terminal	-
C1,C3,C4,C6,C8	Capacitor	0.1 μFarad
C2	Capacitor	10 μFarad
C5	Capacitor	1 μFarad
C7	Capacitor	100 μFarad
DC/DC	Power Converter	Input Voltage 5V;Output Voltage +/-5 V; Output Power 1 Watt
IC1 (IC1A and IC1B)	OpAmp	See Table 4.4
+5V	LED Connected to R5	-
R1	Resistance	1 MΩ
R2, R3	Resistance	100 kΩ
R4	Resistance	3.3kΩ
R5	Resistance	1kΩ

The OpAmp used for this work is a Texas Instruments OPA2132U. The OpAmp's characteristics are displayed in Table 4.4.

Table 4.4 – Characteristics of Texas Instruments OPA2132U (Mouser Electronics Inc, n.d.)

Frequency Response (MHz)	8
Power Supply (V)	+/- 15
Temperature Range (°C)	-40 to 85
Input Voltage Range (V)	+/- 13
Input Offset Voltage (mV)	+/- 0.25

In the case of the piezoelectric film, the connection between the sensor and the signal conditioning board would be guaranteed by electrical wires equipped with small claws, so that the signal conditioning board's terminals could be used. As this connection is not a physically completed connection there will always be losses of signal through this connection, increasing the losses throughout the chain of signal acquisition. The completed board can be seen in Figure 4.10.

Figure 4.10 – Signal Conditioning Board

It is important to state that associated with the use of this signal conditioning there is a bandstop filter between 45 Hz and 55 Hz, to remove the frequency from the electrical current that leaks through the signal conditioning.

4.2.3 Signal Acquisition Experimental Tests

In terms of signal acquisition, and as mentioned, a DAQ device is needed to perform several actions that enable the use of a computer in an analysis. For the MEMS sensor, there were no worries regarding this, as the sensor possesses an internal DAQ device installed in the circuit board, discarding the need for an external device. For the piezoelectric film, in order to enable the capture of the sensor's response, it was necessary to use a DAQ device that was connected to the signal conditioning board (through simple wires). This made possible to visualize the sensor's signal in a computer, using the LABVIEW® interface. The DAQ device used in this work is an NI USB-6008, an acquisition system that transforms the analog signal into digital signal and that is displayed in Figure 4.11.

Figure 4.11 – NI USB-6008

The NI USB-6008 has the possibility of connection to eight single ended analog inputs and four differential analog inputs (as is the case of the piezoelectric film). It also has the possibility of 12 digital inputs or outputs. This DAQ device works with voltages of +/- 10 Volts whilst working with analog signals, and with +/- 5 Volts whilst working with digital signals. In the case of this work, as the DC converter is of +/- 5 Volts type, the DAQ device would be configured to that range of voltage. This system is ideal for low-cost applications, where simplicity is important. One of the best characteristics of this system is that it connects to the computer directly through a USB cable, guaranteeing the connection to the data processing software and also to the power source (National Instruments, 2012). The NI USB-6008 can be used with a multitude of software, but in the case of this work, the compatible software that was used was LABVIEW®. For the experimental tests, the piezoelectric film used the differential screw terminal input, using wires connected to the terminals of the respective sensor. The board's output also used wires that were connected to the output's screw terminal, and connected to the DAQ device. In this situation, the DAQ device was configured to a differential input, rather than a single ended reference.

As mentioned, the piezoelectric sensor was used in combination with a DAQ device that also acted as signal conditioning, as this device was also responsible for the sensor's power supply. Usually, this kind of sensor is connected to what is known as a power couple or power supply, a device that performs the signal conditioning by providing constant current excitation, required by this kind of sensor in order to create a readable signal and a signal within the limits of the acquisition instruments. The DAQ device used was a LAN data acquisition device from Bruel & Kjaer type 3032A, that acts as a signal conditioning and acquisition device. This is a six channel input/output module with a measuring range of 25 thousand Hz.

4.2.4 Signal Processing Experimental Tests

For this work, the signal processing of the data recovered was made using three different software. For the MEMS sensor and piezoelectric film, the signal processing basis were LABVIEW® programs created for this work and Microsoft Excel® worksheets. The piezoelectric sensor used the PULSE® software from Bruel & Kjaer and Microsoft Excel® worksheets.

4.2.4.1 LABVIEW® Programs

LABVIEW® is a graphical programming software designed by National Instruments that allows the user to create several types of programs, internet pages, executables, etc, with numerous purposes using a simple graphic environment, through the usage of icons. It differs from most software available in the market in the fact that uses icons instead of text, which makes it a lot easier for the inexperienced user to employ. This software is mostly used for data processing or automation. In this work, LABVIEW® was used to create programs that would allow the processing of data coming from the sensors or the data acquisition system, enabling the usage of that data to create graphics, tables, etc. The software's interface consists in the Front Panel, the part that the user sees and accesses, in which there are two types of interfaces, indicators that only show certain values or calculations, and controls that the user can control and change, and the Block Diagram where the programming is done.

For this work, two LABVIEW® programs were created, one applied to the piezoelectric film, and one for the MEMS sensor described in the previous chapters. Every program created in LABVIEW® is saved in the format of Virtual Instrument (.vi), so all programs created for this work are .vi files.

The LABVIEW® programs created for this work consist in a series of actions and possibilities given to the user, allowing for the correct interpretation of the data recovered. The programs allow the user to choose between various options, giving at the same time multiple necessary inputs and confirmation displays. For example, the program used with the NI USB-6008 requires the input of the sensor's sensitivity, the sampling frequency and the number of samples to define, whilst the program used with the Phidgets 1041- PhidgetSpatial 0/0/3 Basic requires the Data Rate (the time taken to collect one sample) and the number of samples to define. These are required inputs and the program will not run without them. A LED (Light Emitting Diode) indicator is shown if all the required inputs are completed. The programs also allow signal filtering, through the use of a highpass filter. However, the user may desire not to filter the signal, option that the program allows. Despite this, there is one mandatory signal filtering, a highpass filter with cut frequency of 10 Hz when using the NI USB-6008 program, frequency chosen in order to eliminate noise coming from the signal conditioning board. The programs also calculate the frequency spectrum of the signal captured, allowing the selection of the type of spectrum (peak or RMS) and type of unit (linear or decibel). The type of window used in the spectrum is also available to choose. There are 10 types of windows to choose, from the most common Hanning window, to other like Blackman variants, the Rectangular, the Flat Top, the Hamming, the Low Sidelobe and the B-Harris variants. The programs also have the possibility of a continuum measurement, which means that the program will run until the user presses the stop button, or a limited measurement (sampling time), in which the program will measure only the number of samples that the user defines. When in sampling time mode, the program will display the time of capture, allowing the user to manipulate that time as she/he wishes. In order to create the possibility of both programs to be used in other similar applications, the programs have an instruction manual that can be used to facilitate the use of the program and also has several types of alarms that can be programmed for various uses.

The programs created display a multitude of outputs essential to a vibration analysis. It displays, for example, the RMS value, the global level according to ISO Standard 10816-1995, the crest factor, the time signal, the frequency spectrum and other characteristics. When using the global level alert signals according to ISO Standard 10816-1995, the signal is filtered according to the standard's indications, with a bandpass filter between 10 Hz and 1000 Hz (International Organization for Standardization, 1995). When half of the sampling frequency is lower than 1000 Hz the band of the filter will be between 10 Hz and half of the sampling frequency minus 1 Hz. The time signal is displayed according to the desired unit. The programs enable the user to view the time signal in units of acceleration, velocity or displacement, according to the application desired. This option will also influence the maximum peak's display, which will be shown in the units desired by the user. The programs have a stop button that can be used in continuum mode, and also allow the exportation of the time signal in .tdms format, allowing the use of the data in a Microsoft Excel® worksheet. For this work, a Microsoft Excel® worksheet was created, in which the frequency spectrum was calculated (through FFT), which allowed the possibility of discovering the precise value of every frequency present in the signal. The inputs of this Microsoft Excel® worksheet were the time in seconds, the number of samples and the exported time data coming from the LABVIEW® Program.

The Block Diagram and Front Panel of the LABVIEW® program for the Piezoelectric Film can be consulted in Appendix B of this work, whilst the Block Diagram and Front Panel of the LABVIEW® program for the MEMS Sensors can be consulted in Appendix C of this work. They can also be consulted in the electronic appendixes of this work. An example of the worksheet for the Microsoft Excel® program can be seen in Appendix A.

4.2.4.2 PULSE®

PULSE® is a software platform directed for noise and vibration analysis with a multitude of applications such as accelerometers, impact hammers, microphones, etc. This software allows the user to do several post-processing actions, as exporting all results to various formats (like .txt files) so that they can be used in other software, like Microsoft Excel®, and to parameterize every single aspect of the analysis. It also acts as a signal generating software, meaning that it can be used to configure signals that will be generated, for example, by shakers. It works mostly with Bruel & Kjaer products, but also recognizes products from other manufacturers. In the case of this work, this software was used with an accelerometer from Kistler. Therefore, in the software's properties, the sensor that was in use was defined as a sensor from Bruel & Kjaer with the most similar properties to the ones of the sensor in question. This means that, for the software, the accelerometer in use was a sensor with a sensitivity of 98.1 mV/g, in contrast to the real value of 100.6 mV/g. This difference in sensitivity would create results that would not be entirely accurate. However, the difference is very small and therefore could be considered despicable, as this difference is smothered by the connecting cables and other apparatus. Important to notice that for all experimental tests made for this work, an auto-rage approach was used to optimize the signal in terms of noise level and rejection of overload of signal. For the sensor with data processing performed through PULSE®, the previously described Microsoft Excel® worksheets were also used to construct the frequency spectrums.

4.3 Calibrations

For the MEMS sensor and the piezoelectric sensor, initial calibrations were required to certify that the results provided by these two sensors corresponded to the real values. For the piezoelectric film, no calibration was performed, as the sensor's characteristics did not allow this action (incoherent results given by the piezoelectric film when comparing with the piezoelectric sensor's results).

4.3.1 Calibration Sensor 1

The first action made to the MEMS sensor was a calibration. This calibration was made to ensure that the sensor was giving the correct measurement in the z axis (this would be the only axis used in this work), as there was no knowledge about the conditions of packaging and more importantly transport, meaning that there was a possibility of damage to the calibration made in the factory. The sensor was positioned on a table, without any external interference, position where the sensor's measurement should be 1 g, meaning that the sensor was under gravitational acceleration of 1 in the downward direction. Then, the average measurement given by the sensor was recorded, which in this case was 1.035 g's, as it can be seen in Figure 4.12. Knowing this, the signal from the sensor was multiplied by the relation (4.2).

$$\frac{1}{1.035} \times \text{Time Signal} \tag{4.2}$$

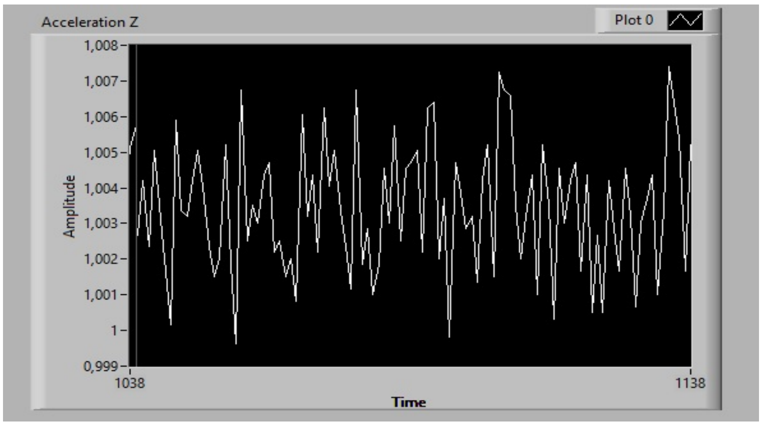


Figure 4.12 – Measurement of Accelerational Gravity

Despite being an imperfect calibration, because, for example, there is no guarantee that the table is exactly straight, or even if the floor is exactly straight, this ensured that the sensor would be calibrated to a more correct value of gravitational acceleration according to the z axis of the Cartesian referential.

4.3.2 Calibration Sensor 3

To validate the results obtained with the piezoelectric sensor, there was a need to calibrate it. This was made by connecting the sensor to the equipment, on top of another accelerometer. This second accelerometer was as Bruel & Kjaer 4507 B 004 with a Sensitivity of 98.8 mV/g, a mounted resonance frequency of 18 thousand Hz and with a frequency range between 0.3 Hz and 6 thousand Hz (Calibration Chart for DeltaTron Accelerometer Type 4507 B 004, n.d.). There was the knowledge that this second accelerometer was calibrated (this sensor is used for other works in Instituto Superior Técnico that require this sensor to be calibrated, with the manufacturer confirmation), and therefore the signal coming from the Bruel & Kjaer accelerometer would be compared to the signal coming from the Kistler accelerometer. The two sensors would be placed in a simple stainless steel beam with 300 ± 0.5 mm of length, 79 ± 0.5 mm of width and 1.8 ± 0.25 mm of thickness. The structure can be seen in Figure 4.13.

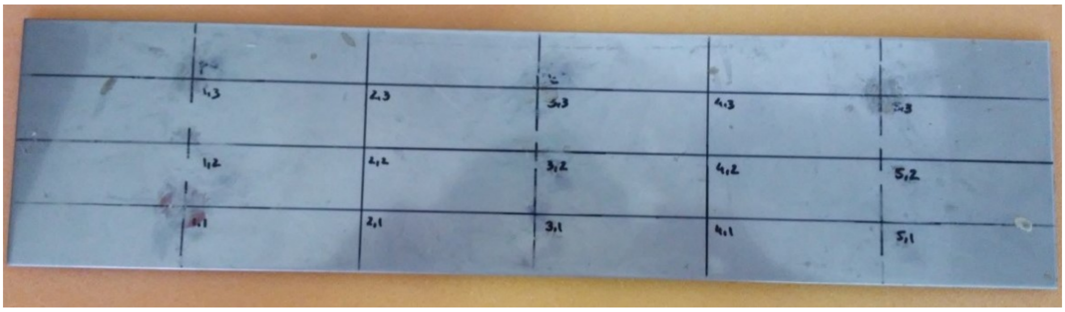


Figure 4.13 – Beam Structure

Afterwards, the structure would be placed in vibration through the use of a random signal coming from a shaker. A shaker is a device used to excite and maintain a system vibrating at a certain frequency (or frequencies), allowing the system's modal testing. The shaker used for this work was a Bruel & Kjaer Hand-Held Exciter Type 5961 and can be seen in Figure 4.14. This is a small shaker with length of 155 mm, diameter of 52 mm and weight of 500 grams designed for modal testing of small and medium systems, that provides a signal with no leakage, low crest factor and easy to operate (Product Data Hand-held Exciter – Type 5961, n.d.), meaning that any inexperienced user can quickly use this exciter in the correct way. This exciter works in a frequency range between 45 Hz and 15 thousand Hz and guarantees almost three hours of battery life when in constant use (Product Data Hand-held Exciter – Type 5961, n.d.). This exciter is used mostly for calibration purposes, but can also be used as a shaker. This shaker would be connected to an input/output module form Bruel & Kjaer type 3109, allowing the generation of certain signals defined in PULSE®.

Figure 4.14 – Bruel & Kjaer Exciter Type 5961 (Product Data Hand-held Exciter – Type 5961, n.d.)

Both signals from the accelerometers were captured with a maximum frequency of 3200 Hz in the frequency spectrum with a total number of points of 6400, with 1000 averages and a Hanning window. The assembly of the sensor's calibration is displayed in Figure 4.15.

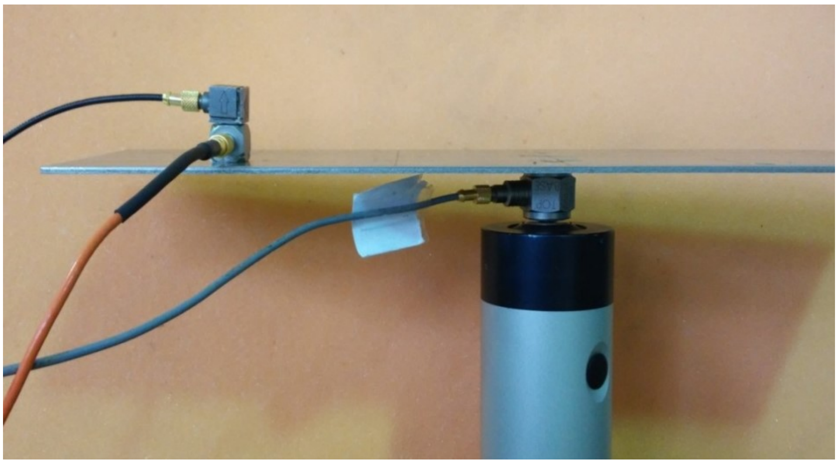
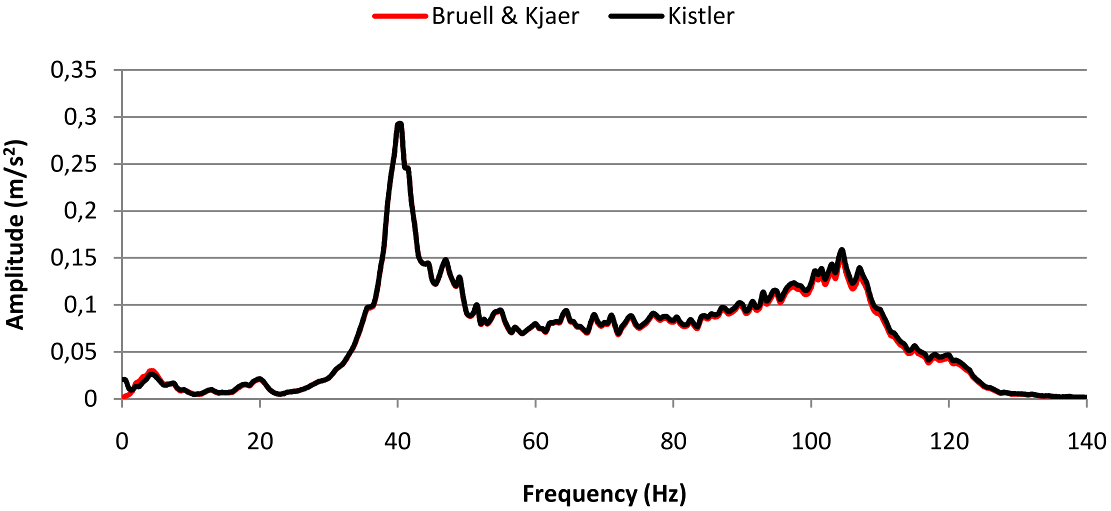


Figure 4.15 – Assembly of Kistler Accelerometer Calibration

For this test, a random signal with a span of 3125 Hz was used (defined in PULSE®), meaning that the structure would vibrate at all frequencies inside that span. The resultant frequency spectrums are presented in Graphic 4.1.



Graphic 4.1 – Superimposed Frequency Spectrums Calibration

As it is possible to visualize in Graphic 4.1, barring minor differences in the lower frequencies, the results given by both accelerometers are incredibly similar. This leads to the conclusion that the accelerometer used for this work (Kistler 8640A50) is calibrated or very close to being calibrated. Therefore, the results given by this sensor are trustable.

4.4 Experimental Tests

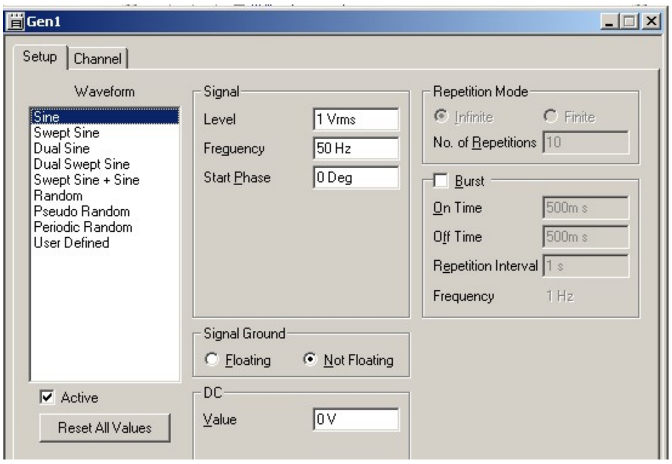
Important considerations have to be made for all sensors involved. The mounting of the sensors is an important aspect to consider when analysing the vibration's transmission to the sensor itself. A more solid connection (a screw for example) will allow for a better vibration transmission. In the case of this work, all sensors were connected to the structures to analyse through the use of adhesive, in the case of the MEMS sensor adhesive tack, adhesive wax for the piezoelectric sensor and adhesive tape for the piezoelectric film. This means that the transmission of vibration will not be at its best, and therefore the results obtained will be affected by that. Also, the positioning of the sensors, or even the positioning of the structures is not always exactly the same. There are always minimal deviations from one positioning to the other, creating a source of error that should be taken into account when comparing different tests.

In this work, four experimental tests were designed and performed, having into account certain aspects. One aspect is the lack of instruments and material available so that more and different tests could be performed, and as such the experimental tests were designed to maximise the material available. Another important aspect that was taken into account when designing the experimental tests was the characteristics of the piezoelectric film. The characteristics of its signal conditioning meant that all analyses had to be made taking only into account the range of zero to 100 Hz. Because of this, all experimental tests of all sensors were performed under those conditions (or approximate conditions). This sensor also imposed several limitations in terms of space occupied by the test. As the wires in the connections of this sensor had to be of the smallest size possible in order to minimize noise, only tests where the instruments were close to the sensor could be performed. Another important consideration related to the piezoelectric film is the fact that this sensor requires the use of cables and the use of certain instruments that were not available for this work. Therefore, certain instruments were improvised, such as the cables and the signal conditioning. Ideally, the terminals of this sensor should be welded to the cable that would transmit the signal from the sensor to the signal conditioning board. However, this would not be practical for the applications of this work, as this would create problems in positioning the sensor in the structure to analyse. The solution found was to use cables with claws that would be attached to the sensor's terminals, guaranteeing versatility. This can create problems such has an increased level of noise. It is also important to notice that this sensor, especially considering the connection to the terminals of it, requires extreme caution, as the claws of the cables that take the signal from the sensor to the signal conditioning board are unstable, can move and create errors in the results.

Ideally, the sampling conditions would be the same for all sensors. However, the MEMS sensor's characteristics in terms of sampling frequency (by construction this sensor can only be used with a selection of sampling frequencies) combined with the limitations in terms of sampling frequency of the piezoelectric sensor's data acquisition equipment (defined in PULSE®) made it impossible to combine the same sampling frequency for all sensors. Having this in mind, it was chosen that with the sensors where the data processing was made using the LABVIEW® programs, the sampling size was of 1024 points and the sampling frequency was of 250 Hz. The number of points used was selected taking into account the mandatory condition for a frequency spectrum according to the Fourier analysis to be performed using Microsoft Excel®, i.e., for a Fourier analysis to be performed in this software the number of points in the time signal should be a power of two. The sampling frequency was selected to ensure the most approximate sampling conditions between all sensors, most importantly that the spacing between each frequency (Δf) analysed is the most similar in all sensors. The signals from the sensors that use LABVIEW® programs as data processing software have a Δf of approximately 244 mHz. For the piezoelectric sensor, the sampling conditions that are defined using PULSE® are related not with the time signal, but with the signal's frequency spectrum. Therefore, in PULSE® the user defines the number of lines (points) that the frequency spectrum should have and the spectrum's frequency span, i.e., the maximum frequency analysed. The two inputs have pre-defined values that can be used, and according to the values chosen, the value of Δf is displayed. For the tests made in this work, it was defined the number of lines of 400 and a frequency span of 100 Hz. This ensured a Δf of 250 mHz. Consequently, the sampling conditions for all sensors was as similar as possible. More powerful data acquisition equipment allows for higher values of sampling frequency, and therefore, a more accurate measurement. However, the equipment available meant that the options described were the more appropriate. Important information that should also be taken into account is that for all experimental tests, the window used in data processing is the Hannning window (unless it is referred that was not the case). Also, the number of averages used was the default value for the software, 10 for LABVIEW® and 1000 for PULSE® (unless it is referred that was not the case). This value is important for the reduction of noise in the analysis and for an increased statistical reliability (Fonseca, 2011). One important aspect to take into account is the fact that in all experimental tests only one axis was tested (z axis of the Cartesian referential), as two of the sensors used for this work are one axis sensor only.

4.4.1 Assembly and Results - Experimental Test 1

The first experimental test was made using the hand-held exciter (or shaker) from Bruel & Kjaer Type 5961. In this test, the sensors were placed on top of the exciter and a series of sine signals with different frequencies and with level of 1 VRMS (Volt Root Mean Square) were simulated, meaning that the sine waveform created by the shaker would have an input voltage with a value of RMS of 1 Volt. In the case of this work, the frequencies used were 50 Hz, 60 Hz, 65 Hz, 70 Hz, 75 Hz, 80 Hz, 85 Hz, 90 Hz and 95 Hz. These frequencies were chosen taking into account the shaker's range, but also the resonant frequencies of the sensors (most notably the piezoelectric film's resonance frequency, because it is the lowest) and the best combination of sampling frequency and sample number in all data processing software. The objective of this test would be to create a linear curve with the amplitudes correspondent to the frequencies tested. This is a test to study the linearity of the different sensors, the accuracy of the amplitude of movement and accuracy in frequency. The PULSE® configuration for generation of one of the frequencies, in this case 50 Hz, is seen in Figure 4.16.



Waveform: Sine

Level 1 Vrms

Frequency 50 Hz

Start Phase 0 Deg

● Infinite ○ Finite

No. of Repetitions 10

☐ Burst

On Time 500m s

Off Time 500m s

Repetition Interval 1 s

Frequency 1 Hz

○ Floating ● Not Floating

☑ Active

Value 0 V

Figure 4.16 – PULSE® Configuration for Experimental Test 1

4.4.1.1 Assembly Experimental Test 1 - Sensor 1

Sensor 1, the MEMS sensor from Phidgets, was tested for its linearity using the assembly shown in Figure 4.17 and the signal processing from LABVIEW®.

Figure 4.17 – Assembly - Experimental Test 1 (Sensor 1)

4.4.1.2 Assembly - Experimental Test 1 (Sensor 2)

Sensor 2, the piezoelectric film described previously, was tested for its linearity using the previously described method and the assembly shown in Figure 4.18. It is important to notice that for this sensor there was no tested frequency of 50 Hz, as this sensor is associated with a bandstop filter between 45 Hz and 55 Hz to remove the frequency from the electrical current that leaks through the signal conditioning.

Figure 4.18 – Assembly - Experimental Test 1 (Sensor 2)

4.4.1.3 Assembly - Experimental Test 1 (Sensor 3)

Sensor 3, the piezoelectric sensor, was tested for its linearity using the previously described method and PULSE® for data processing. After the data processing, the results were exported to a .txt format, so that they could be treated using Microsoft Excel®, to create graphics that would be able to be compared with the remainder of the results. The assembly of the test with this sensor is shown in Figure 4.19.

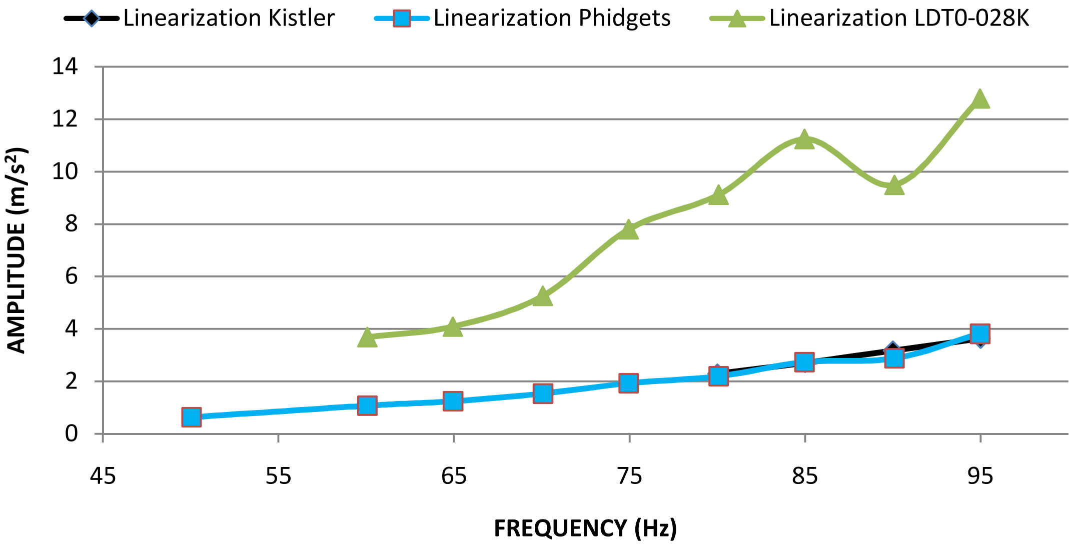
Figure 4.19 – Assembly - Experimental Test 1 (Sensor 3)

4.4.1.4 Comparison of Results - Experimental Test 1

The ultimate goal of this test was to create a graphic that would illustrate the behaviour of the sensors when subjected to different sine curves with different frequencies, but this test could also be used to test sensor accuracy. With the sampling conditions used, an accuracy analysis of the low-cost sensors can be made, as the difference in Δf is inferior to 6 mHz. In the context of this experimental test, the important aspect is if the dominant frequency value is as close as possible to the input value. This makes the accuracy of the sensors comparable, but with the reservations previously mentioned. Table 4.5 has the results of the dominant frequencies tested during this experimental test. Graphic 4.2 is the graphical representation of the results shown in Table 4.5.

Table 4.5 – Results Linearization Tests

Sensor 1 (PHIDGETS)		Sensor 2 (LDT0-028K)		Sensor 3 (KISTLER)	
Dominant Frequency [Hz]	Amplitude [m/s^2]	Dominant Frequency [Hz]	Amplitude [m/s^2]	Dominant Frequency [Hz]	Amplitude [m/s^2]
50,049	0,638	-	-	50	0,610
60,059	1,075	60,059	3,684	60	1,012
64,941	1,246	64,941	4,092	65	1,272
70,068	1,536	70,068	5,260	70	1,571
74,951	1,929	74,951	7,797	75	1,914
80,078	2,199	80,078	9,117	80	2,296
84,961	2,736	84,961	11,240	85	2,714
90,088	2,882	90,088	9,501	90	3,173
94,971	3,818	94,971	12,797	95	3,633



Graphic 4.2 – Results Experimental Test 1

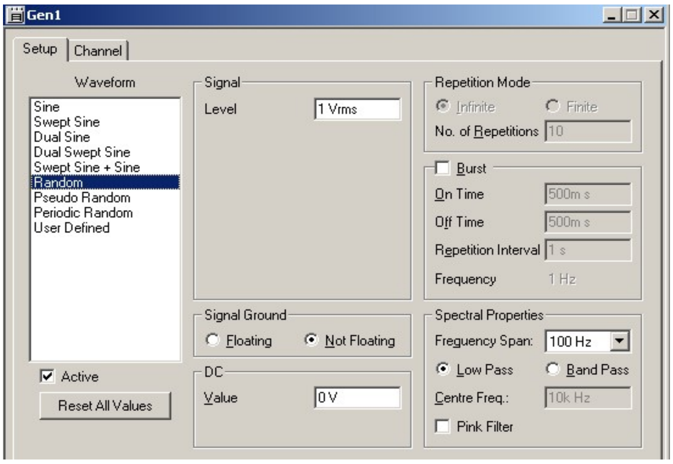
Using the piezoelectric sensor as benchmark, it is clear that the MEMS sensor gives very similar results in terms of amplitude; the small differences in the dominant frequency's accuracy are related with the differences in sampling frequency. This indicates that this sensor is very usable as an alternative to the piezoelectric sensor when analysing the dominant frequency of a certain signal or when the signal has very low interferences from external signals. This line of thought can also be transported to the piezoelectric film, but not in terms of amplitude of movement, as it visible in Graphic

4.2. It is possible to conclude that the MEMS sensor has a very similar behaviour to the benchmark sensor, and that the piezoelectric film is good to detect the signal's frequency, but not so good to determine the signal's characteristics. It is also perceptible that the MEMS sensor has a more similar behaviour to the benchmark sensor when dealing with lower frequencies. Analysing the slope of the results of this experimental test, it is clear that the piezoelectric sensor is the most linear of all in terms of results. Of the two low-cost sensors used, the MEMS sensor is clearly the most linear of the sensors analysed.

4.4.2 Assembly and Results - Experimental Test 2

For this work to be precise, and to obtain valid work conclusions, the decision was made to select a structure as simple as possible. This minimized the possibilities of disturbances in the tests made, such as structural damage in the structure. This test consisted in the structure described in Chapter 4.3.2 being forced into a random vibration by the shaker. As such, the sensors would be placed on the structure that would be connected to the shaker, simulating a free-free beam. Using the exciter described in Chapter 4.3.2, a random signal was created. This would place the structure and the sensors attached to it in vibration. As the main purpose of this work is the comparison of the low-cost sensors with the piezoelectric sensor, the experiment consisted in a test with both the piezoelectric sensor and one of the low-cost sensors. After that, a frequency spectrum was constructed and with it, a comparison between the several frequency spectrums was made, involving not only the frequencies captured by each sensor but also the curve's shape and the frequencies' amplitude. This test allows the user to analyse the sensor's behaviour in these conditions, but also allows a level of noise analysis, as the comparison of the frequency spectrums of the different sensors would give an idea of the noise levels that are present in the signal. Also, the noise level could be compared in the frequency range of zero to 45 Hz. The shaker's working frequency range is between 45 Hz and 15 thousand Hz, meaning that up to 45 Hz, in theory, the signal should not have any amplitude in the frequency spectrum. If it has, it can indicate the sensor's level of noise.

The structure used has a small attachment on the middle of it, used to connect the shaker to structure, and after this a random signal with level of 1 VRMS (the input voltage in the shaker would have a level of RMS of 1 Volt) and a span of 100 Hz (the structure would vibrate at all frequencies inside that span) was simulated using PULSE®, as seen in Figure 4.20. The sensors were placed in the structure's same positions distancing 50 mm front the right edge and 20 mm front the front edge (one in top and the other in the bottom) in both sides of the structure. The two positions of test can be seen in Figure 4.21.



Gen1

Setup | Channel

Waveform
Sine
Swept Sine
Dual Sine
Dual Swept Sine
Swept Sine + Sine
Random
Pseudo Random
Periodic Random
User Defined

☑ Active

Reset All Values

Signal
Level 1 Vrms

Signal Ground
○ Floating ● Not Floating

DC
Value 0 V

Repetition Mode
● Infinite ○ Finite
No. of Repetitions 10

☐ Burst
On Time 500m s
Off Time 500m s
Repetition Interval 1 s
Frequency 1 Hz

Spectral Properties
Frequency Span: 100 Hz
● Low Pass ○ Band Pass
Centre Freq.: 10k Hz
☐ Pink Filter

Figure 4.20 – PULSE® Configuration for Experimental Test 2

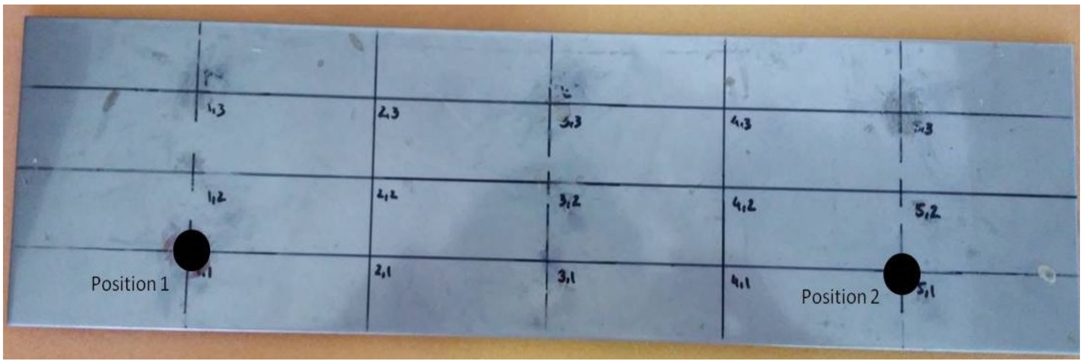


Figure 4.21 – Positions of Experimental Test 2

4.4.2.1 Assembly and Results - Experimental Test 2 (Sensor 1 and Sensor 3)

For this experimental test sensor 1 (MEMS) and sensor 3 (piezoelectric sensor) were placed in the positions described, one on each side of the structure as seen in Figure 4.22. After this the structure was placed into forced vibration using the shaker.

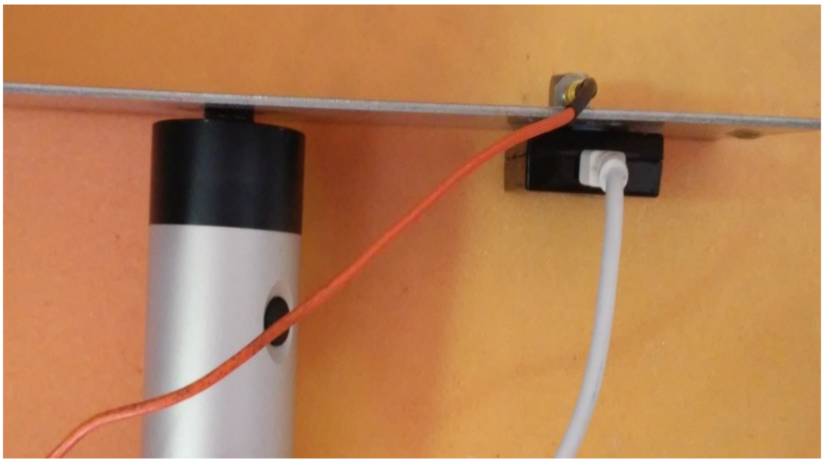
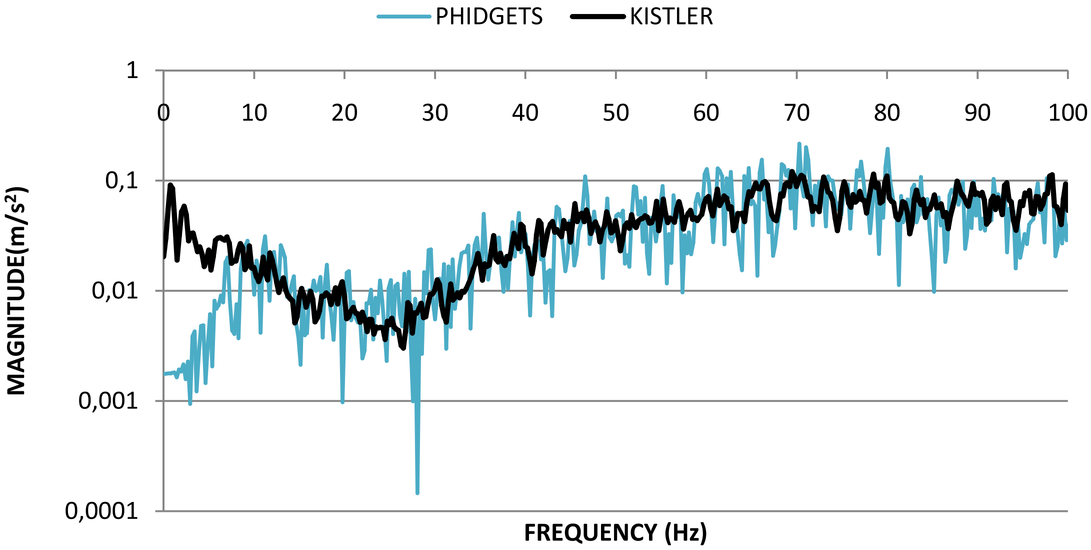
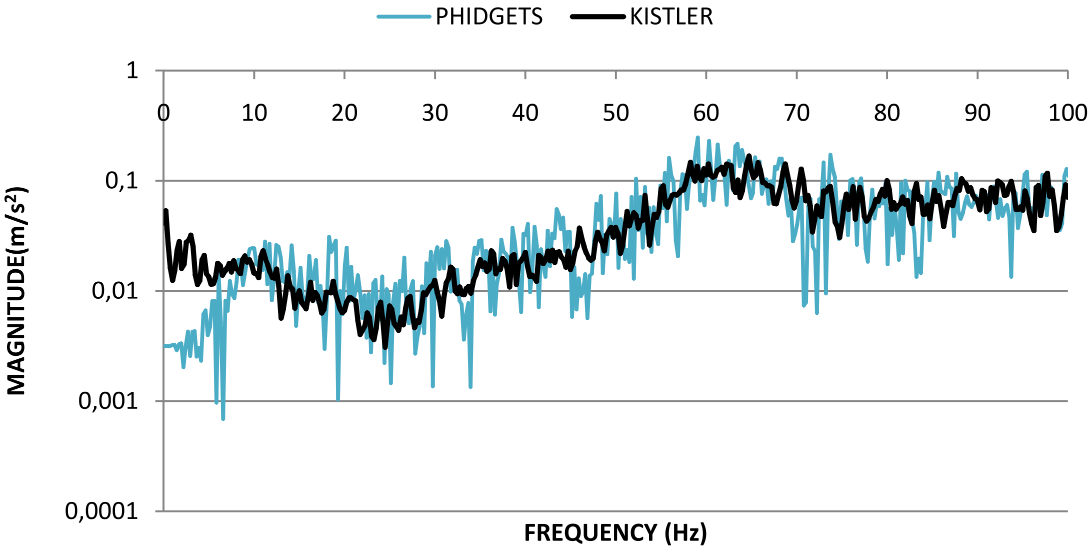


Figure 4.22 – Assembly - Experimental Test 2 (Sensor 1 and 3)

The results of this experimental test are shown in Graphic 4.3 and in Graphic 4.4.



Graphic 4.3 – Results - Experimental Test 2 (Sensor 1 and 3 Position 1)



Graphic 4.4 – Results - Experimental Test 2 (Sensor 1 and 3 Position 2)

The first important question to notice is that the spectrum's format is similar for both sensors. The major difference is in terms of amplitude that in the case of the MEMS sensor is higher than the benchmark sensor. This is coherent with the indicated characteristics by the manufacturer that this is not the most ideal sensor to determine the amplitude of a certain movement. However, the majority of frequencies present in the signal detected by the benchmark sensor are also detected by the MEMS sensor, with small differences in the exact value of frequency, which can be explained by the differences in sampling frequency. The biggest difference between the two sensors is the value of amplitude. Therefore, it is possible to state that this MEMS sensor has good accuracy when comparing frequencies, but has some limitations in terms of amplitude.

In the frequency range of zero to 45 Hz, the shaker does not provide signal, as its functioning frequency range starts at 45 Hz. This makes it possible to analyse the level of noise present in both sensors. It is clear that the piezoelectric sensor has a high level of noise in the lower frequencies, up to 10 Hz, that is expected, as this is a characteristic of the piezoelectric sensors (more noise in the lower frequencies when comparing to the MEMS sensor). However in the remainder of the range the level of noise is similar. It is, nevertheless, possible to detect more noise in the MEMS sensor signal than in the piezoelectric sensor's signal, indicating that, in this characteristic, this MEMS sensor is not quite at the same level as the piezoelectric sensor. The combined amplitude level of the piezoelectric sensor in the zero to 45 Hz range is 0.016 m/s^2 and the combined amplitude level of the MEMS sensor is 0.014 m/s^2, when in theory this value should be zero as there is no input. Despite the combined amplitude level of the piezoelectric sensor in this frequency range being larger than the value of the MEMS sensor, this is largely explained by the difference in the lower frequencies.

4.4.2.2 Assembly and Results - Experimental Test 2 (Sensor 2 and Sensor 3)

For this experimental test, sensor 2 (piezoelectric film) and sensor 3 (piezoelectric sensor) were placed in the positions described in Chapter 4.4.2 one on top and the other on the bottom, as seen in Figure 4.23, and after this the structure was placed into forced vibration using the shaker.

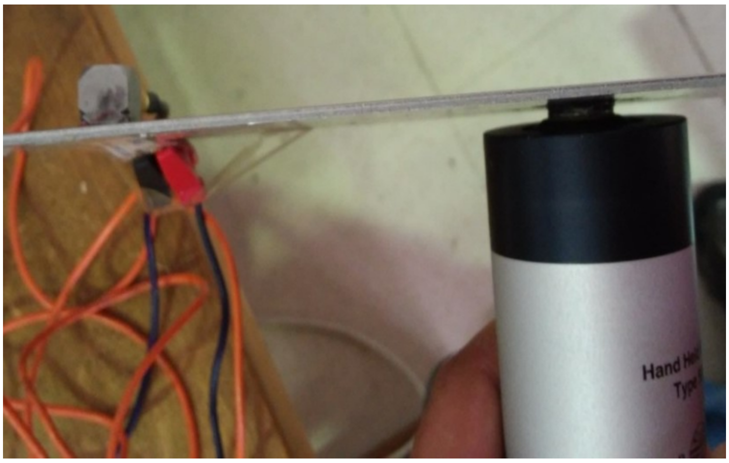
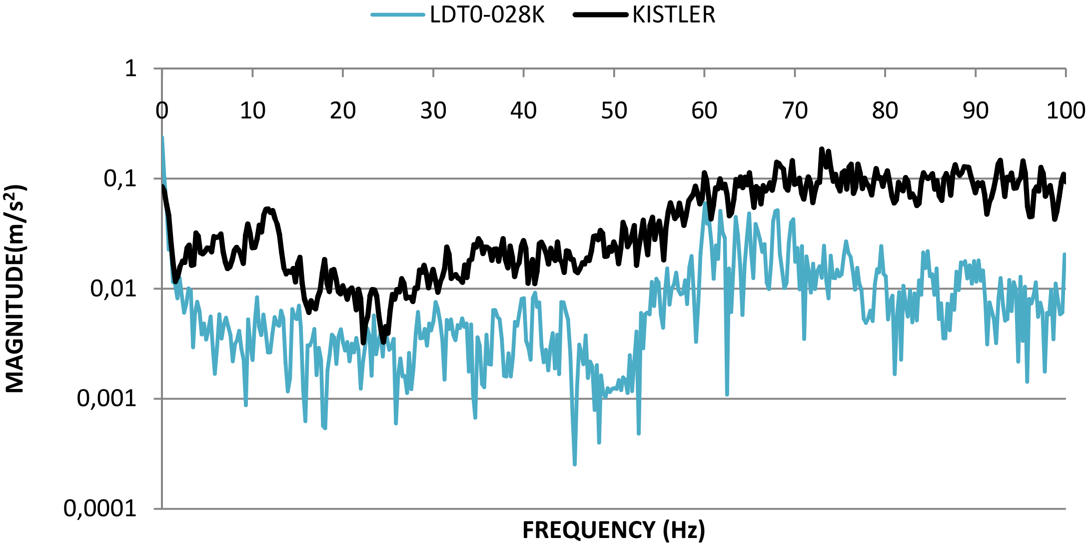
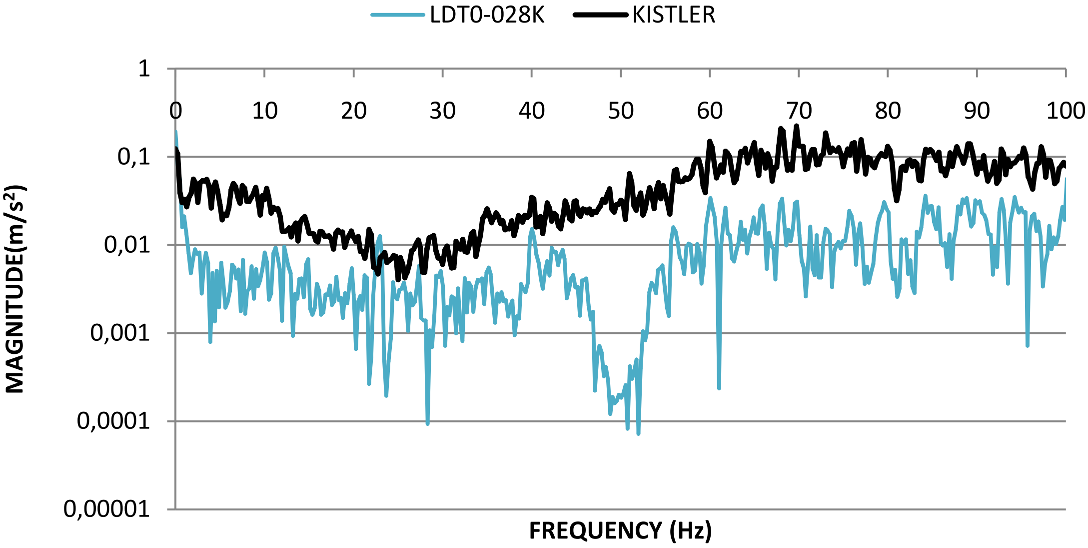


Figure 4.23 – Assembly - Experimental Test 2 (Sensor 2 and 3)

The results of this experimental test are shown in Graphic 4.5 and Graphic 4.6.



Graphic 4.5 – Results - Experimental Test 2 (Sensor 2 and 3 Position 1)



Graphic 4.6 – Results - Experimental Test 2 (Sensor 2 and 3 Position 2)

Analysing the results presented, it is possible to examine that in position 2, the curve of the piezoelectric film's frequency spectrum is the most similar to the signal captured by the benchmark sensor. However, in position 1 the two frequency spectrums are similar only in certain ranges of frequencies, not the entire frequency spectrum. This can lead a user to believe that this sensor is very influenced by the position where the analysis is made, or at least much more influenced than the piezoelectric sensor. Despite the similarities in the frequency spectrum's format, the amplitude of movement is not similar in any range of frequency and in none of the positions. In some frequencies, the difference of amplitude between the results is superior to 100 % the benchmark value. Again, this indicates that this sensor is not the most adequate when all signal characteristics are needed, indicating that the accuracy is not the best. In terms of level of noise in the range of zero to 45 Hz, the differences in amplitude are very big, indicating that the piezoelectric film has a lot of noise. Also, it is detectable the presence of noise in the piezoelectric sensor's frequency spectrum up to 10 Hz. This is expected, but can also be explained by the positioning of the sensor (upside down). Despite being used for vibration analysis, it seems that the piezoelectric film is most indicated when only the frequency present in the signal is needed, and even in that situation, the measurements with this sensor are not the most reliable, as the accuracy and the noise levels are not ideal and are unfavourably comparable to the piezoelectric sensor.

4.4.3 Assembly and Results - Experimental Test 3

The third experimental test was a frequency analysis of a structure. Again, the experiment consisted in a test with both the piezoelectric sensor and one of the low-cost sensors (at the same time). In this case, a plate made with iron-zinc alloy electroplated galvannealed steel was used, with 455 ± 0.5 mm of length, 390 ± 0.5 mm of width and 2 ± 0.25 mm of thickness. The structure can be seen in Figure 4.24.

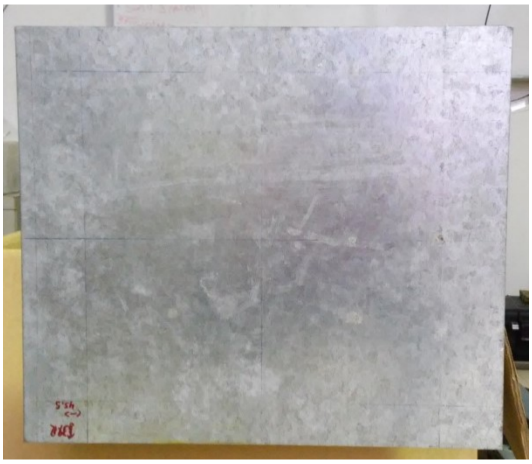


Figure 4.24 – Structure Experimental Test 3

This test was made in two different positions, with impact in two different positions, in a combination of three tests. Changing the position of impact guarantees a similar behaviour to the vibration, as the reciprocity effect comes into action. In an ideal situation (and in most of real cases) if the accelerometer is placed in position A and the impact is made in position B, the results will be the same if the accelerometer was placed in position B and the impact would be in position A. For this work, a Bruel & Kjaer Type 8202 impact hammer, equipped with a force transducer from PCB, type 208C01 were used. In this case, the force transducer was placed in the tip of the impact hammer and in the tip of the force transducer was placed a rubber tip, to avoid damage to the transducer. The force transducer could be used to calculate the frequency response function, where the natural frequencies are calculated having into account the force that is present upon impact (this technique was not used in this work). The impact hammer's setup is shown in Figure 4.25.

Figure 4.25 – Setup Impact Hammer Experimental Test 3

The experimental test was made with the placement of the sensors in pairings, and then, the structure was placed in free vibration with the use of the impact hammer, through a small impact on the plate. This would ensure that the structure, vibrating freely, would vibrate at its resonant frequencies. The structure was hanged using two small wires connected through holes on top of the structure distancing 5.8 ± 0.5 mm of each edge and with despicable size, to simulate a free plate. After positioning the sensors, a small impact with the impact hammer would put the structure in vibration. For this work, a special setup of PULSE® had to be used, due to the use of the impact. A total of 5 averages were used to diminish the impact of repeatability associated with an impact test. Unlike previous experimental tests, an Exponential window was used instead of the Hanning window.

For the two pairings of sensors, the experimental tests were made with the placement of the sensors in position 1 and impact in impact position 1, placement of the sensors in position 2 and impact in impact position 1 and placement of the sensors in position 2 and impact in impact position 2. The positions used were purposely chosen outside of the influence of the structure's mean line, to minimize the risk of a natural frequency not being detected because the sensor is placed in a node (a point in a vibrating structure that does not move). The positions and impact positions can be seen in Figure 4.26.

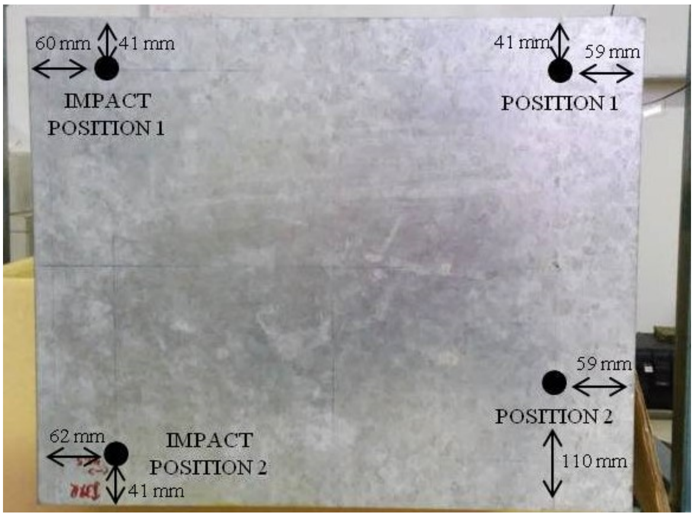


Figure 4.26 – Positions Experimental Test 3

4.4.3.1 Assembly and Results - Experimental Test 3 (Sensor 1 and Sensor 3)

For this experimental test, sensor 1 (MEMS) and sensor 3 (piezoelectric sensor) were placed as seen in Figure 4.27, in this case for position 1, and after this the structure was placed in vibration.

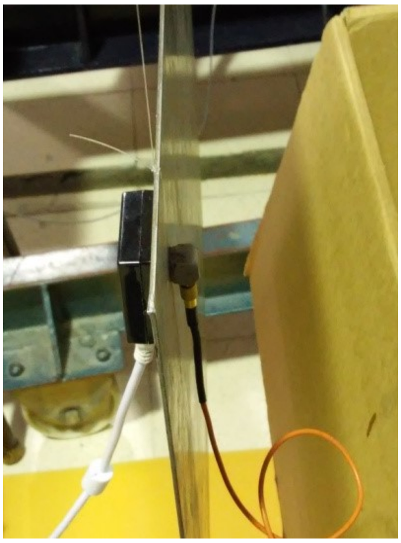
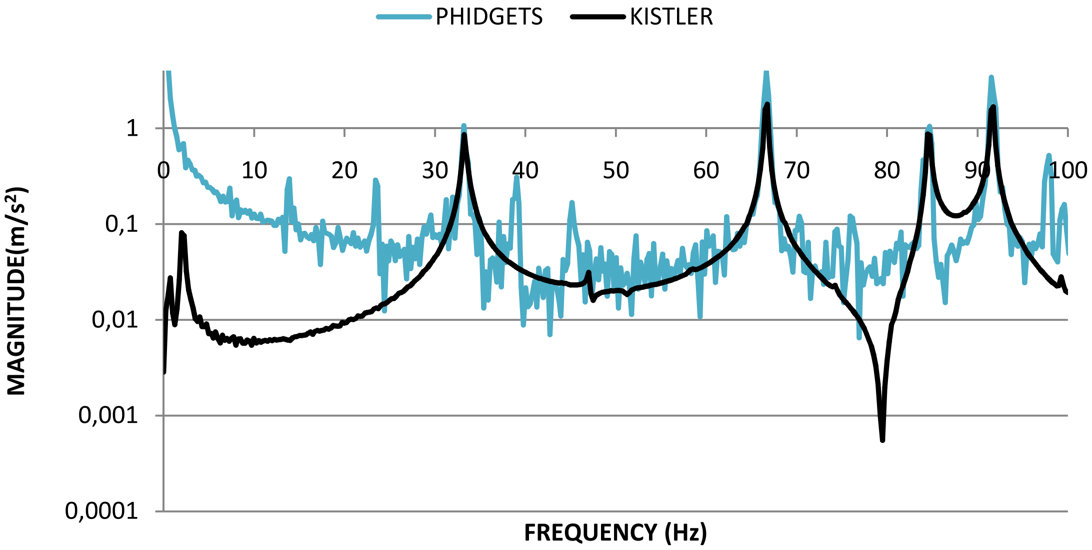
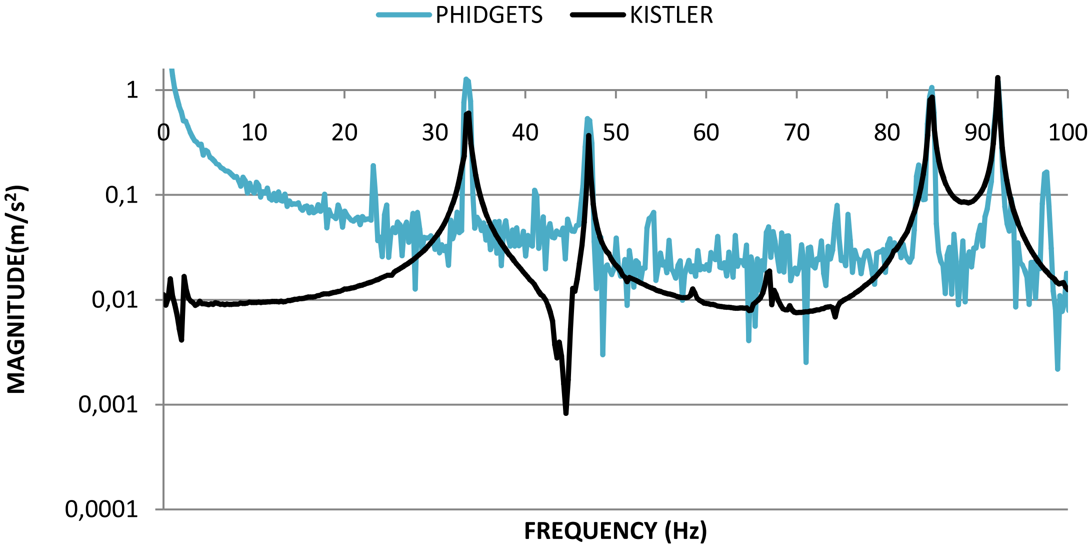


Figure 4.27 – Assembly - Experimental Test 3 Position 1 (Sensor 1 and 3)

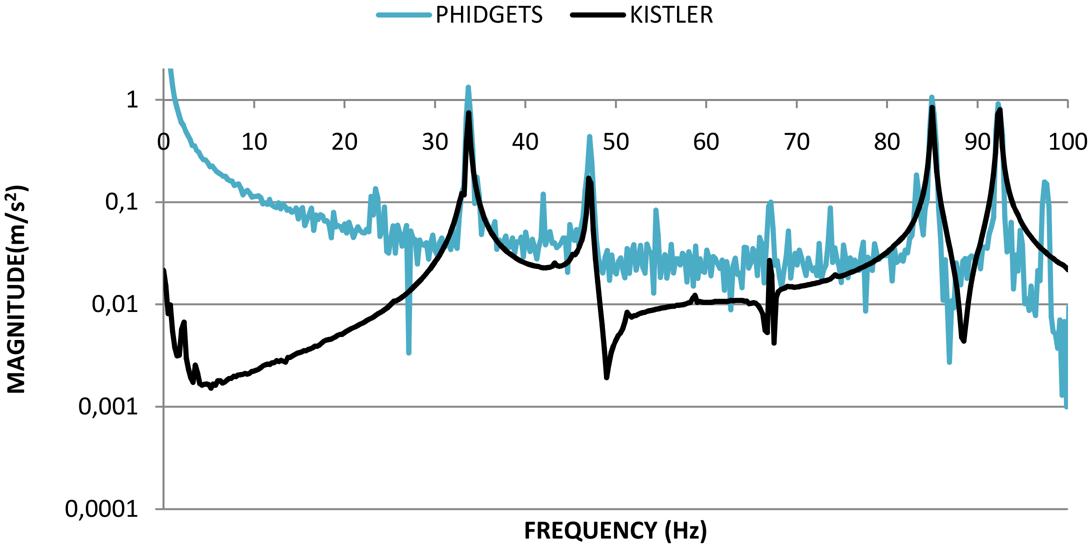
The results of this experimental test are shown in Graphic 4.7, Graphic 4.8 and Graphic 4.9.



Graphic 4.7 – Results - Experimental Test 3 Position 1 Impact Position 1 (Sensor 1 and 3)



Graphic 4.8 – Results - Experimental Test 3 Position 2 Impact Position 1 (Sensor 1 and 3)



Graphic 4.9 – Results - Experimental Test 3 Position 2 Impact Position 2 (Sensor 1 and 3)

Both sensors capture most of the structure’s natural frequencies present in the frequency range of zero to 100 Hz. However, taking the piezoelectric sensor as the benchmark, the values of amplitude captured by the MEMS sensor are not exactly equal, once again corresponding to the manufacturer notification that this sensor is not the most adequate to determine the amplitude of movement. One more characteristic that can be seen is the noise level in the MEMS sensor, which is clearly higher than the piezoelectric sensor, indicating they are not quite ate the same level. Table 4.6 contains the numerical results of the natural frequencies and the amplitude of the movement for all positions, where ΔFrequency=|Frequency$_{\text{Piezo}}$-Frequency$_{\text{MEMS}}$| and ΔAmplitude=|Amplitude$_{\text{Piezo}}$-Amplitude$_{\text{MEMS}}$|.

Table 4.6 – Numerical Results - Experimental Test 3 (Sensor 1 and 3)

POSITION 1 IMPACT POSITION 1					
PIEZO SENSOR		MEMS		-	
Frequency (Hz)	Amplitude (m/s^2)	Frequency (Hz)	Amplitude (m/s^2)	ΔFrequency (Hz)	ΔAmplitude (m/s^2)
2	0,081	UNDETECTED		-	-
33,25	0,860	33,203	1,065	0,047	0,205
47	0,031	45,166	0,168	1,834	0,137
66,75	1,778	66,650	3,880	0,100	2,102
84,5	0,872	84,717	1,052	0,217	0,180
91,75	1,682	91,553	3,412	0,197	1,730
POSITION 2 IMPACT POSITION 1					
PIEZO SENSOR		MEMS		-	
Frequency (Hz)	Amplitude (m/s^2)	Frequency (Hz)	Amplitude (m/s^2)	ΔFrequency (Hz)	ΔAmplitude (m/s^2)
2,25	0,017	UNDETECTED		-	-
33,75	0,604	33,447	1,268	0,303	0,664
47	0,369	46,875	0,533	0,125	0,164
67	0,019	66,895	0,050	0,105	0,031
85	0,857	84,961	1,056	0,039	0,199
92,25	1,315	92,285	1,210	0,035	0,105
POSITION 2 IMPACT POSITION 2					
PIEZO SENSOR		MEMS		-	
Frequency (Hz)	Amplitude (m/s^2)	Frequency (Hz)	Amplitude (m/s^2)	ΔFrequency (Hz)	ΔAmplitude (m/s^2)
2,25	0,007	UNDETECTED		-	-
33,75	0,741	33,691	1,315	0,059	0,574
47	0,171	47,119	0,437	0,119	0,266
67	0,027	67,139	0,100	0,139	0,073
85	0,838	84,961	1,052	0,039	0,215
92,5	0,796	92,285	0,908	0,215	0,112

As it is possible to see in Table 4.6, the most problematic situation is in position 1 impact position 1, as there is a maximum difference in frequency of 1.8 Hz in one of the natural frequencies. However, it all points to this position being a node of this vibration mode, as the amplitude of movement of that natural frequency detected by the piezoelectric sensor is very diminutive. Apart from that position, tests indicate that the MEMS sensor is a very good alternative to the piezoelectric sensor when it comes to detecting the structure's natural frequencies, as the maximum difference in frequency is 0.303 Hz, being most of that difference due to the disparities in sampling frequency.

Everything indicates good accuracy from the MEMS sensor. One important aspect that as to be taken into account when analysing these results is the fact that, because of its positioning in a vertical stance, the MEMS sensor has a lot of noise at very low frequencies, incapacitating it of detecting the first natural frequency of this structure. This is problematic, as this is the fundamental frequency and it is the easiest frequency to be forced as it requires fewer repetitions per second. Again, in terms of amplitude, there are several differences that can reach 100 % the value detected by the piezoelectric sensor. All these factors indicate that, in natural frequency detection, the MEMS sensor is a good alternative

4.4.3.2 Assembly and Results - Experimental Test 3 (Sensor 2 and Sensor 3)

For this experimental test, sensor 2 (piezoelectric film) and sensor 3 (piezoelectric sensor) were placed as seen in Figure 4.28, in this case for position 1 (front a) and side view b) of the structure).

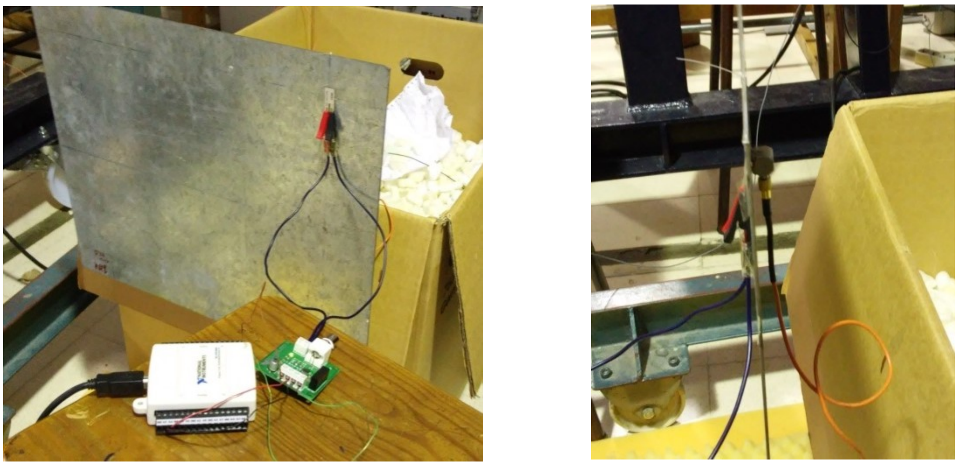
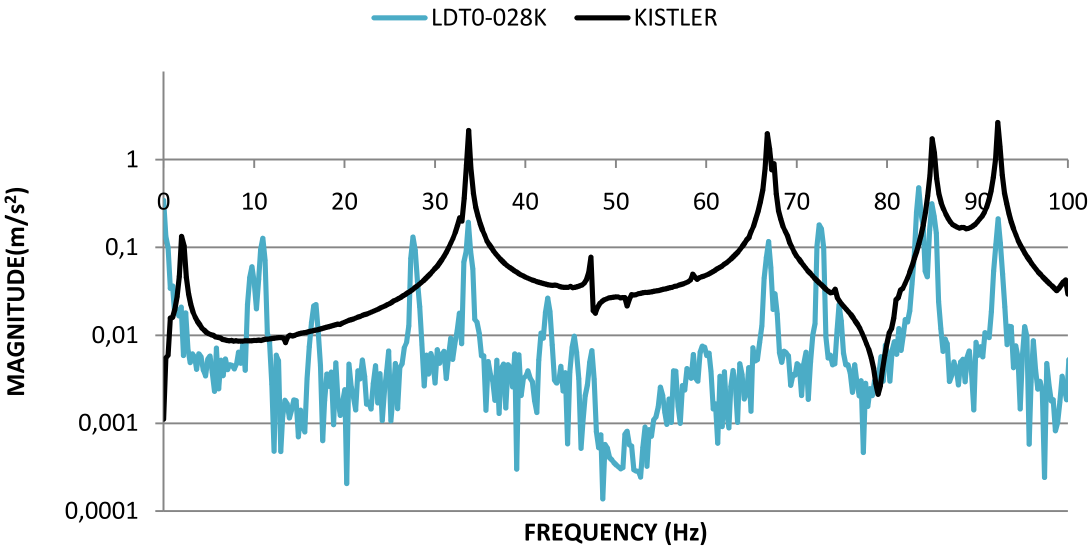
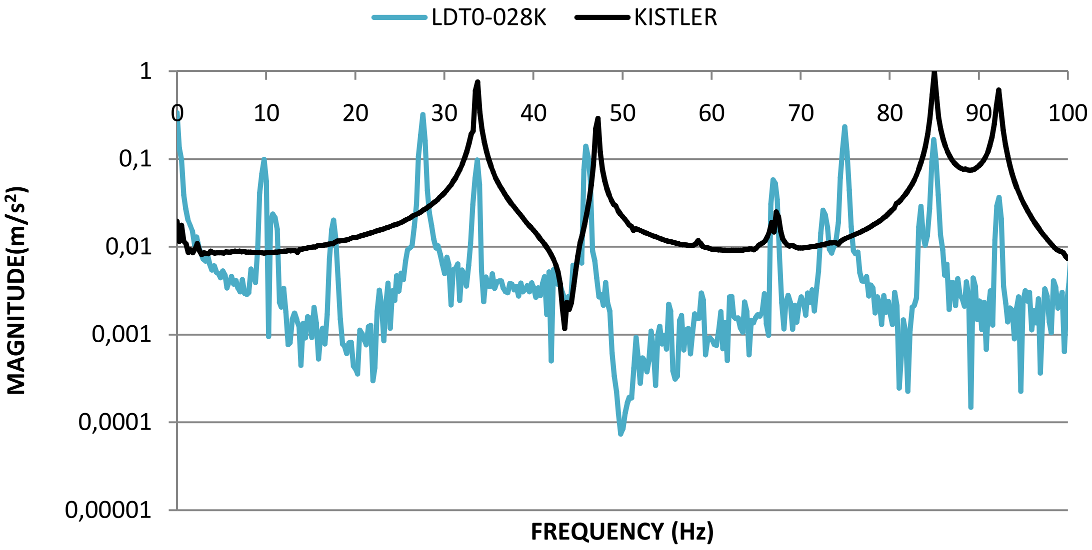

a) b)

Figure 4.28 – Assembly - Experimental Test 3 Position 1 (Sensor 2 and 3)

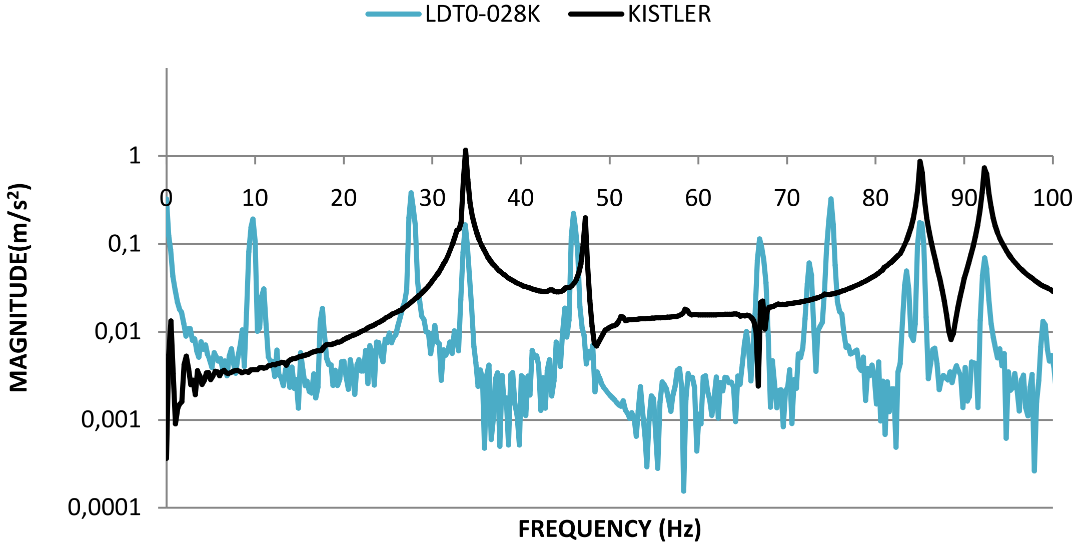
The results of this experimental test are shown in Graphic 4.10, Graphic 4.11 and Graphic 4.12.



Graphic 4.10 – Results - Experimental Test 3 Position 1 Impact Position 1 (Sensor 2 and 3)



Graphic 4.11 – Results - Experimental Test 3 Position 2 Impact Position 1 (Sensor 2 and 3)



Graphic 4.12 – Results - Experimental Test 3 Position 2 Impact Position 2 (Sensor 2 and 3)

As it can be seen, the piezoelectric film detects the frequencies present in the signal, in this case the structure's natural frequencies, but also detects a number of other frequencies that should not be present in the signal, indicating a lot of noise present in the signal or certain frequencies that are originated by the measuring chain and that are captured by the sensor. For example, the 10 Hz frequency is captured in all positions, leading to believe that this is a characteristic of the signal conditioning used, or even a frequency related to the instrumentation that leaks into the results. This can lead to mistakes in analysing the natural frequencies of certain systems, as certain frequencies appear when they should not be present. This can mistake the user to consider them as natural frequencies when they are not truly the system's natural frequencies. Table 4.7 contains the numerical results for all natural frequencies and the amplitude of movement for all positions, where $\Delta\text{Frequency}=|\text{Frequency}_{\text{Piezo}}-\text{Frequency}_{\text{PiezoFilm}}|$ and $\Delta\text{Amplitude}=|\text{Amplitude}_{\text{Piezo}}-\text{Amplitude}_{\text{PiezoFilm}}|$.

Table 4.7 – Numerical Results - Experimental Test 3 (Sensor 2 and 3)

POSITION 1 IMPACT POSITION 1					
PIEZO SENSOR		LDT0-028K		-	
Frequency (Hz)	Amplitude (m/s^2)	Frequency (Hz)	Amplitude (m/s^2)	ΔFrequency (Hz)	ΔAmplitude (m/s^2)
2	0,133	2,441	0,018	0,441	0,115
33,5	0,857	33,691	0,193	0,191	0,664
47,25	0,077	45,410	0,010	1,840	0,068
66,75	1,972	66,895	0,117	0,145	1,855
85	1,717	84,961	0,314	0,039	1,403
92,25	2,635	92,285	0,212	0,035	2,422
POSITION 2 IMPACT POSITION 1					
PIEZO SENSOR		LDT0-028K		-	
Frequency (Hz)	Amplitude (m/s^2)	Frequency (Hz)	Amplitude (m/s^2)	ΔFrequency (Hz)	ΔAmplitude (m/s^2)
2,25	0,011	2,197	0,013	0,053	0,002
33,75	0,755	33,691	0,098	0,059	0,658
47	0,222	45,898	0,140	1,102	0,082
67,25	0,025	66,895	0,058	0,355	0,033
85	0,997	84,961	0,167	0,039	0,830
92,25	0,611	92,285	0,037	0,035	0,575
POSITION 2 IMPACT POSITION 2					
PIEZO SENSOR		LDT0-028K		-	
Frequency (Hz)	Amplitude (m/s^2)	Frequency (Hz)	Amplitude (m/s^2)	ΔFrequency (Hz)	ΔAmplitude (m/s^2)
2,25	0,005	2,441	0,011	0,191	0,006
33,75	1,160	33,691	0,164	0,059	0,996
47,25	0,197	45,898	0,223	1,352	0,026
67,25	0,022	66,895	0,114	0,355	0,091
85	0,866	84,961	0,175	0,039	0,691
92,25	0,732	92,285	0,069	0,035	0,663

The main difference that can be seen in the numerical results presented is in the natural frequency close to 47 Hz. This can be explained by the fact that the signal conditioning of the piezoelectric film requires the use of the bandstop filter that affects the frequency of 47 Hz. The natural frequency captured by the piezoelectric film is the last frequency detected without influence of the filter, hence the difference. This constitutes a limitation of the setup of this piezoelectric film. Apart from this, the difference between the natural frequencies captured is minimal and can be explained in the most part by the differences in sampling frequency. However, the differences in amplitude are considerable, being in some cases 100 % the amplitude value captured by the piezoelectric sensor, indicating once again that in terms of amplitude, this sensor is not recommendable.

4.4.4 Assembly and Results - Experimental Test 4

This experimental test consisted in a low frequency test using for this effect a Newton's Cradle with 140 ± 0.5 mm of length, 140 ± 0.5 mm of width and 150 ± 0.5 mm of height. The balls have 15.7 ± 0.25 mm of diameter each. The Newton's Cradle can be seen in Figure 4.29 a). This structure was created to demonstrate the works of Isaac Newton in the area of conservation of momentum and energy.

The structure used for this experimental test was a Newton's Cradle equipped with a small plywood beam on top of it. The vibration caused by the pendulum's movement would create vibration in the cradle, which would be transmitted to the plywood beam with 173 ± 0.5 mm of length, 72 ± 0.5 mm of width and 2.7 ± 0.25 mm of thickness. The experimental test was made by positioning the piezoelectric sensor and one of the low-cost sensors in the plywood beam, in the positions demonstrated in Figure 4.29 b), and after this, the structure was put into motion. One of the balls was released against the remaining balls, and this movement created a vibration that was transmitted to the position where the sensors were located, through the cradle. The movement was a low frequency one, as the movement and impact of the balls are relatively slow. The frequency of movement was calculated using a stopwatch. This particular cradle has a frequency of movement of around 3 Hz, meaning that, when analysing the results, this frequency should be present, if the sensor has enough sensitivity to detect this motion. One important aspect of these analyses is related to the data processing. In order to diminish the impact of the undesired frequencies, in the program where the data processing was made using LABVIEW®, a lowpass filter with a cut frequency of 10 Hz was added in the software so that only the low frequencies would be present in the signal to be analysed, providing easier conclusions. For the piezoelectric film, the highpass filter that was designed in the program was removed. Also for this test, a change in data processing for PULSE® was made. Instead of the pre-defined highpass filter with a cut frequency of 7 Hz, a highpass filter with a cut frequency of 0.7 Hz was used. The ideal situation was to not use any filter at all, but PULSE® does not allow that. As previously explained, a relative comparison between the values of sensitivity can be made using this test. As the exact value of the MEMS sensor's sensitivity is unknown, this would be very helpful to determine if this low amplitude movement would be detected by the sensor.

a) b)

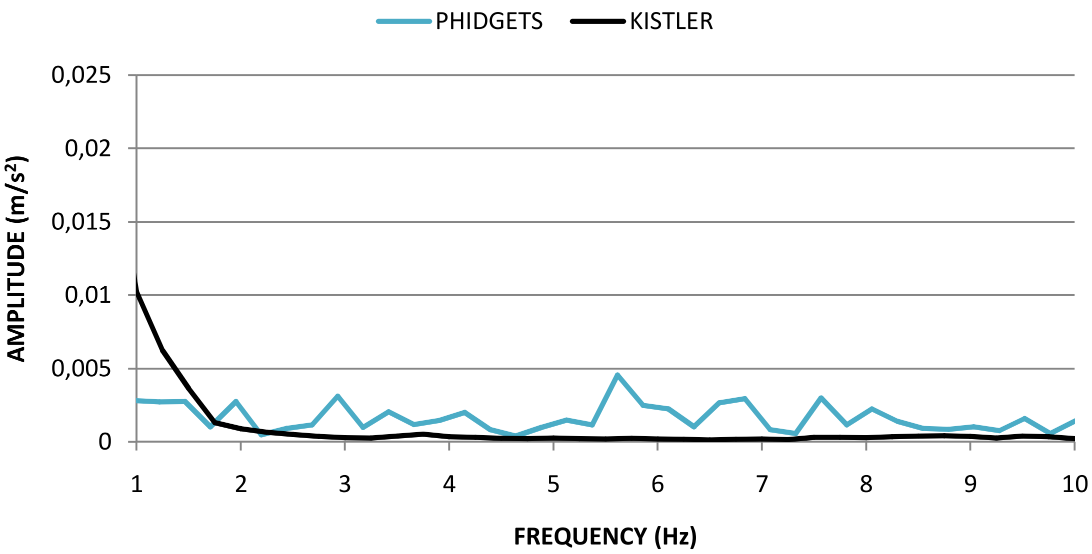
Figure 4.29 – a) Newton's Craddle b) Positions - Experimental Test 4

4.4.4.1 Assembly and Results - Experimental Test 4 (Sensor 1 and Sensor 3)

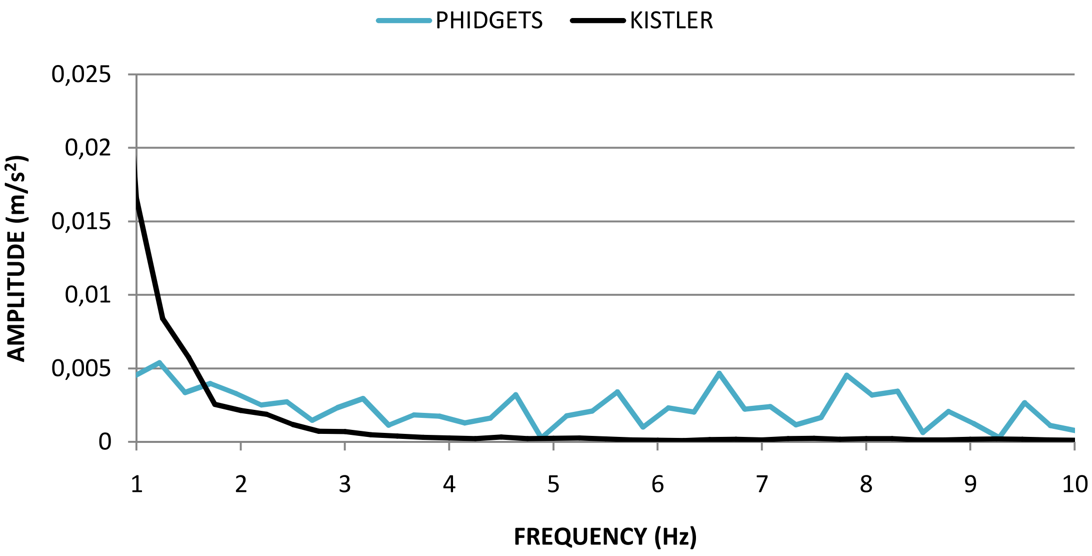
For this experimental test, the sensors, sensor 1 (MEMS) and sensor 3 (piezoelectric sensor), were placed in the positions shown in Figure 4.29 b), one on top and the other on the bottom of the structure, as seen in Figure 4.30. After this, the pendulum was set into motion, with the approximate frequency of 3 Hz.

Figure 4.30 – Assembly - Experimental Test 4 (Sensor 1 and Sensor 3)

The results of this experimental test are shown in Graphic 4.13 and Graphic 4.14.



Graphic 4.13 – Results - Experimental Test 4 Position 1 (Sensor 1 and 3)



Graphic 4.14 – Results - Experimental Test 4 Position 2 (Sensor 1 and 3)

Both graphics for both positions only show the frequencies between 1 Hz and 10 Hz. This decision was made so that the expected frequency of movement, 3 Hz, could be more visible. Also, the resolution of both graphics is not the ideal, but the resolution shown is the maximum attainable with the material available. In both positions, the piezoelectric sensor and the MEMS sensor have different behaviours. Despite the amount of noise present in the MEMS sensor's frequency spectrum, both positions show a peak around the 3 Hz mark. This indicates that the MEMS sensor is able to detect the movement present in the structure, even if it is a small amplitude movement, whilst the piezoelectric sensor does not capture this movement and shows the aforementioned noise level at very low frequencies due to the upside down position (this behaviour is seen in other experimental tests). Therefore, it is possible to conclude that the MEMS sensor has a higher sensitivity level than the piezoelectric sensor, because it is able to detect motion that the benchmark sensor is not. This is coherent with the research's findings in terms of standard sensitivity levels for MEMS sensors. Albeit the used MEMS sensor's exact sensitivity level is unknown, it is possible to conclude that the value of sensitivity is higher than the piezoelectric sensor's sensitivity value, as normally the value of this characteristic for MEMS sensors can be from 140 to 550 mV/g (Albarbar et al, 2008).

4.4.4.2 Assembly and Results - Experimental Test 4 (Sensor 2 and Sensor 3)

In this experimental test the sensors, sensor 2 (piezoelectric film) and sensor 3 (piezoelectric sensor), were placed in the previously described positions, as shown in Figure 4.31, one on top of the structure and the other on the bottom of the plywood beam. After this, the pendulum was set into motion at the approximate frequency of 3 Hz.

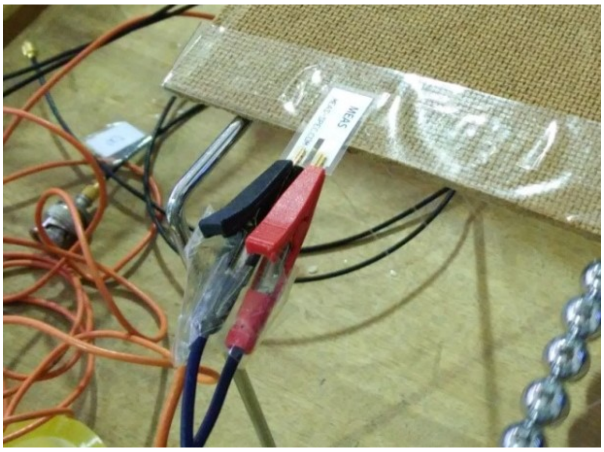
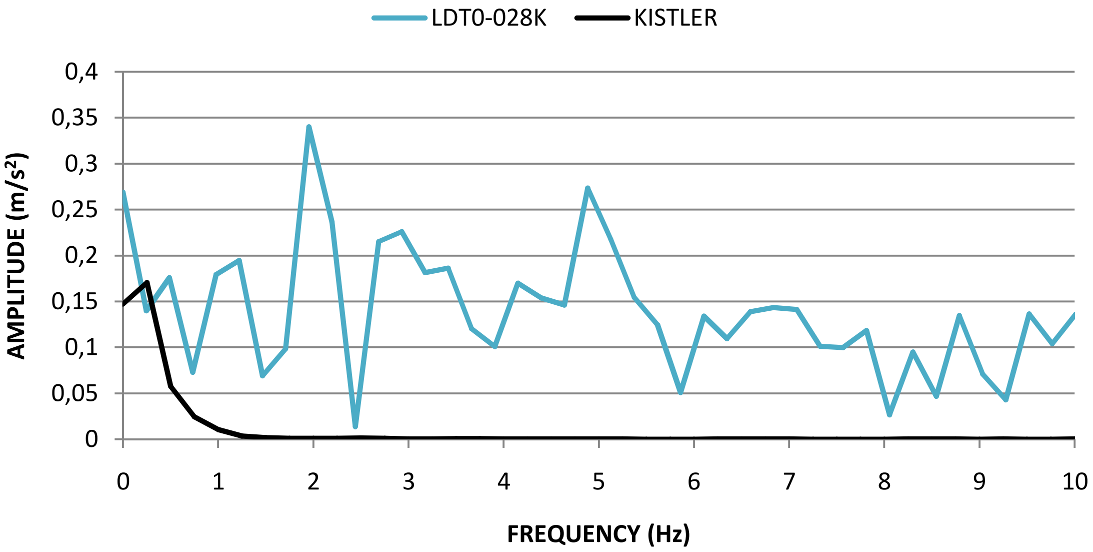


Figure 4.31 – Assembly - Experimental Test 4 (Sensor 2 and Sensor 3)

Using the data processing from PULSE® and LABVIEW® for the respective sensors and after treatment using the appendixes aforementioned, the results of this experimental test for position 2 is shown in Graphic 4.15.



Graphic 4.15 – Results - Experimental Test 4 Position 2 (Sensor 2 and 3)

In this experimental test, only the results for position 2 are shown. This decision was made because the results in both positions, after several tests, are inconclusive and do not allow for a correct assessment of the characteristics of the sensors, being the results for position 2 the ones where the differences are easily seen. There is a lot of noise present in the piezoelectric film's signal, as seen in Graphic 4.15, and there are no evidences that the motion with the 3 Hz frequency is detected by any of the sensors. This indicate that the sensitivity of both sensors is too low for small amplitude movements, and again shows that the piezoelectric film is not the most indicated sensor for vibration detection. The behaviour shown by the piezoelectric film can be explained by the sensor's characteristics. Being a low sensitivity sensor, it is expected that it would have a very large difficulty in capturing movement with small amplitudes, as is the case of this experimental test.

4.5 Comparison through manufacturer information

In Table 4.8 a selection of characteristics of the MEMS sensor (Phidgets Inc, 2012), the piezoelectric film (LDT0 Solid State Switch/Vibration Sensor- Application Note 111398, n.d.) and the piezoelectric sensor (Kistler Instrument Corporation, 2011) can be found.

Table 4.8 – Comparison Characteristics Manufacturer Information

-	PHIDGETS 1041	LDT0-028K	KISTLER 8640A50
Frequency Range (Hz)	Up to 500	Up to Resonant Frequency	0.5 to 5000
Sensitivity (mV/g)	-	50	100.6
Amplitude Range (g)	± 8	-	± 50
Resonant Frequency (Hz)	-	180	25000
Temperature Range (°C)	-40 to 85	Up to 85	-40 to 65
Mass (grams)	13.54	Negligible	3.5
Size (mm)	39 x 36 x 15	30.1 x 13 x 0.4	16.8 x 10.2 x 10.2

As it is possible to see in the previous table, some of the characteristics of the MEMS sensor are similar to the ones of the piezoelectric sensor. The MEMS sensor’s limitations are mostly related to amplitude range, where this model of MEMS sensor only allows measurements up to 8 g’s, whilst the piezoelectric sensor allows measurements up to 50 g’s, and frequency range, much larger in the case of the piezoelectric sensor. Some of the MEMS sensor’s characteristics are not available through manufacturer information, but are comparable using the experimental tests. In the case of the piezoelectric film, the comparison with the piezoelectric sensor is not favourable. The low resonant frequency, small frequency range and low sensitivity make the piezoelectric film a very limited sensor, only usable in applications where, for example, the frequencies in analysis are low. All three sensors have a usable temperature range that is very similar, meaning that in terms of temperature all sensors are usable in the same conditions. The user has, however, to take into account if the environment where the sensor is to be used is contaminated or is rough. In that case, the piezoelectric sensor’s titanium housing makes it the most recommendable. One characteristic that makes the MEMS sensor more versatile is the fact that it is able to collect acceleration data not only from one axis (like all other sensors in study), but from the three Cartesian axles.

5. **Conclusions**

Chapter five is where all the conclusions from the experimental tests and about the applicability of the sensors are presented. It is also possible to find in this chapter the questions that the author believes should be addressed as future works to deepen the conclusions.

5.1 Conclusions from Experimental Tests

The set of all experimental tests allowed for a number of conclusions to be taken. The initial conclusions are related to the mounting of the sensors studied. As previously described, all sensors were mounted using adhesive. Each type of adhesive was used taking into account the characteristics of each sensor. In terms of versatility of mounting, the piezoelectric sensor allows more mounting versions, as adhesives, pins, studs, etc, making it a more reliable sensor. This has to do with the transmission of vibration. A sensor that is mounted through a pin to the system to analyse has more vibration transmitted to it than a sensor that is connected to the system through the use of an adhesive, as a sensor connected through a pin is almost an integral part of the system. The use of an adhesive tack also creates a damping of the vibrations transmitted to the structure. This means that there is the risk that the MEMS sensor, that had to be connected to the structure through an adhesive tack, could not detect the totality of the vibrations to which the structure is subjected (both in terms of frequency and amplitude). The piezoelectric film ideally should be connected to the structure using some sort of weld. This makes it much less versatile, as a sensor that is connected through weld will not be removed easily and not all systems have the possibility of having a welded sensor to it, meaning that the piezoelectric film cannot be used in many applications.

Another conclusion that can be obtained through the experimental tests has to do with size. The piezoelectric sensor has a very diminutive size, making it more applicable to vibration analysis in tight spaces, in opposition to the MEMS sensor that is much larger and heavier. The piezoelectric film is a special case, as the sensor’s size is very small, but associated to it there is always the signal conditioning and acquisition apparatus, that has to be very close to the sensor. As such, the limitations in space of certain applications, and even limitations in positions of test make this an unviable option.

Similar conclusions can be made about the mass of the sensors. Comparing the two most reliable sensors in use, the MEMS sensor and the piezoelectric sensor, this last one has a smaller mass, meaning that is the one that will have less impact in the characteristics of the system in analysis. The piezoelectric film has a very small mass, despicable in fact, meaning that it will not affect the structure's characteristics. However, the user has to take into account the measuring chain that cannot be placed on the system itself, but has to be very close to the sensor, meaning that there has to be a compromise.

One of the most important characteristics to consider when choosing a sensor for vibration analysis is sensitivity. The low amplitude test results point to the MEMS sensor having a higher sensitivity, meaning that, for applications where the amplitude of movement is small, the MEMS sensor is even more recommendable than the piezoelectric sensor. The piezoelectric film, in the format that was used for this work, is not recommendable for low frequencies or low amplitudes, as it is not very sensitive to low frequency movements and is very sensitive to noise, as seen in all ranges of frequencies (including the supposedly clean frequency range of experimental test 2). The MEMS sensor's noise level, as shown in experimental test 2, is very similar to the noise level present in the benchmark sensor, leading to believe that the signal conditioning present in the MEMS sensor's construction is extremely effective, in some ranges even better than the one used with the piezoelectric sensor, pointing to the validity of the results acquired by the MEMS sensor.

Experimental test 1 shows once again the similarity in characteristics between the MEMS sensor and the piezoelectric sensor. The accuracy of both can be considered equal, as the difference in the dominant frequency calculated can be attributed to the difference in sampling frequency, but the similarities in accuracy are mostly seen in the amplitude of the dominant frequencies used. The values recorded are almost precisely the same between the MEMS sensor and the piezoelectric sensor, indicating once again the excellent MEMS sensor's characteristics in terms of accuracy. The same cannot be said about the piezoelectric film, which has values of amplitude very different from the values registered by the piezoelectric sensor, indicating a very poor accuracy.

Experimental test 3 once again shows that the MEMS sensor is a true alternative to the piezoelectric sensor in terms of natural frequency identification. The analysis of the amplitude of movement shows some limitations, but that is informed in the MEMS sensor's user manual. The readiness to use of the MEMS sensor once more proves to be an advantage, as it is easier to use than the piezoelectric sensor and certainly much easier to use than the piezoelectric film. The piezoelectric film is acceptable when it comes to determining the natural frequencies, but in terms of amplitude is not viable, and in terms of setup and instruments to use it imposes a lot of constraints.

5.2 Applicability of Sensors Used and Final Conclusions

The initial objective of the experimental tests was to compare the two low-cost sensors that were available to the piezoelectric sensor in a number of characteristics, chosen because of their influence in condition monitoring and SHM. This would include an analysis of natural frequencies because this analysis has an implication in condition monitoring and SHM, being an important part of them, as it is extremely important to determine natural frequencies of systems so that they would not be forced to enter resonance, or even to detect changes in the natural frequencies. In condition monitoring and SHM it is also important to determine with accuracy the frequency and amplitude at which a system is vibrating, as this is important to compare with the knowledge of the system characteristics but also to help in the diagnosis of certain problems. For example, the amplitude of vibration can indicate the severity of a problem.

The objective of this work was achieved, even if the approach to the experimental tests was not the initially planned. As the means available for this work were scarce, that meant that the tests made had to be adapted having in mind the work's final objective and what was available. The tests performed, despite the limitations in equipment, allowed the comparison of not only the characteristics described previously but also when certain systems are under two different types of vibration, forced and free. The ultimate conclusion of this work is that today, MEMS sensors are a very good alternative to piezoelectric sensors and can be used with confidence, but always with the reservations described in previous chapters. It has the advantages of being reliable in several conditions, fairly accurate when comparing to the piezoelectric sensor, being much cheaper and very ready to use. When comparing, the cost of use of this MEMS sensor is much inferior to the piezoelectric sensor's cost of use, as this sensor needs all the equipment indicated, and this fact only comes to show that MEMS sensors are in fact a very good alternative to piezoelectric sensors, even better than the piezoelectric film, that is cheaper than the MEMS sensor but also needs all the apparatus that inflates the cost of its use. The piezoelectric film also does not provide the most accurate results and is a lot more difficult to use. Many users, accustomed to using the piezoelectric sensor, will not be open to the use of MEMS sensors, but increased research and the studies of this work have shown the viability of this technology. One of the biggest advantages of the MEMS sensor used was that it can be utilized using portable equipment (portable computer), whilst the piezoelectric sensor has the signal conditioning and acquisition equipment fixed in a position, meaning that the system to analyse has to be placed in a position close to the equipment. This is one of the plusses of using MEMS based technologies, indicating once again that this is a true alternative to the established piezoelectric technology.

5.3 Future Works

In order to obtain further information about the sensors studied, one of the solutions that could be adopted would be the use of more specialized equipment, such as low and high frequency shakers, noise analyzers or tilt tables to perform more experimental tests and to take conclusions about more characteristics of the sensors. Other structures or even machines could be analysed, as that would allow for more conclusions related to the sensor's behaviour in a true vibration analysis environment. An ideal situation would be using the sensors in a machine that had a previous vibration analysis performed (with other vibration sensors) and an historic of results. With this, a comparison of results would be possible between the results of the sensors studied in this work and the historic of results of that machine. One improvement that could also have been made for this work would be the use of only two software for signal processing. LABVIEW® has the potential to perform advanced signal processing, dispensing the use of other software (Microsoft Excel®) and it even has the possibility of integration with other software (for example PULSE®). Another option to extend the analysis made in this work would be the use of other sensors, of different technologies or even similar technologies but more advanced.

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