FACULTY OF TECHNOLOGY

THE SUITABILITY OF LOW-COST MEASUREMENT SYSTEMS FOR ROLLING ELEMENT BEARING VIBRATION MONITORING

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ABSTRACT

The Suitability of Low-Cost Measurement Systems for Rolling Element Bearing Vibration Monitoring

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Supervisors at the university: Toni Liedes

The aim of this thesis is to study if inexpensive vibration monitoring systems could be suitable for condition monitoring of rolling element bearings and if they could be able to detect bearing defects at an early stage. As a starting point the following set of requirements for the system have been defined: the system should be priced below 100 €, it should be able to measure the vibrations reaching up to 10 000 Hz frequencies and the amplitude resolution of the system should be at minimum 16-bits. The ability of the system to be part of internet of things (IoT) is also seen as a positive thing and an advantage. While searching for an adequate system, a market review consisting low-cost vibration monitoring devices and low-cost vibration monitoring components has been done. A secondary aim of the work is to highlight the impact of different components of the signal chain to the measured vibration signal itself and familiarize the reader with the signal chain found in vibration monitoring.

To fulfill the main objective of the thesis, a broad market review was performed and it was mainly done by searching the Internet. Experimental tests for the low-cost equipment were also done to find out their real competence. The suitability of the found components were tested in various ways including calibrations of accelerometers and an investigation of the capability of Raspberry Pi 3 model B single board computer. The capability of Raspberry to act as a platform for accelerometers and its ability to sample the incoming high-frequency signals from accelerometers were checked. The effects of the vibration monitoring components to the gathered data were examined through simulations done with math software called Mathcad. The literature review that was carried out is used to introduce the signal path of the vibration monitoring signal hand in hand with the simulations.

The results of the work include state-of-the-art information of low cost vibration monitoring devices and introduction to some not so familiar vibration monitoring options that may have the potential to be used in bearing condition monitoring. The documented signal chain simulation models shown in the appendixes contribute to the understanding of vibration signal chain and allow for their further use. The conclusion of this thesis is that a 100 € budget is too tight for a high-quality and general-purpose vibration monitoring device for early bearing defect detection.

Keywords: condition monitoring, bearings, vibration

TIIVISTELMÄ

The Suitability of Low-Cost Measurement Systems for Rolling Element Bearing Vibration Monitoring

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Oulun yliopisto, Konetekniikan tutkinto-ohjelma

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Työn ohjaaja yliopistolla: Toni Liedes

Työn tavoitteena on tutkia kykeneekö edullinen värähtelynmittauslaitteisto vierintälaakereiden kunnonvalvontaan ja laakerivian aikaiseen tunnistamiseen. Lähtökohtana annettujen vaatimuksien mukaan laitteiston tulisi olla hinnaltaan alle 100 €, sen olisi kyettävä mittamaan värähtelyä yltäen jopa 10 000 Hz taajuuksiin ja laitteiston amplitudiresoluution tulisi olla minimissään 16-bittiä. Myös laitteiston kyky olla osa laitteiden Internetiä (internet of things; IoT) katsotaan eduksi. Kykenevää laitteistoa etsiessä työssä esitellään myös katsaus tällä hetkellä markkinoilta löytyviin edullisiin värähtelymittauslaitteisiin ja värähtelymittauskomponentteihin. Toissijaisena tavoitteena työssä on tuoda esille värähtelymittauslaitteistoissa olevien komponenttien vaikutus värähtelysignaaliketjuun ja mittauslaitteistolla saatuun dataan sekä perehdyttää lukijaansa värähtelysignaaliketjuun.

Päätavoitteen täyttämiseksi suoritettiin laaja markkinakatsaus pääosin Internetiä käyttäen. Myös markkinoilta löydettyjen värähtelymittauskomponenttien soveltuvuutta testattiin kokeellisesti muun muassa edullisia kiihtyvyysantureita kalibroiden sekä tutkien Raspberry Pi 3 model B - yhden piirilevyn tietokoneen ominaisuuksia. Työssä arvioitiin ja testattiin Raspberryn kykenevyyttä toimia alustana kiihtyvyysantureille ja kyvykkyyttä näytteistää kiihtyvyysantureilta tulevaa korkeataajuuksista signaalia. Värähtelymittauskomponenttien vaikutusta värähtelysignaaliin ja siitä saatavaan informaation tutkittiin Mathcad -laskentaohjelmalla tehtyjen simulointien myötä. Värähtelysignaaliketjuun tutustuttiin simulointien lisäksi ja simulointien tukena kirjallisuuskatsauksen muodossa.

Työn tuloksena saavutettiin laaja katsaus tämän hetken edullisiin värähtelymittauslaitteistoihin ja tuotiin esiin myös mahdollisesti hieman tuntemattomiakin värähtelymittausratkaisuja, joilla voi olla potentiaalia kunnonvalvonnan värähtelymittauksiin. Työn liitteenä olevat signaaliketjun simulointimallit edesauttavat ymmärtämään värähtelymittauksen signaaliketjua sekä mahdollistavat myös niiden jatkokäytön. Työ myös paljastaa, että 100 € budjetti on liian tiukka laadukkaaseen ja yleiskäyttöiseen värähtelymittaukseen perustuvaan vierintälaakereiden kunnonvalvontalaitteeseen.

Asiasanat: kunnonvalvonta, laakerit, värähtely

PREFACE

This Master's thesis was done for VTT Technical Research Centre of Finland Ltd during the end of the year 2016 and the beginning of the year 2017. The objective of the thesis was to figure out the available low-cost vibration monitoring systems and their capability for vibration monitoring of rolling element bearings

I want to thank VTT for giving me this opportunity to write the thesis and be part of the company, and my supervisors Erkki Jantunen from VTT and Toni Liedes from the university of Oulu. Also I want to thank Jouni Laurila from the university of Oulu for examining the thesis.

Oulu, 19.04.2017

Jarno Junnola

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LIST OF ABBREVIATIONS

ADC	Analogue-to-Digital Converter
AFE	Analogue Front End
ALU	Arithmetic and Logic Unit
AMP	Amplifier
ASIC	Application Specific Integrated Circuit
CPU	Central Processing Unit
DAC	Digital-to-analogue converter
DSC	Digital Signal Controller
DSP	Digital Signal Processing
DSP	Digital Signal Processors
FPGA	Field Programmable Gate Arrays
GPIO	General-Purpose Input-Output
I/O	Input/Output
I2C	Inter-Integrated Circuit
I2S	Inter-IC Sound
IC	Integrated Circuits
IDE	Integrated Development Environment

IoT	Internet of Things
MCU	Microcontroller Unit
MEMS	Micro Electro Mechanical Systems
MISO	Master-In Slave-Out
MOSI	Master-Out Slave-In
OP-AMP	Operational Amplifier
PCB	Printed Circuit Board
SAR	Successive Approximation
SBC	Single-Board Computer
SBM	Single-Board Microcontroller
SoC	System on a Chip
SPI	Serial Peripheral Interface
Sps	Samples per second
SS	Slave Select
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus

1 INTRODUCTION

Vibration monitoring is the most used method in condition monitoring of rotating machines and it can also be used in operational control and troubleshooting (Nohynek, Lumme 2004, p. 17). Bearings are seen as one the most critical parts defining the health of machines and their remaining lifetime in current production machines (El-Thalji 2016, p.11). The condition of a bearing is usually followed by monitoring vibrations and normally accelerometers are used as instruments to sense the vibrations (Tandon, Choudhury 1999, p.469 & p.474, Safizadeh, Latifi 2014, p.2).

Unfortunately, the total price of a vibration monitoring device for detecting bearing faults may be a five figure number which motivates the search for cheaper options (TEquipment 2017). The decrease in price of vibration monitoring devices makes it economically beneficial to carry out vibration monitoring also with assets that do not cause so huge risks to production or to safety. When introducing condition monitoring to new machines there is always the financial question i.e. does the company gain or lose with condition monitoring. The gain is usually measured in money and thus the price of the measuring equipment has a meaning. The gain could also be a safer working environment or better product quality earned through condition monitoring.

1.1 Research questions and objectives

Inspired from few euro accelerometers that have come to market, like LIS2DH and LIS2DS12 from STMicroelectronics, it is interesting to know if these low-cost accelerometers are capable to be used in condition monitoring of rolling element bearings. Consequently, the first research question is: *Are accelerometers cheaper than 10 euros capable to be used in rolling element bearing condition monitoring applications for early defect detection?*

A low-cost complete measurement system for bearings from accelerometer to processed vibration signal was another motivation. Are there complete measurement systems which can measure signals up to 10 000 Hz with a minimum resolution of 16-bit and are these available under 100 euros. It was also hoped that the measurement system would have some sort of readiness level for IoT. The second research question is: *Is it possible to get a vibration monitoring system under 100 euros that is capable to measure signals with frequency content up to 10 000 Hz, to give processed vibration signal information of bearing faults and is connectable to be a part of internet of things?*

Related to the previous questions, the third question handles about what kind of parameters measurement devices have and what kind of meaning do they have related to the gathered data. The third question is: *What is the meaning of individual vibration monitoring components (ADC, filter, amplifier etc.) in signal chain and how do they affect to the gathered information?*

In summary, it can be said that the main objective of this thesis is to find out if it is possible to do bearing condition monitoring with really cost-effective equipment. To reach this main objective, a number of secondary objectives have to be reached: evolution of bearing faults have to be known at some state, the needed properties for bearing measurement devices have to be defined so that the devices are able to detect bearing failures in an early stage and a market review has to be done to get the knowledge of the available measurement systems and components nowadays.

1.2 Contents of the thesis

The thesis covers areas from explaining why condition monitoring is done to the availability of low-cost bearing monitoring systems. The thesis tries to shed light on which kind of components are included in vibration measurement devices, which kind of properties do these components have, which kind of changes come to measurement results if these properties are changed and which kind of properties are needed from vibration measurement device components to be used in the rolling element bearing condition monitoring. The following content of the thesis is divided into six chapters to cover the subjects mentioned:

- Chapter 2 explains why condition monitoring is done and presents ways how rolling element bearing condition monitoring is done including vibration monitoring, temperature monitoring and lubricant analysis.
- Chapter 3 explains the features of different measurement device components and shows their effect on measuring results.
- Chapter 4 summarizes the market review of vibration measurement devices.
- Chapter 5 presents the testing of Raspberry Pi3, EVAL-AD7609, ADXL001 and ACH 01.
- Chapter 6 discusses about the results gained from chapters 4, 5 and 6.
- Chapter 7 offers the thesis summary and proposals for future work.

1.3 Scientific contribution of the thesis

This thesis shows the current state of cheap vibration measuring devices and possible few considerable low-cost approaches to be used in vibration based condition monitoring. Some of the vibration monitoring components are simulated and the simulation methods are described in the appendixes. Simulations clarify the suitability of different kind of vibration monitoring devices.

2 CONDITION MONITORING

Condition monitoring tools are used in Condition Based Maintenance to analyse the current health condition of an asset and consequently, set up proper preventive maintenance schedules (Bengtsson 2004, p.1) . Without knowing the state or the usage of the machine it is impossible to do condition based or predictive maintenance. Condition monitoring has shown a huge positive effect on increasing the utilization rate of machines and increasing profitableness (Nohynek, Lumme 2004, p.7 & p.11). The profits of condition monitoring are an increase in productivity, a better possibility to do scheduled/planned maintenance, a better utilization of downtime, a decrease in unplanned shutdowns and an increase in the lifetime of machines (Nohynek, Lumme 2004, p.11).

2.1 Financial benefits

By sacrificing working hours and financial resources to condition monitoring gives huge savings from maintenance (Nohynek, Lumme 2004, p.13). By doing the condition monitoring right, it decreases unexpected shutdowns, decreases unnecessary machine openings, reduces the need for big spare part storages and shortens the unavoidable, planned and necessary downtimes (Nohynek, Lumme 2004, p.13). Downtimes can be divided in two parts: waiting time and maintenance time (Nohynek, Lumme 2004, p.12). Waiting time consists of noticing the failure, picking up the proper documents for the case, reserving personnel to do the maintenance, reserving tools for maintenance, reserving spare parts from a storage and purchasing spare parts if those cannot be found from storage (Nohynek, Lumme 2004, p.12). Just after following all the previous steps that are included in the waiting time it is possible to start the maintenance itself.

All of the tasks of the waiting time can be done while processes are running if condition monitoring is used and thus shorten the downtime and consequently save money. Also, the maintenance time itself can be reduced if condition monitoring is applied. The maintenance time reduction comes from the facts that maintenance can be planned more precisely when the failure is known beforehand and failures can be fixed before they grow for more serious breakdowns.

Other financial benefit comes from the decrease of unplanned shutdowns. When there are fewer shutdowns, the usage times of machines are higher and, therefore, the availability of the asset increases. This way the Overall Equipment Efficiency also increases, thus, increasing the profitability. In most cases, unplanned shutdowns can be reduced more than 50 % when moving from corrective maintenance to condition monitoring based maintenance (Nohynek, Lumme 2004, p.12).

2.2 Safety aspects

Machine failures or improper use can cause very expensive financial loses, but more importantly, the worst scenario would be if the personnel get injured. Machines with high safety risks are equipped with measurement systems i.e. condition monitoring systems that control the machine by themselves. For example, if a failure or malfunction is detected the safety system can shut down the machine or otherwise put it in safe-mode and consequently prevent expensive failures or personnel injuries (Nohynek, Lumme 2004, p.15). Typical systems among others that have this kind of safety systems are turbines, compressors, machines with pistons, grinders and big electric motors (Nohynek, Lumme 2004, p.15). Consequently, in generalization big, expensive and high revolution rate machines usually have safety systems.

2.3 Rolling element bearing condition monitoring

Historically condition monitoring was mainly done using senses: bearings were listened using a wooden stick, temperatures of machines were felt by hands, vibrations of machines were checked by hands or feet and so on (Nohynek, Lumme 2004, p.13). Also, the quality of the manufactured products was one way to follow the condition of production machinery (Nohynek, Lumme 2004, p.13). These previously used methods have still a place in condition monitoring and they should not be underestimated but, nowadays, condition monitoring is based on different measuring methods (Nohynek, Lumme 2004, p.13). Rolling element bearings are mainly monitored using three methods: vibration monitoring, temperature monitoring and wear debris analysis which includes lubrication analysis (Tandon, Choudhury 1999, p.469). Out of those three previously mentioned methods vibration monitoring is the most used one (Tandon, Choudhury 1999, p.469). The following paragraph will introduce all of these three methods.

2.3.1 Vibration monitoring

Vibration monitoring is the most used method and when used correctly it is the best condition monitoring method to follow the condition of a rotating machine (Nohynek, Lumme 2004, p.17, Shahzad, Cheng et al. 2013, p.670). Vibration monitoring can also be used for operation control to adjust the parameters of a process. Also because of the wide usage and the effectiveness of vibration monitoring, this thesis will mainly focus on this method.

To detect rolling element bearing failure in an early stage of failure evolution, vibration monitoring should be done in the natural frequency area of a bearing. Natural frequencies are better information sources of defect than commonly followed bearing fault frequencies in an early stage because amplitudes of fault frequencies are so small in the beginning of degradation and because of the phenomenon called slippage (El-Thalji 2016, pp. 46-47). Slippage causes that impacts do not follow the fault frequencies so accurately and thus the amplitudes of fault frequencies do not increase in the matter that they are expected to increase. When the rolling element passes the early stage fault, the contact and the impact between rolling elements and raceways might awake the natural frequencies of bearing raceways and thus it is wise to monitor the natural frequencies of bearing raceways to detect bearing failures in an early stage. A rough estimation of natural frequency of a raceway can be calculated with the following equation (1):

$$\omega = E/(\pi D) \tag{1}$$

where E is the speed of sound in the material and D is the diameter of a raceway (Sassi, Badri et al. 2007). If more information like the moment of inertia of the race cross section, the mass per unit length and/or the cross-sectional constant of a bearing is available, then more accurate functions, that are collected together also by El-Thalji (2016, pp.46-47), can be used when calculating natural frequencies.

The mentioned goal of this thesis to find a measurement system that is capable to measure up to 10 000 Hz signals would lead to a system which is capable to measure the natural frequencies of steel bearings from diameter 3 cm upwards. The capability to measure 10 000 Hz signals means of course that an ADC has to fulfill the Nyquist theorem and it has to be able to sample at least 20 000 samples per second (Gatti, Ferrari 2002, pp.754-755). In comparison, a system with the capability to measure 1 000 Hz signals would lead to a device which could detect natural frequencies starting from 30 cm diameter bearings. Diameters are calculated with equation (1) firstly solving the diameter out of the equation and then putting variables in place. When we know that E is 5900 m/s in steel, $\boldsymbol{\omega} = 2\boldsymbol{\pi}$f and f is 10 000 Hz or 1000 Hz in these cases, we can calculate the diameter in the following way (J. Johansson, P. e. Martinsson et al. 2007, p.1980, Mäkelä 2008, p.95):

$$D = E/(\omega\pi) = E/(2\pi f \times \pi) = 5900/(2\pi \times 10000 \times \pi) \approx 0{,}030 \text{ m},$$

$$D = E/(\omega\pi) = E/(2\pi f \times \pi) = 5900/(2\pi \times 1000 \times \pi) \approx 0{,}299 \text{ m}.$$

There are plenty of vibration monitoring methods but those can be categorized into two classes: the first class methods are used for monitoring overall vibrations and simple statistical vibration signal parameters of rolling bearings while the second class methods are more focused on monitoring detailed vibration and a wider range of bearing parameters (Nohynek, Lumme 2004, p.18). With the first class methods it is normal to use two vibration measurement devices: one device to monitor overall vibration in the range of 10 Hz – 1000 Hz and a second one to measure frequencies typically above 2000 Hz. The overall vibration in the frequencies from 10 Hz to 1000 Hz roughly reveals the problems related to a rotating shaft such as imbalance, misalignment and looseness of connections (Nohynek, Lumme 2004, p.18). The second measuring device to monitor frequencies above 2000 Hz is mainly used to detect rolling element bearing failures. It should be noted that vibration in high frequencies noticeably increase when lubrication is poor in rolling bearing, an indentation occurs or when other bearing failures appear (Nohynek, Lumme 2004, p.18). The second measurement device might also be an ultrasonic measurement device which is used to detect bearing failures but also to detect gas and liquid leakages (Nohynek, Lumme 2004, p.18). First class methods are sensitive enough to monitor simple machines which do not have multiple shafts spinning at multiple speeds (Nohynek, Lumme 2004, p.18).

When machines have multiple shafts with different rotational speeds and/or power transmission units, the second class measurement devices must be used. The first class devices are not able to separate different vibration sources from each other and it is hard to detect the source of the problem (Nohynek, Lumme 2004, p.18). For example, high overall vibration levels could be caused by a big unbalance in some of the shafts, a misalignment error, a bearing failure, a looseness of mounting, a resonance of a structure or the cavitation of a pump, but the first class equipment are not capable to locate the source (Nohynek, Lumme 2004, p.18). In these more complex cases one or various multichannel spectrum analyzers is needed.

With a spectrum analyzer it is possible to separate different frequencies and their amplitudes from the signal. Different frequencies are caused by different parts of the machine and thus it is conceivable to follow the state of different machine components pretty reliably (Nohynek, Lumme 2004, p.19). Spectrum analyzers enable the analysis and more complex monitoring that uses signal analysis methods like envelope analysis, phase-analysis and cepstrum analysis (Nohynek, Lumme 2004, p.19).

Kuntoon perustuva kunnossapito – handbook (title translation in English: Condition Based Maintenance) has a different approach in categorizing vibration monitoring devices: vibration pens and other basic handheld meters, portable data collectors, multiple channel FFT analyzers and PC based measurement devices and permanently mounted online analyzers & data collectors (Miettinen, Miettinen et al. 2009, pp.259-263). Vibration pens and other basic handheld meters measure one or multiple parameters (most commonly overall velocity of vibration from a fixed bandwidth) and they can have data transferring and storing capabilities. Vibration pens and other basic handheld meters can be used for very basic condition monitoring carried out for example by an operator while operating a machine. Portable data collectors usually have a large memory, a display and a wide variety of frequency and time domain tools for signal analysis. Portable data collectors can be used by their own or in an interaction with a computer. Multiple channel FFT analyzers and PC based measurement devices have commonly 8-64 channels, very high sample rate and very wide range of signal analysis tools. Multiple channel FFT analyzers and PC based measurement devices are used in case of difficult vibration problems and their usage needs expertise and theoretical knowledge. Permanently mounted online analyzers and data collectors are used with machines that need to be often monitored or the measurement needs to be continuous. Permanently mounted online analyzers and data collectors have usually versatile tools for signal analysis and signal plotting.

PSK standardisation registered association has also their own perspective to categorizing vibration monitoring devices. PSK 5705 standard categorizes vibration monitoring devices depending on the installation on the measurement location: permanently mounted, half-fixed and portable devices/systems. Permanently mounted and portable devices are easily understandable but half-fixed means that sensors are permanently fixed in place but they are measured with portable device. PSK 5710 standard categorises measurement devices into 4 types depending on their signal and data processing capabilities. Type 1 devices measure the total/overall level of vibration and one parameter is showing that value. Type 2 devices measure High frequencies (typically above 5000 Hz) and the level of vibration is expressed with maximum of two parameters. Type 3 devices have selectable frequency bandwidth and the measured vibration can be expressed in time or frequency domain. Type 4 measurement systems are able to do failure detection and even to do prediction about the safe usage time left.

2.3.2 Temperature monitoring

There are three types of temperature sensors available: touch type, infrared thermometer and infrared camera (Nohynek, Lumme 2004, p.20). Touch type thermometers are the simplest ones to use. With touch type thermometers the user does not have to worry about emission factors of materials or about possible interference caused by reflecting heat waves (Nohynek, Lumme 2004, p.20). The disadvantages of touch type thermometers are that they need quite long settling times and that there is not always a possibility to touch the monitored location (Nohynek, Lumme 2004, p.20).

With infrared thermometers it is possible to measure temperatures from a distance up to 100 meters away from the monitored location (Nohynek, Lumme 2004, p.20). It is worth noting that the distance will affect the accuracy of the measurement. Infrared thermometers have wider usability range than touch type thermometers. The possibility to measure temperature from a distance has made it easier to use thermometers for example to monitor electric components. Infrared thermometers have been used for a long time to monitor electric components such as, fuses, switches and transformers

If there is a need to measure temperature from multiple spots near to each other simultaneously then infrared camera is the best method (Nohynek, Lumme 2004, p.21). The needed knowledge about different interference sources is greater with infrared camera and also with infrared thermometer than with a touch thermometer. With infrared cameras and thermometers, the user must take in consideration emission factors of different materials and colours, different heat reflections especially from reflecting surfaces and also the rate of accuracy when measured from a distance.

Temperature measurements were popular with bearing monitoring but because they were not able to detect the failure early enough, they have been replaced with different methods like vibration monitoring (Nohynek, Lumme 2004, p.20, Li, Liang et al. 2015). Because almost all faults emit a noticeable amount of heat once the failure is in a more serious stage, it is good to use temperature measurements as a secondary or supportive monitoring method (Nohynek, Lumme 2004). Temperature monitoring is used for example to observe unbalance load or bad condition of rollers of paper machines, valve leakages or poor lubrication of seals (Nohynek, Lumme 2004, p.21).

2.3.3 Lubrication monitoring

Lubrication analysis is one way to monitor the condition of machines and it is done by taking samples from the lubricant oil, lubricant grease or even from hydraulic oil (Miettinen, Miettinen et al. 2009, p.428). Lubricant analysis can bring information about the wearing of parts of a machine, the operation of a process, the effectiveness of the lubricant and even the lubricant condition itself (Miettinen, Miettinen et al. 2009, p.428). By following the amount of particles in a lubricant, the material of particles and by measuring the size and the shape of particles it is possible to notice how harsh the wear of the machine is, what components of the machine are suffering from wear and how the components wear (abrasion, removal of chips etc.) (Nohynek, Lumme 2004, p.23, Miettinen, Miettinen et al. 2009, pp.432-436). In the normal state when lubricated surfaces are moving against each other the particle size could be about 10 micro meters but when the wearing is severe the amount of particles rises notably and the sizes of particles could be 10 to 100 times larger than in the normal state (Nohynek, Lumme 2004, p.23).

With lubricant analysis it is possible to detect gearbox and hydraulic system failures at an early stage (Miettinen, Miettinen et al. 2009, p.429). Also, it is claimed that in many cases the lubricant analysis detects a beginning failure earlier than basic vibration measurements like the overall vibration measurements do (Miettinen, Miettinen et al. 2009, p.435 & 437). According to Miettinen et al. (2009, p.429), a very powerful condition monitoring system is achieved if lubricant analysis is combined with vibration measurements and especially if also process parameters (like speed and load) are followed at the same time.

Instead of manual particle counting there are also less time consuming options available. As a different method to determine the amount of particles or solids in a lubricant is to measure the mass of solids in a very thin membrane after the oil has gone through it (Miettinen, Miettinen et al. 2009, p.431). Automated counters are also available which can count the complete number of particles in lubricant and also count the number of particles of different size (Miettinen, Miettinen et al. 2009, p.432).

3 COMPONENTS OF A VIBRATION MONITORING SYSTEM

In Figure 1 can be seen a basic block diagram of digital data acquisition (DAQ) system. First a physical signal is sensed with a sensor/transducer. Electrical components always introduce some noise into a signal and so do also transducers/sensors. After the physical phenomenon is converted to an electrical signal with a transducer, the signal goes to the signal conditioning block. Signal conditioning includes amplifying, filtering and impedance matching between the transducer and an analogue-to-digital converter (ADC). When transducer´s properties are improved in the signal conditioning block it is time to feed the signal to an ADC. In the ADC the signal is quantized and the signal gets a binary or digital representation. When the signal is in digital format it can be read by a processor which could be for example inside of a computer. The digital signal can be analysed, stored, processed digitally (e.g. using Fast Fourier Transform) and/or graphs of the signal can be plotted to the user. The following paragraphs will explain each of these blocks more in detail and also describe the key features of each component involved in a vibration monitoring signal chain from the vibrating component to the processor.

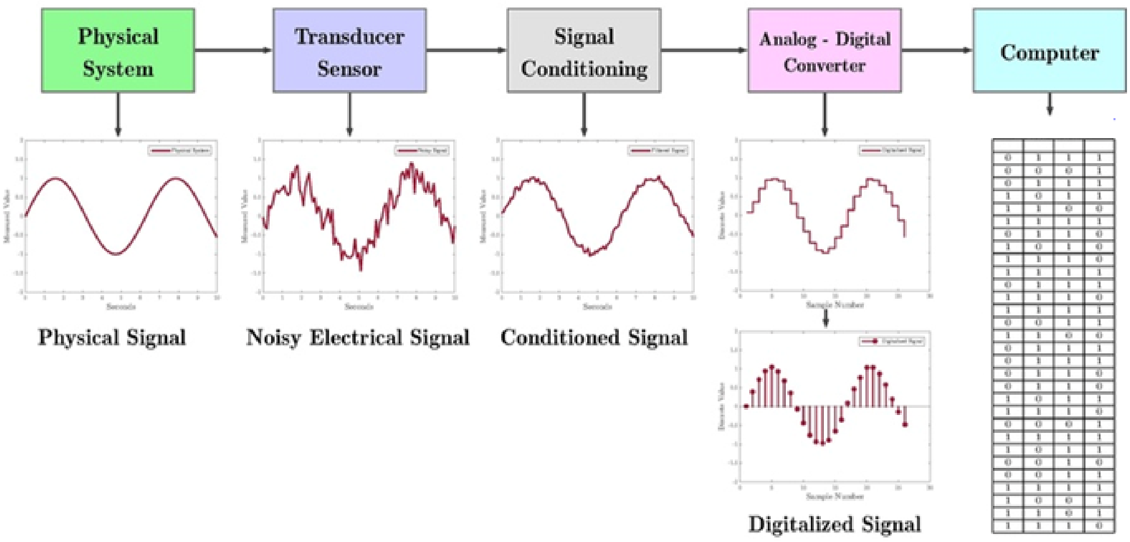

Figure 1. Digital Data Acquisition System (Zarate 2016).

3.1 Accelerometers

An accelerometer is a transducer which produces a current or a voltage value proportional to the acceleration level to which it is exposed to (Broch 1980, p.100). There are different designs to reach this accelerometer definition and the following chapters will introduce some of the designs.

Accelerometers have characteristics which specify their properties: transfer function, sensitivity, measurement range, linearity, noise, bandwidth and resonant frequency are some of the used qualifying factors for accelerometers (Urban 2016, pp.396-397, Wilson 2005, p.151). A transfer function tells the relation between the measured voltage/charge and the acceleration level. Sensitivity is the factor defining how much voltage or current is produced per acceleration unit and it can be measured in *mV/g*. The measurement range character defines the overall acceleration range in *g*'s that the accelerometer can measure. Linearity defines the maximum error from a linear transfer function over the specified measurement range. Noise tells the amount of unwanted distortion that every sensor produces to the output signal. Bandwidth states the frequency range of vibration that the accelerometer is able to catch. Resonant frequency of the accelerometer is one of the factors that define the bandwidth of the accelerometer.

3.1.1 Piezoelectric

A piezoelectric accelerometer is the most common accelerometer type and it is broadly used in vibration analysis (Wilson 2005, p.137). The functionality of a piezoelectric accelerometer is based on the piezoelectric material inside of them. These piezoelectric elements are usually made of quartz or artificially polarized polycrystalline ceramic (Broch 1980, p.100, Wilson 2005, p.141). When a piezoelectric material is compressed, stretched or sheared, it generates an electric charge on the surface. This kind of charge creation is called the piezoelectric effect (Urban 2016, pp.104-105). To capture this electric charge, at least two electrodes are needed.

A seismic mass inside a piezoelectric accelerometer is attached to the piezoelectric material and when exposed to acceleration the mass starts to move and shares, compresses or stretches the piezoelectric material (Broch 1980, p.100). The voltage or charge coming out of the accelerometer is relative to the acceleration it is subjected to. By following the voltage/charge and knowing the transfer function it is possible to know the acceleration level.

There are two common types of piezoelectric accelerometers: share and compression type. Figure 2 shows a drawing of a compression type piezoelectric accelerometer that includes an amplifier. In the share type the moving mass causes sharing to the piezoelectric element/elements and in the compression type the mass causes compression (Broch 1980, p.100). The share type is usually used for all-around applications whereas the compression type is usually designed for more particular ones.

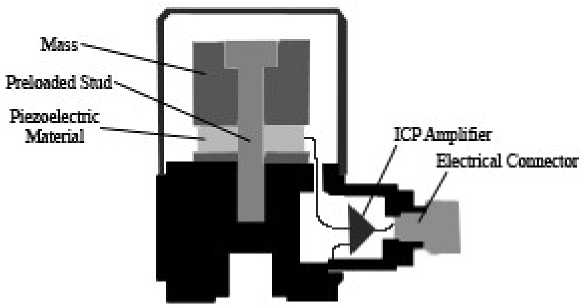

Figure 2. Compression type piezoelectric accelerometer with amplifier (Archiem 2016).

The piezoelectric accelerometers have wide linear amplitude range, wide frequency bandwidth, brilliant durability and thus wide usability (Broch 1980, p.100, Wilson 2005, p.137). They are considered to be all around accelerometers and they are widely used in condition monitoring (Broch 1980, p.100). As a drawback, piezoelectric accelerometers are much more expensive than the MEMS or piezo film accelerometers (Doscher 2016, p. 23).

3.1.2 Piezo film

The piezo film accelerometers are a specific form of piezoelectric accelerometers. The piezo film accelerometers are very light, flexible, bendable, deformable, mechanically durable and easy to form for a specific measuring location (Gatti, Ferrari 2002, p.674, Urban 2016, p.112). The piezo film accelerometers are coated with metal electrodes and also protecting plastic can be used (Measurement Specialties 1999). The piezo films are commonly made out of polyvinylidene fluoride (PVDF/PVF2) which is shaped in thin layers (Gatti, Ferrari 2002, p.674).

3.1.3 MEMS

MEMS acronym comes from the words Micro Electro Mechanical Systems. There are different MEMS sensors for different applications. For example, it is possible to find MEMS gyroscopes, MEMS accelerometers and MEMS pressure sensors from the markets. With the term MEMS sensors it is meant sensors that are made using the same kind of manufacturing methods as with integrated circuits (IC) called semiconductor manufacturing processes (Frank 2013, p.1). MEMS are often highly integrated apparatuses which combine microelectronics and micro machined structures together (Frank 2013, p.9). By using these semiconductor manufacturing processes it is possible to produce a lot of sensors to one wafer at once and thus get a low price tag for a single sensor (Miettinen, Miettinen et al. 2009, p.244).

The MEMS sensors are tiny and light in weight and thus they are good in measuring locations where the accelerometer must be light and the size must be small (Agoston 2012, p.278). The MEMS accelerometers' functionality is based usually either capacitive or piezoresistive phenomenon (McGrath, Scanaill 2013, p.21). The capacitive MEMS accelerometers have capacitor plates attached to a spring with a suspended mass which is capable to move when the accelerometer is subjected to acceleration. Other capacitor plates are anchored in place and when the mass moves the gap between the anchored and the attached capacitor plates changes and so changes the capacitor's geometry and the capacitance which is measured (Agoston 2012, p.278).

The piezoresistive MEMS accelerometers have piezoresistive material attached to cantilever beams which move when the accelerometer is exposed to acceleration. When the beams deform their resistive properties change and this change is proportional to the acceleration level (McGrath, Scanaill 2013, p.21). The change in resistivity is measured and the level of acceleration is derived from the measured change (McGrath, Scanaill 2013, p.20).

3.2 Amplifiers

An amplifier´s basic task is to amplify the incoming signal while introducing low electrical noise or other errors like offset and gain error. Amplifiers have also other purposes: improving the signal to noise ratio, being a frequency filter, being an impedance matching block and being an isolator between a sensor and the rest of the coming circuit after the sensor (Urban 2016, p.199). Amplifiers can be made from components (semiconductors, resistors, capacitors, inductors etc.) but there are also readymade amplifier integrated circuits in which these components are already included (Urban 2016, p.198).

After amplifying the signal, it goes to a filter and to an ADC. An amplifier enables the use of the resolution of the ADC more efficiently even with low level signals. There are different types of amplifiers available: operational amplifiers, programmable-gain amplifiers, instrumentation amplifiers, programmable-gain instrumentation amplifiers, chopper amplifiers, isolation amplifiers etc. (Measurement Computing corp. 2012, pp.39-47, Wilson 2005, p.45). The simulations shown in Figure 3 - Figure 6 show the effect of amplification to the gained information. The simulations are done with math software called Mathcad and the whole simulations can be found in appendices 1 and 2. Some of the parameters shown in appendices 1 and 2 (including for example the gain) need to be changed to match the different cases.

In Figure 3 and Figure 4 the effect of amplification is simulated by using a sine signal with an added shock signal which simulates the impulses generated by bearing defects. The impulse vibrates at 3000 Hz. The raw signal is shown in blue and the sampled signal in red in both figures. The analogue to digital conversion is done with an 8-bit ADC which has the input range from -5 volts to +5 volts. In Figure 3, the signal is sampled without amplification and in Figure 4 the signal is amplified by a factor of 10 (please notice the scales of figures). The amplification can be also expressed as decibels which is often the case.

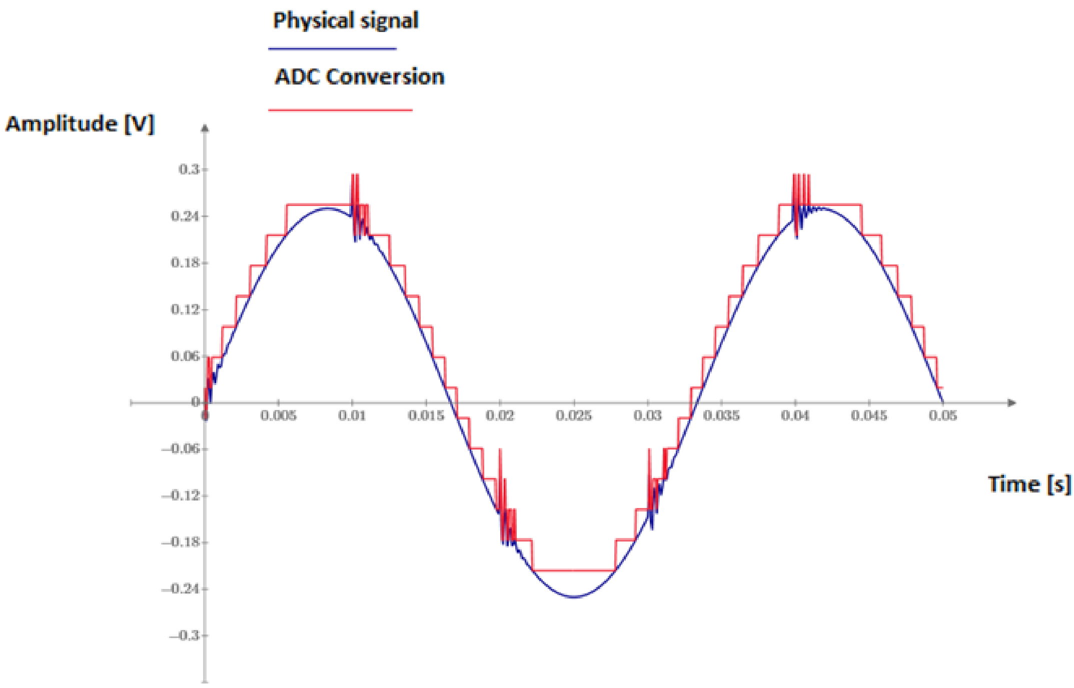

Figure 3. Analogue to digital conversion for an unamplified signal.

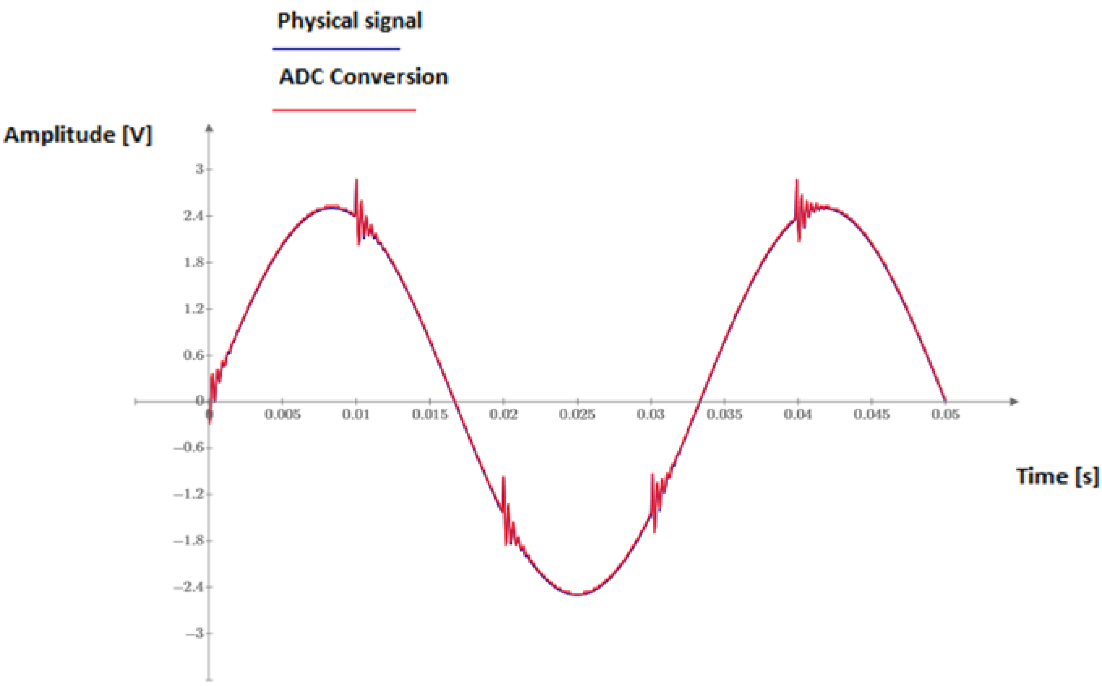

Figure 4. Analogue to digital conversion for a signal which is amplified by a factor of 10.

In Figure 5 and Figure 6 the previously shown signals can be seen in the frequency domain and it can also be seen how the information at high frequencies is lost if the signal is sampled without proper amplification. The information at high frequencies is very important for early bearing defect detection (Nohynek, Lumme 2004, p.18, El-Thalji 2016, p.46). Interestingly a phenomenon of FFT and sidebands is also more clearly shown in the spectrum of the amplified signal.

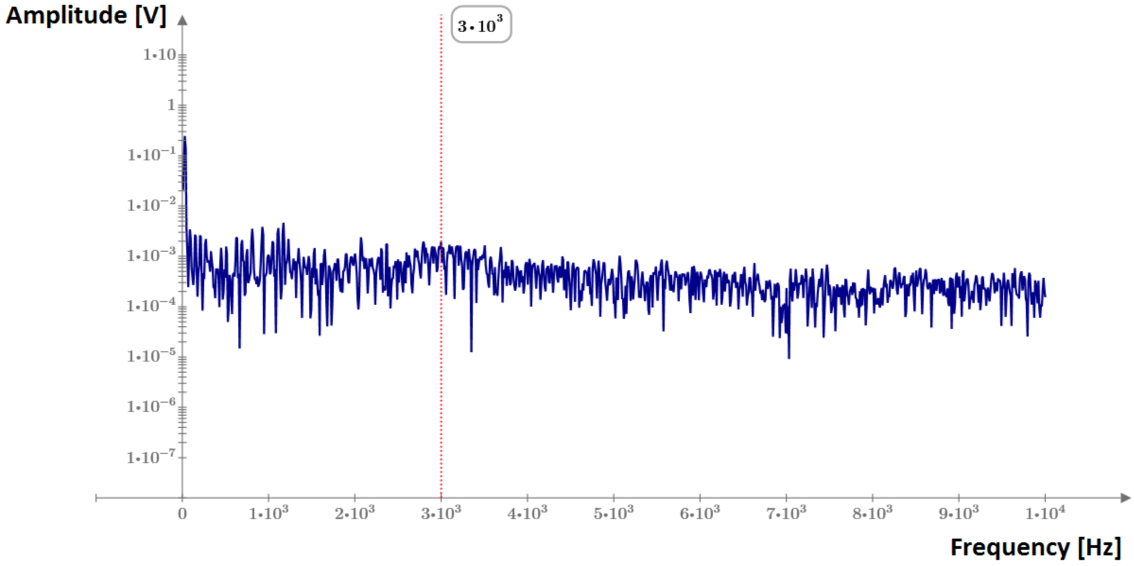

Figure 5. Spectrum from unamplified signal.

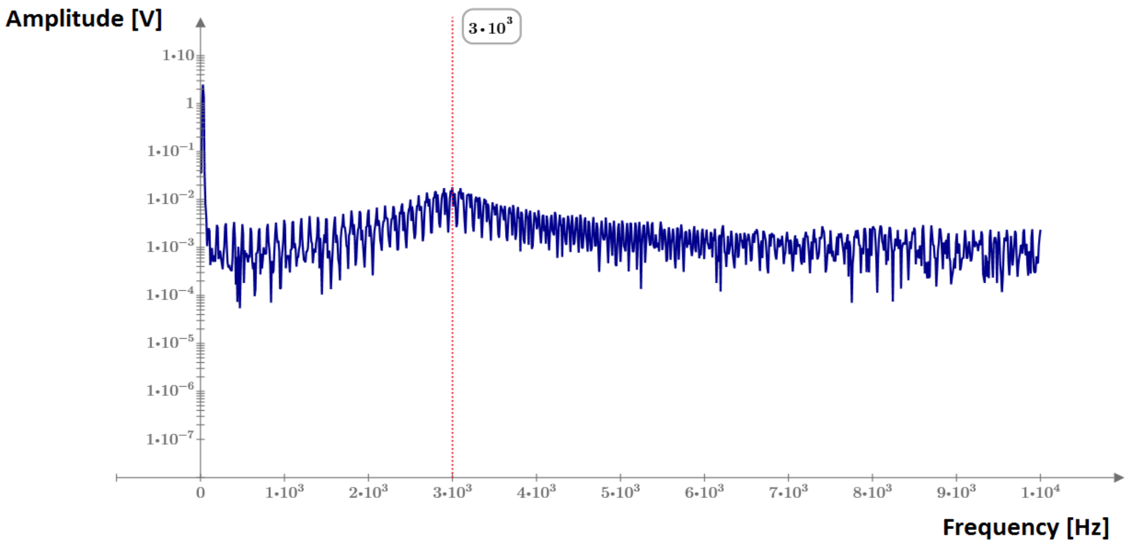

Figure 6. Spectrum from signal which is amplified by a factor of 10.

Operational amplifier or OP-AMP is seen as one of the principle building blocks for amplifiers (Urban 2016, p.199). A good OP-AMP has the following features: high input resistance (measured in GΩ), low output resistance (a fraction of ohms), ability to drive capacitive loads without becoming unstable, low input offset voltage, low bias current, very high open-loop gain (up to 10^4 – 10^6), low noise, high operating bandwidth and low sensitivity to power supply and environmental variations (Urban 2016, pp.199-200).

The mentioned open-loop gain is frequency depended and it also changes according to variations in the supply voltage, load and temperature (Urban 2016, p.200). This open-loop instability is the reason why the OP-AMPs are rarely used in the open-loop mode. Usually the OP-AMPs are used with feedback components in a so called closed-loop mode which improves the gain stability, linearity and output impedance (Urban 2016, p.201). As a rule of thumb, it is said that the closed-loop gain should be 100 times smaller than the open-loop gain at the highest frequency of interest for moderate accuracy and 1000 times smaller for more accurate needs (Urban 2016, p.201).

3.3 Filters

The most common filter types are Butterworth, Bessel and Chebyshev (Measurement Computing corp. 2012, p.47, Gaura, Newman 2006, p.131). All of these can be used for low-pass, high-pass, band-pass and band-reject filtering (Measurement Computing corp. 2012, p.47). Low-pass filtering means the attenuation of high frequencies. High-pass filtering means the opposite to the low-pass filtering: attenuation of low frequencies. Band-pass filtering allows a certain bandwidth of frequencies to go through but attenuates the rest. Band-reject filtering attenuates a certain frequency bandwidth but lets the rest go through.

All of the three filter types have their own characteristics. Butterworth has the flattest passband but it introduces a non-linear phase response (Measurement Computing corp. 2012, p.48, Gaura, Newman 2006, p.131). Chebyshev has the steepest attenuating curve but it has a ripple effect before the cutting point frequency, ring effect with a step response and even more non-linear phase response than Butterworth (Measurement

Computing corp. 2012, p.48, Gaura, Newman 2006, p.131). Bessel is something in between the two previous ones. Bessel does not have a steep response curve but is has the best phase linearity and step response (Measurement Computing corp. 2012, p.48, Gaura, Newman 2006, p.131). In Figure 7 are shown the low-pass filter responses for different filter types. The Chebyshev type I filter is shown in blue, the Bessel in red and the Butterworth in yellow. All the shown filters are modeled using Mathcad's own filter functions and all of them have the cut off frequency at 10 Hz which is marked with a dash line. The simulation for filters can be found in appendix 2.

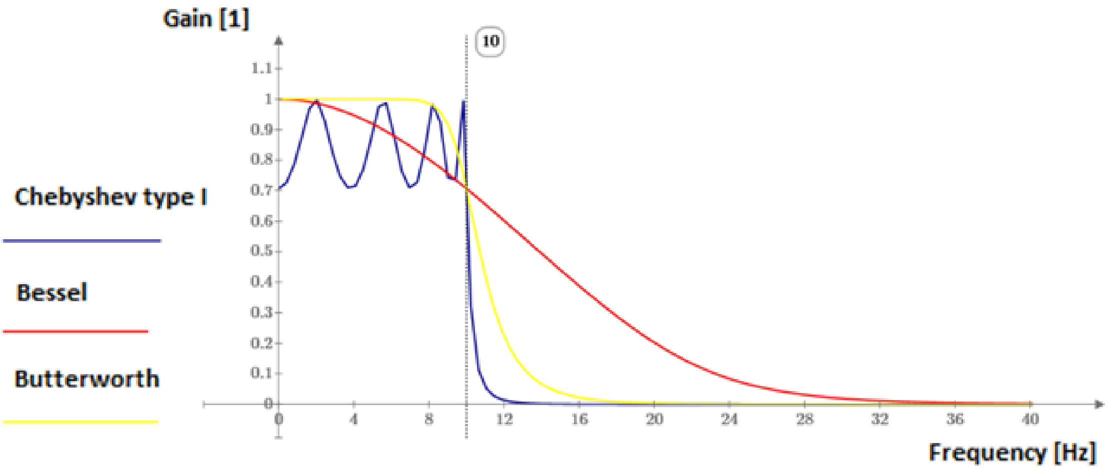

Figure 7. Chebyshev I, Bessel & Butterworth filter gain responses (cut-off at 10 Hz).

3.3.1 Anti-Aliasing Filters

Aliasing is a phenomenon that occurs when a signal is not sampled with a high enough sample rate. The Nyquist theorem says that a signal should be sampled at least twice as fast as the signal's highest frequency (Gatti, Ferrari 2002, pp.754-755). If the Nyquist theorem is not followed, high signals will be reflected to low frequencies when sampled and this will ruin the sampled result and this phenomenon will be difficult to notice from the result (Gatti, Ferrari 2002, pp.754-756). In Figure 8 and Figure 9 the anti-aliasing phenomenon is simulated. This simulation was done in a similar way that is shown in appendix 2 with a little variation: in this simulation the example signal was combined from sine waves with different frequencies than shown, the FFT was done twice with different sampling frequencies and Hanning window, noise and logarithmic scale on FFT were not used.

Figure 8 and Figure 9 show the spectrum analysed from a signal which is constructed from four sine waves having the amplitude of 1 each at the following frequencies 100 Hz, 250 Hz, 300 Hz and 500 Hz. In Figure 8, the signal is sampled with the sample rate of 512 samples per second and in Figure 9 it is sampled with 1024 samples per second. By looking at the figures it is easy to notice how the Nyquist theorem holds up and how aliasing occurs if the signal is not sampled with a sample rate that is high enough.

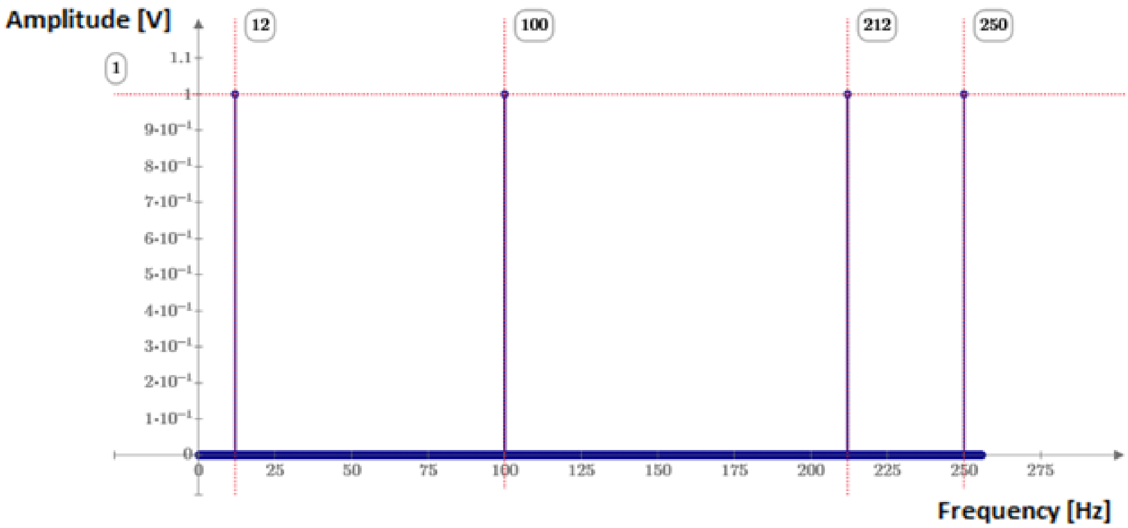

Figure 8. Aliasing occurring when the highest frequency component is 500 Hz and the sample rate is 512 Hz.

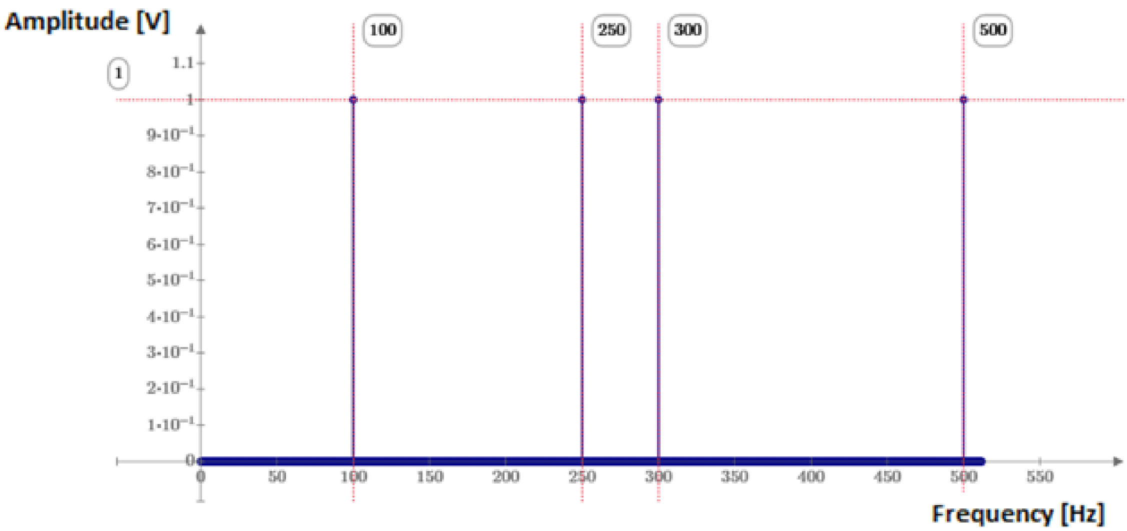

Figure 9. No aliasing taking place when the Nyquist theorem is followed: the highest frequency component is 500 Hz and the sample rate is 1024 Hz.

Often, a signal contains unknown high frequencies that might also be higher than the feasible sample rate in the used ADC or higher frequencies than is reasonable to sample to catch the phenomenon that is really of interest. Because of these high frequencies an anti-aliasing or low-pass filter is needed and it must be analogue and before the ADC in the signal path (Gatti, Ferrari 2002, p.763). With these low-pass filters, it is possible to cut off these high frequencies and the need for high sample rate is reduced.

An ideal filter would have a sharp cutting frequency point, rectangular shape, flat transition section before the cutting frequency and straight to zero value after the cutting point without a transition section (Gatti, Ferrari 2002, p.756). The real life filters do not have these features but instead they have a smooth cutting frequency point and a transition section before and after the cutting point (see Figure 7 and Figure 10). The behaviour of the filter around the cutting point depends on the type of the filter. There are four different anti-aliasing filter types: Bessel, Butterworth, Chebyshev and elliptic. The filter response of Butterworth, Chebyshev type 1, Chebyshev type 2 and Elliptic filter can be seen in Figure 10. Filter's order defines the steepness of the transition section after the cutting frequency point.

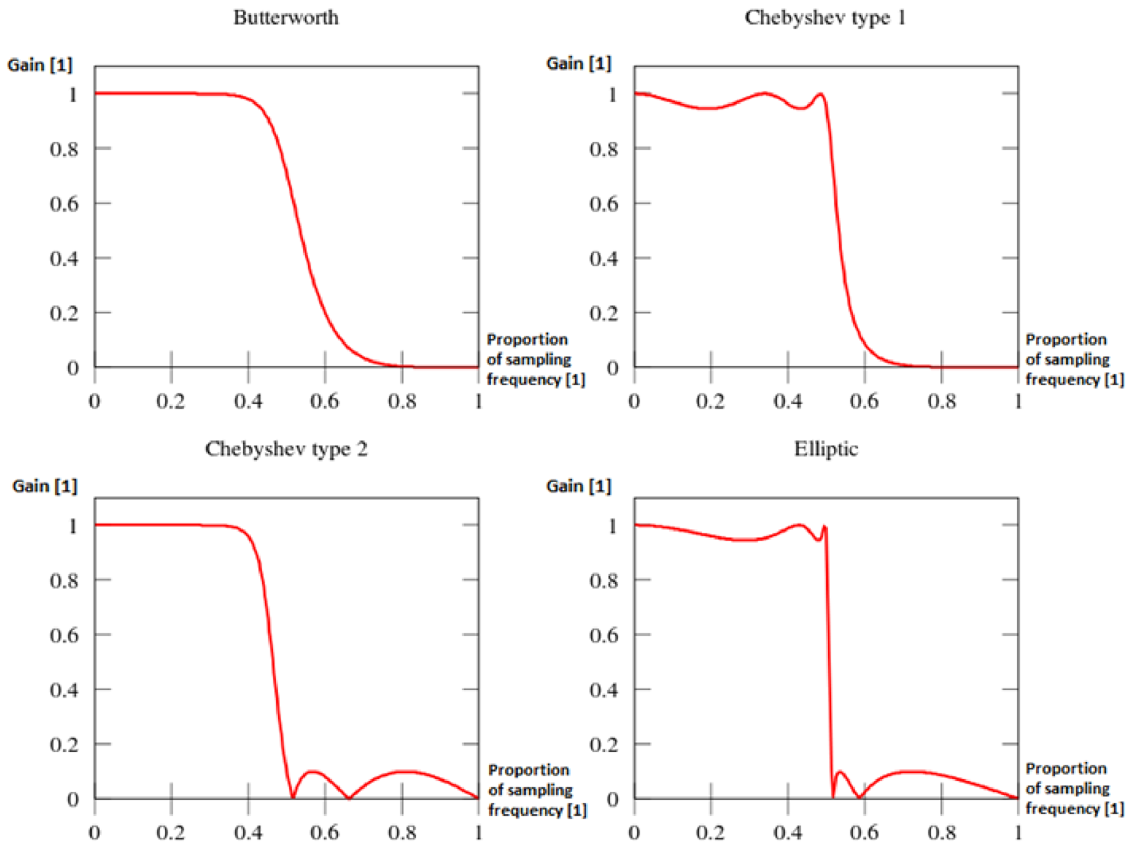

Figure 10. Response curves of different low-pass filters (Damato 2016).

3.4 Analogue-to-digital converters

The task of an analogue-to-digital converter (ADC) is to convert analogue signals to digital signals. ADC will give a rounded or quantized digital value of the analogue signal whenever a certain amount of time has passed by (sampling time). In other words, previously continuous analogue signal is converted to defined values at discrete time instants and depending on the resolution, there are certain finite steps offered within a range (Gatti, Ferrari 2002, p.750 & p.752). This sampling and quantization are the main steps in performing analogue-to-digital conversion (Gatti, Ferrari 2002, p.750)

There are several characteristics that are good to know when dealing with ADCs. The resolution is measured in bits and the number of bits define how small changes are possible to be detected (Gatti, Ferrari 2002, p.752). The sample rate is also an important factor as seen in the previous section handling the phenomenon of aliasing. The sample rate defines the number of samples that is possible to gather in a second (Gatti, Ferrari 2002, p.751). Sometimes the sample rate is given per channel and sometimes it is the total sample rate/throughput rate of an ADC that should be divided by the number of channels if the sample rate per channel is wanted. The number of channels can also be meaningful when the ADC chips or measurement devices with ADCs are chosen. Also, the valid input range and valid input type should be taken into consideration. The input range defines the acceptable input voltage variation that the ADC can handle (Gatti, Ferrari 2002, p.752). The input type can be either differential or single-ended (Measurement Computing corp. 2012, p.39).

Figure 11-Figure 14 show the effect of the resolution of an ADC. ADC has an input range from -5V to +5V and the resolution of 8 bit in Figure 11 and 18 bit in Figure 12. From the figures it is possible to see what kind of effect the resolution has on the results. It is worth mentioning that if the impulses are sampled without adding them to the sine wave as shown in the figures, the 8-bit ADC does not react to those small impulses at all. In Figure 11 and Figure 12 the analogue signal is in blue and the signal after sampling is in red.

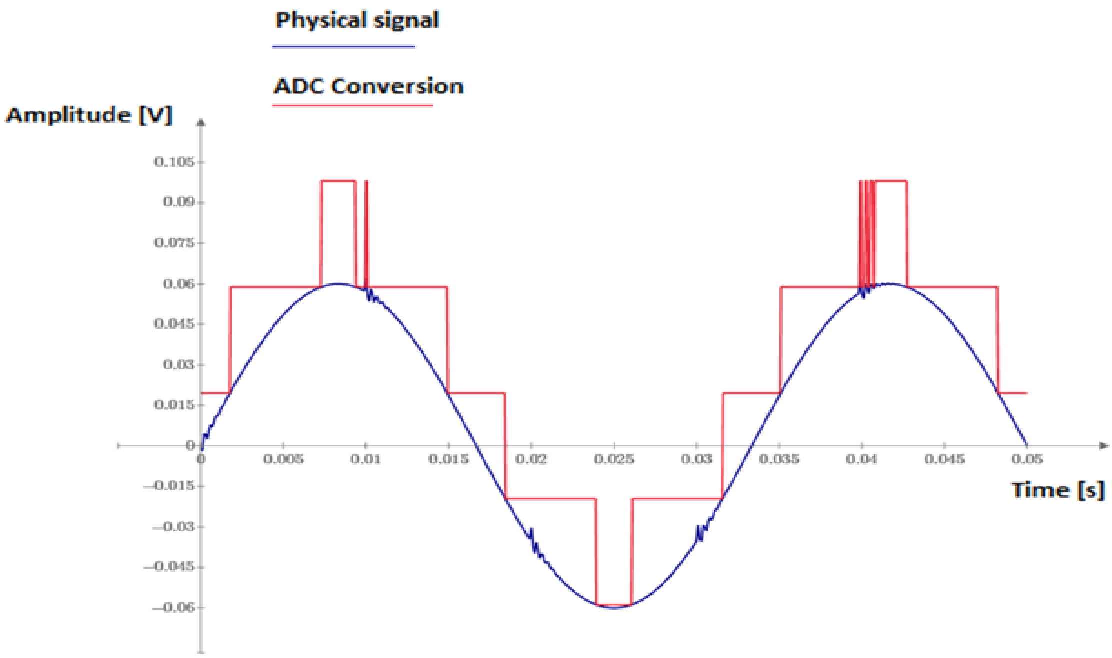

Figure 11. 8-bit ADC conversion.

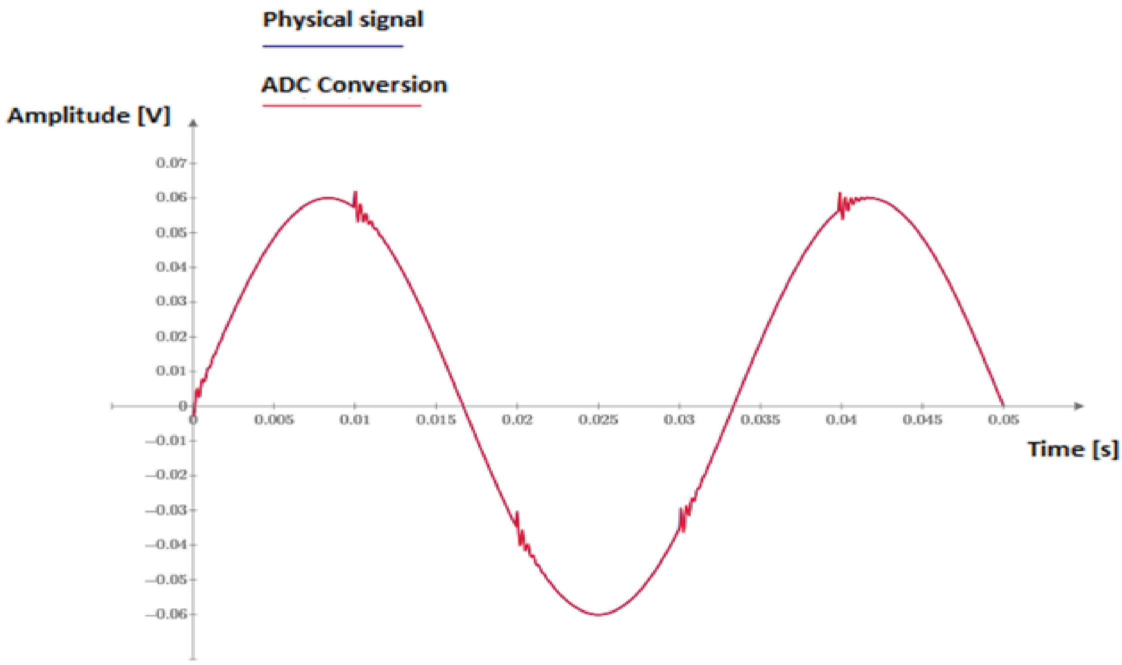

Figure 12. 18-bit ADC conversion.

Figure 13 and Figure 14 show the same kind of results as did the previously shown frequency domain figures related to the amplification: the impulse is vibrating at 3000 Hz and this kind of high frequency information is lost due to the low resolution. The spectrum of the higher resolution signal reveals also sidebands like did the spectrum of the amplified signal. As mentioned before, the information related to the high frequencies is crucial for early detection of a bearing defect. The simulations have been done using Mathcad and detailed mathematical presentations can be found in appendix 1 and 2.

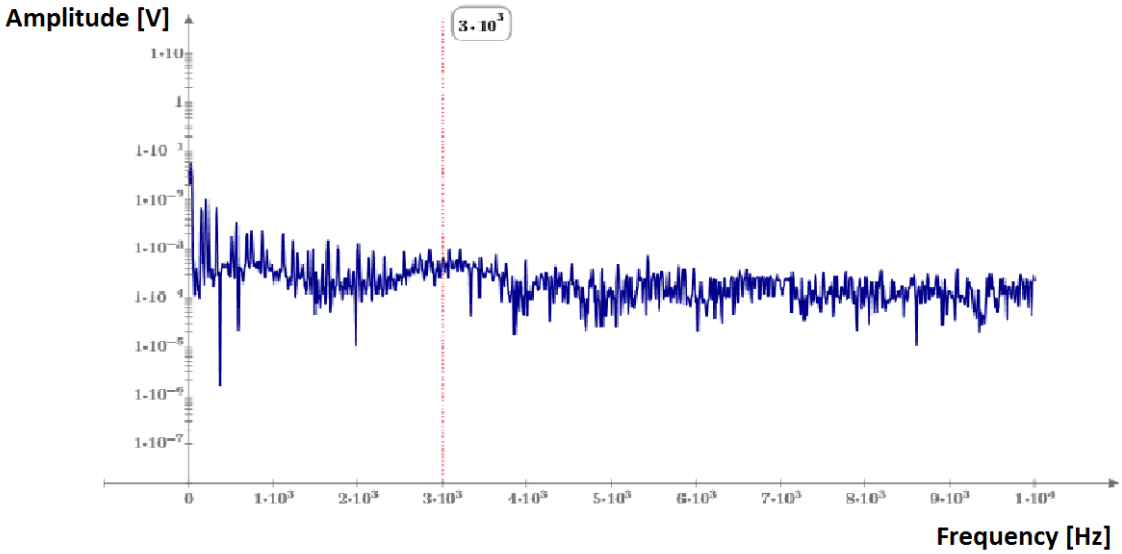

Figure 13. The spectrum of a signal which is sampled with 8-bit ADC.

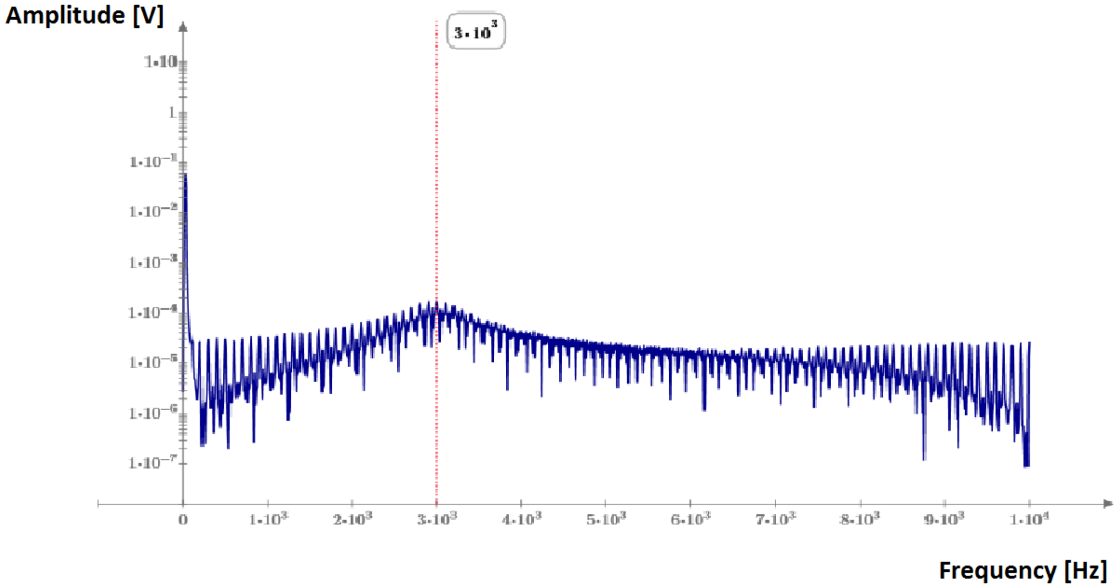

Figure 14. The spectrum of a signal which is sampled with 18-bit ADC.

The mentioned sideband effect of FFT is reduced when overlapping is included with Hanning windowing. In Figure 15 and Figure 16 a Hanning-window with overlapping is applied to the previously shown 8-bit and 18-bit signal data. 2048 samples are used from the ADC data which leads to 3 set of data when the windows are 1024 points wide and 50 % overlapping is used. After windowing, FFT is carried out to these individual windows and the average of these spectra is calculated. These averaged spectra can be seen in Figure 15 and in Figure 16 that support the conclusion that high frequency information is lost if the ADC does not have high enough resolution.

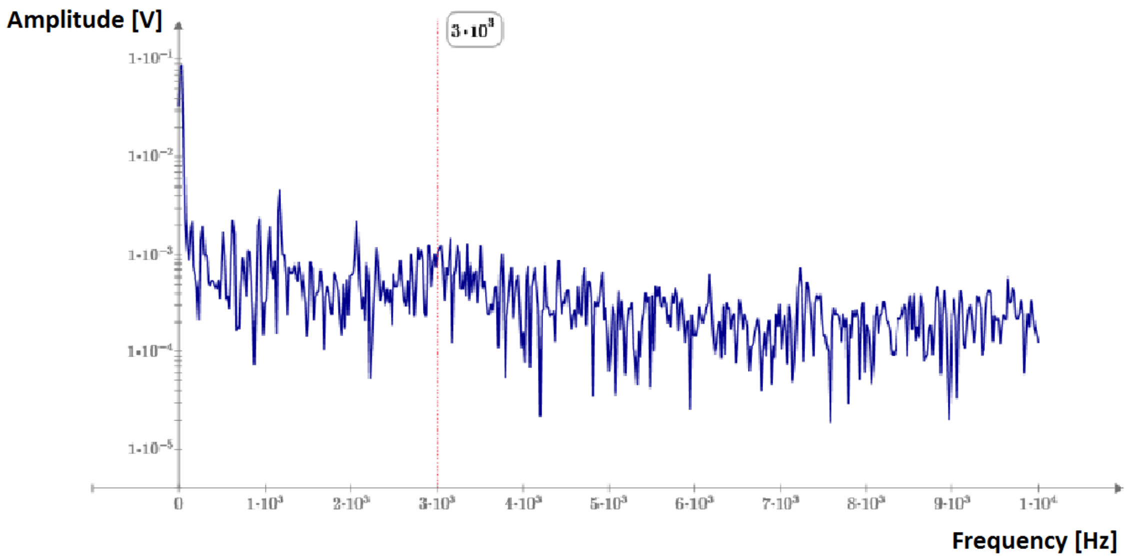

Figure 15. Spectrum, 8-bit ADC, Hanning-Window with 50% overlapping.

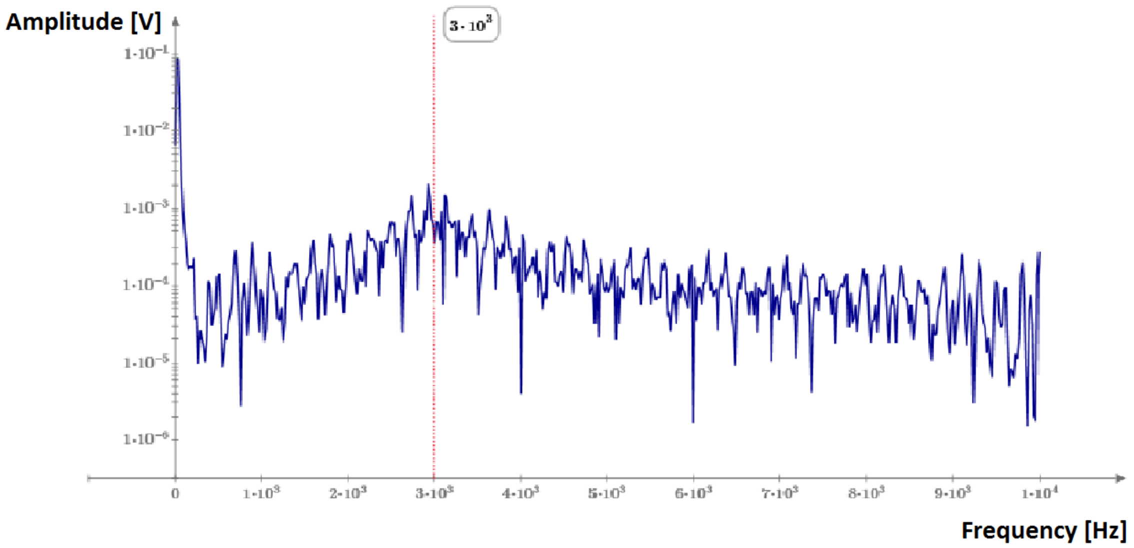

Figure 16. Spectrum, 18-bit ADC, Hanning-window, with 50 % overlapping.

There are several ADC designs in the market. Usually, when choosing an ADC there is a trade-off between the accuracy, the sample rate, the resolution, noise and power consumption (Frank 2013, p.76). Popular analogue-to-digital conversion techniques include successive approximation, parallel/flash and sigma-delta (Frank 2013, p.77). The next chapters will talk a bit more about parallel, successive approximation and sigma-delta conversion techniques.

3.4.1 Flash/Parallel ADC

The parallel ADC's functionality is built on comparators, voltage dividers and encoders (Gatti, Ferrari 2002, p.757). The voltage divider divides the attached reference voltage to 2^n-1 equal steps, where n is the resolution/bit number of the ADC, and passes these voltages to comparators (Gatti, Ferrari 2002, p.757). The input signal is fed to all comparators at once. After the comparators the signal goes to the encoding block (Gatti, Ferrari 2002, p.757).

The parallel ADC is the fastest ADC type and with the parallel ADC it is conceivable to reach the sample rate of hundreds of mega samples per second (Gatti, Ferrari 2002, p.757). The fast sample rate is enabled because of all the bits are determined parallel at once at the same time instant (Gatti, Ferrari 2002, p.757). The parallel ADCs are used in digital scopes and digitizers (Gatti, Ferrari 2002, p.757). The resolution is usually relatively low because of the price is defined by the needed number of comparators (Gatti, Ferrari 2002, p.757). Usually the maximum resolution for a parallel ADC is 8 bit, which leads to 255 comparators (Gatti, Ferrari 2002, p.757).

3.4.2 Successive Approximation (SAR) ADC

The SAR type ADC consists of a successive approximation register (SAR), digital-to-analogue converter (DAC), one comparator, a reference voltage and usually a sample and hold circuit. An analogue signal is fed to a comparator where it is compared to the voltage coming from the DAC. The DAC represents a voltage that is defined by the SAR in a digital from. The voltage that the DAC feeds changes and those changes follow a strategy of binomial search. The binominal search lasts *n* clock pulses where *n* is the number of ADC bits. After the search the ADC's out coming result is the last SAR's digital binary value before the DAC. (Gatti, Ferrari 2002, pp.757-758).

The SAR ADCs are referred as general ADCs. The SAR ADCs are relatively fast (up to 1 MHz sample rate) and their price is also moderate. The price and the speed have led to the situation where the SAR ADCs are the most common ADCs that can be found in data acquisition boards. (Gatti, Ferrari 2002, p.758).

3.4.3 Sigma-Delta (ΣΔ) ADC

The sigma-delta or the delta-sigma analogue-to-digital converter is based on high sample rate and digital filtering and it is easy to connect this converter model to the digital signal processing (DSP) integrated circuit (Frank 2013, p.78). The sigma-delta converter has integrators, summers, DAC and a quantizer (Frank 2013, p.78). The number of integrators and summers depend on the order of the converter. After the summer, integrator and quantizer the signal goes to a decimation filter. In the decimation filter, the signal's out-of-band quantization noise is removed, the decimation/sample rate reduction happens and the extra anti-aliasing rejection is provided (Frank 2013, p.79). Getting the noise down improves the number of effective bits, the sample rate reduction helps signal's post-processing (data transmission, storing etc.) and the additional anti-alias rejection loosens the requirements for anti-aliasing filter.

3.5 Processors

After an analogue phenomenon is caught with a sensor, amplified, filtered and converted to a digital form, the signal is transferred to some processor which processes, stores and possibly presents graphs of the data. The processor might be for example in a computer, in a microcontroller unit (MCU) or in a special data acquisition system made for logging data from sensors. The digital signal processing offers much wider signal conditioning and signal manipulation capabilities than the analogue signal processing (Gaura, Newman 2006, p.137). For example, with the digital signal processing it is possible to use almost any kind of transfer functions which are useful in digital filtering (Gaura, Newman 2006, p.138).

A microprocessor is one processor type that is sometimes confused with the terms microcomputer and microcontroller (McGrath, Scanaill 2013, p.56). A microprocessor is a central processing unit (CPU) that is integrated to a single chip (McGrath, Scanaill 2013, p.56, Gaura, Newman 2006, p.141). The CPUs used to be made of multiple components or chips prior to 1970 and in microprocessors, those components and chips are combined to the form of just one single chip (McGrath, Scanaill 2013, p.56). It is expected that microprocessors include an arithmetic and logic unit (ALU), a sequencer, a system bus, and a register array, but do not include memory or peripherals (Gaura, Newman 2006, p. 140, McGrath, Scanaill 2013, pp.57-58). The microprocessors are usually used in sensor systems where a lot of processing power and memory is needed and these cannot be integrated into a microcontroller or the I/O hardware capability of the microcontroller is not suitable to particular sensor types (Gaura, Newman 2006, p.141). The microprocessors tend to have easier to use instruction sets and better software developing tools than some of the following options and this is good to take into consideration especially if complicated software is needed (Gaura, Newman 2006, p.141).

The already mentioned microcontroller units (MCU) are single chip configurations that typically consist of a processor, peripheral interfaces, data memory and program memory (typically read only memory) (Gaura, Newman 2006, p.141, McGrath, Scanaill 2013, p.56). The microcontrollers were basically developed for embedded devices and those can be found in mobile phones, washing machines, microwave ovens and so on (McGrath, Scanaill 2013, p.58, Gaura, Newman 2006, p.141). The microcontrollers provide a good option for sensor systems depending on the needed processing power, memory and peripherals (Gaura, Newman 2006, p.141). Many features in the so-called smart sensors (integrated sensing capability, analogue circuity, ADC, input/output bus etc.) are driven with microcontrollers (McGrath, Scanaill 2013, p.51).

There are also more sophisticated microprocessors available for digital signal processing called digital signal processors (DSP). The digital signal processors are optimized for signal processing requirements which mean, for example, the ability to perform fast multiplication operations and a single clock execution cycle (Gaura, Newman 2006, p.141). The DSPs use the so-called Harvard architecture where there are separate memory ports for instructions and data allowing the instructions and data to be transferred simultaneously (Gaura, Newman 2006, p.141). The DSPs are faster and give a possibility to extract more information from the sensors than the general-purpose microprocessors, have improved development tools that ease the designer's job and give a possibility to run more diagnostics (Holmberg, Adgar et al. 2010, p.100). The DSPs are a worthy option in applications that need more sophisticated signal processing like is the case with digital filter applications (Gaura, Newman 2006, p.141). In the same way as with the processor, by integrating memory and peripherals to the DSP a controller is formed but in this case it is called digital signal controller (DSC) (Gaura, Newman 2006, p.141).

When the technology has improved also those above-mentioned boundaries between the different processors and microcontrollers has blurred. Nowadays it possible to find microprocessors that have single cycle arithmetic operations, can perform signal processing computation at the level of DSPs, have Harvard architectures, integrated memories and peripherals (Gaura, Newman 2006, pp.142-143). Even though these microprocessors have all the features of microcontrollers or digital signal controllers they are not marketed as such (Gaura, Newman 2006, p.143).

4 MARKET REVIEW

The market review was done mainly using the internet. Various data acquisition components and systems were taken into account and various manufacturers' products were studied. The market review has been done partly having the Raspberry in mind and thus this can occasionally be seen in some of the chosen components/systems as Raspberry compatibility like 3.3 V logic levels, 5V/ 3.3V devices or SPI data interfaces. There were technical demands for the system like the capability to measure 10 kHz signals, to have better than 16-bit resolution and the price tag of the whole system should be below 100 €. The market review includes also components and systems that were found during the market review and do not fulfill the above listed limits but give perspective to what is available in the market and at what price. Multiple websites of manufacturers and suppliers were checked to learn about the state of the art of low cost data acquisition devices. For example, the availability and prices of electronic components were checked for well known and big suppliers like Farnell element 14, Digi-key Electronics, RS Components, Mouser Electronics and Arrow Electronics. During the market overview it was noticed that sometimes the information in the data sheets, and especially in the data sheets of cheaper products, could be quite unclear and it might take a bit of time to find the information one is looking for. Also, in some cases all of the necessary information simply was not available.

4.1 Accelerometers

The pages of a great number of sensor manufacturers including STMicroelectronics, Bosch, NXP, Panasonic, Denso, Invensense, Analog Devices, Sony, Kionix, MEMSIC, Murata, TE Connectivity, SICK, Monitran, Knowles, IMI Sensors, Meggitt Endevco, and Sensor Dynamics were studied when low cost accelerometers were searched. A table of the most interesting accelerometers with their features is given in appendix 3. It is possible to find really cheap accelerometers like KX122-1037 MEMS from Kionix and LIS2DS12 MEMS and LIS2DH MEMS from STMicroelectronics just for a few euros. These really cheap accelerometers naturally have their limitations. For example, the resonance frequency can be low (KX122-1037: 1800 Hz) together with low amplitude range (LIS2DS12 & LIS2DH: 16 g) (Kionix 2016, p.7, STMicroelectronics 2016a, p.1, STMicroelectronics 2016c, p.1). There are also positive features with these above mentioned MEMS accelerometers like that they have ADCs integrated in them: KX122-1037 has 16-bit resolution ADC and LISDS12 & LIS2DH have 12-bit resolution ADCs (Kionix 2016, STMicroelectronics 2016a, STMicroelectronics 2016c). These low-cost accelerometers are not even close to be able to catch 10 000 Hz but sometimes the resolution might match the wanted 16-bits. As long as the frequency response curve is linear, high frequencies could be measured. Unfortunately, the data sheets of these above mentioned accelerometers do not show the frequency response curves and thus it is hard to say anything about their capability at higher frequencies. The mentioned accelerometers might be useful in condition monitoring of larger bearings because larger bearings have low natural frequencies.

One observation that was made during the market view of the low cost sensors was that often the cheap sensors do not have good specification notes: the notes might not reveal for example the resonance frequency, bandwidth or show a frequency response curve. The lack of appropriate information makes it extremely difficult to choose a proper low cost accelerometer for certain applications.

Two accelerometers stood out from the rest when the accelerometer specifications were trawled through: ACH 01 from TE Connectivity and ADXL001 from Analog Devices. The ACH 01 and the ADXL001 use different technologies: the ACH 01 is a piezofilm accelerometer and the ADXL001 is a MEMS accelerometer (Analog Devices 2016d, TE Connectivity 2016). Both accelerometers have high resonance frequencies, wide bandwidth and broad amplitude range compared to the mentioned Kionix and STMicroelectronics accelerometers. The ADXL001 has a resonance frequency of 22 kHz, depending on the model a ±70g or ±250g or ±500g amplitude range and with proper circuitry 22 kHz bandwidth (-3 dB) (Analog Devices 2016d, p.1, Analog Devices 2016e, p.3). The ACH 01 has the bandwidth from 2 Hz to 20 kHz, the amplitude range of ± 150 g, the resonant frequency of 35 kHz and a noise floor of 6-130 µg/$\sqrt{Hz}$ at 10-1000 Hz which is smaller than the noise floor of ADXL001 (2,15 – 4,25 mg/$\sqrt{Hz}$ at 10 – 400 Hz) (Analog Devices 2016d, TE Connectivity 2016). With the mentioned specifications and price tags of about 30 € for the ADXL001 (including only

IC chip without wiring or any circuit board) and 55 € for the ACH 01 (including cover and wiring) give hope for a reasonably cheap vibration monitoring system for the bearing condition monitoring purposes and to be able to reach the goal of a measurement system capable to measure signals up to 10 000 Hz.

In Figure 17 are shown the three previously mentioned accelerometers: the MEMS ADXL001 (A), the digital MEMS accelerometer KX122-1037 (B), and the piezofilm accelerometer ACH01 (C). They are all small in size but the KX122-1037 really goes way beyond in being small. The KX122-1037 accelerometers will not take a lot of space from the printed circuit board and thus they can be easily included to small devices such as mobile phones or even much smaller devices.

Figure 17. Accelerometers ADXL001 (A), KX122-1037 (B) and ACH01 (C).

4.2 Measurement system from integrated circuits

One option to make data acquisition systems is to create them from components like IC (integrated circuit) amplifiers, IC ADCs, IC filters and so on. The reason why building the measurement system out of integrated circuits seems to be an interesting option is of course the low price of the components compared to the complete measurement systems. For example, 24-bit IC ADCs with a sample rate above 100 kHz can be bought just with a few euros. An IC filter like MAX7427EUA+ could be found at the price of less than 3 euros. The mentioned MAX7427EUA+ is a switched capacitor 5th order elliptic low-pass filter with adjustable cutting frequency which can be tuned from 1Hz to 12 kHz (Maxim Integrated 2016b). Programmable amplifiers like MCP6S21 cost about 1 euro and the MCP6S21 has up to 12 MHz bandwidth and gain up to 32 (Microchip 2016). After adding a reference voltage like MCP1525-I/TO, that costs under 1 euro, all the major components of a measurement system (excluding sensor) before a processor are covered and the total cost of the whole system is less than 25 euros.

There are also ICs that are highly integrated and have a lot of features installed in a single chip. For example, one highly integrated IC is the AD7608 from Analog Devices. It has integrated analogue input clamp protection, input buffer with 1 Mohm analogue input impedance, a second-order antialiasing analogue filter, a reference voltage, a reference buffer, an 18-bit and 8 channel ADC with the sample rate of 200 000 samples per second per channel, track and hold amplifiers and a digital filter (Analog Devices 2016a). The AD7608 is marketed as a data acquisition system and it truly has a lot of features that typical data acquisition systems have. There are also other integrated chips that have many components included as well, and thus, this kind of highly integrated chips should be taken into account when buying/building data acquisition systems is considered.

ICs are sold in different sizes and different packages. In Figure 18 there are ten different ICs including amplifiers, ADCs, filters and a reference voltage. In the first column from left there are 4 different ADCs which are from up to down: AD1871YRSZ (A), PCM1803ADB (B), ADS131A04 (C) and PCM4201 (D). In the second column from left there are amplifiers which are from up to down: AD8606 (E), AD626ANZ (F), MCP6S21 (G). In the third column there are two low-pass filters which are from up to down: MAX7427 (H) and MAX7410CPA+ (I). Lastly, there is a reference voltage (J). The features and prices of multiple ADC ICs can be found from appendix 4.

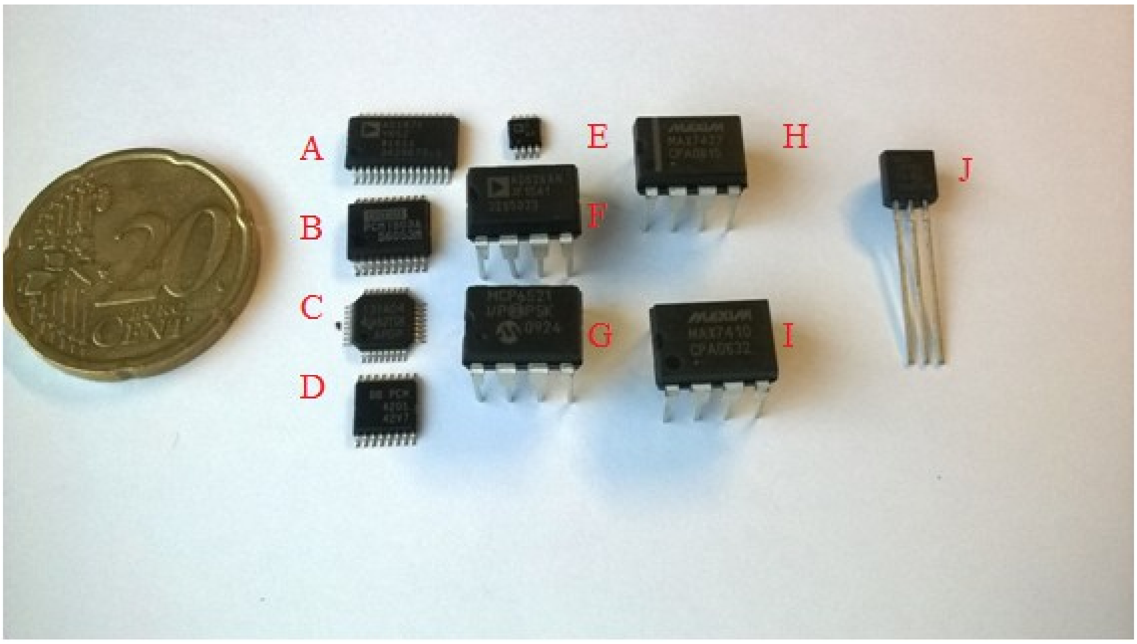

Figure 18. ICs: ADCs (A-D), amplifiers (E-G), low-pass filters (H-I), reference voltage (J).

Even though integrated circuits are simpler than building up the system from basic electric components (like capacitors and resistors) some work is still needed. Most likely, the work involved to make a good and operational measurement system out of ICs would need a lot of knowledge related to electronics including noise cancellation, choosing compatible ICs with each other, wiring, connecting electric components (for example soldering) and choosing also other electronic components than ICs like capacitors and resistors. The needed wide knowledge behind the measurement systems is naturally a demotivating factor to build up measurement systems even from ICs.

4.3 Smart Sensors

The Institute of Electrical and Electronic Engineer (IEEE) committee defines a smart sensor/transducer as a sensor/transducer that "*provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity. This functionality typically simplifies the integration of the transducer into applications in a networked environment.*" (IEEE 1998, p.8). Smartness is integrated in smart sensors trough the integration of microcontroller units (MCU), digital signal processors (DSP), field programmable gate arrays (FPGA) or application specific integrated circuits (ASIC) to the same package with a sensor (Frank 2013, p.1). Usually a smart sensor package also includes analogue circuitry, an ADC and an input/output (I/O) bus interface (Huijsing 2008).

Joseph Giachino predicted already in 1986 that "*Smart sensors are becoming integral parts of systems performing functions that previously could not be performed or were not economically viable*" (Giachino 1986). Wireless sensors are helping this integration and they can also be classified as smart sensors. Wireless sensors can be found in the market at affordable prices. For example, Texas Instrument has their own wireless sensor system called SensorTag and it is aimed for internet of things (IoT) markets having a price tag of 29 $ (Texas Instruments 2016). It has 1 year battery lifetime, Bluetooth/6LoWPAN/ZigBee communication options (Wi-Fi version is coming), cloud connection and multiple sensors integrated into it. Integrated sensors include ambient temperature sensor, infrared sensor, 9-axis motion sensor (accelerometer, gyroscope, compass), humidity sensor, barometric pressure sensor, ambient light sensor, magnet sensor and digital microphone (Texas Instruments 2016). The 9-axis motion sensor is the MPU-9250 from InvenSense and its accelerometer specifications are interesting from the vibration monitoring point of view: the accelerometer has 16-bit ADC, the maximum amplitude range of ±16g, a digital programmable low-pass filter (from 5 Hz to 260 Hz), the maximum output data rate of 4000 Hz and typical noise power spectral density of 300 µg/√Hz (Texas Instruments 2016, InvenSense 2016). Unfortunately, there is no data available about the frequency response, information about resonant frequency or anything about the bandwidth of the accelerometer (InvenSense 2016). Of course, the low-pass filter frequency range gives a hint about the bandwidth of the accelerometer i.e. the accelerometer does not seem to be able to measure high frequencies.

Another wireless sensor system comes from Ruuvi and it is called RuuviTag (RuuviTag 2016). The RuuviTag includes features and components like a temperature sensor, a humidity sensor, an air pressure sensor, an accelerometer, Bluetooth, years of battery lifetime, the ability to form mesh networks of thousands of nodes, it´s open source and it can be used as a standard Eddystone/iBeacon proximity beacon (RuuviTag 2016). The used accelerometer is the LISDH12 3-axis accelerometer from STMicroelectronics (RuuviTag 2016). The features of LISDH12 are as follows: a maximum 12-bit ADC, the maximum sample rate of 2650 sps, the maximum amplitude range of ±16g and typical noise density of 200 µg/√Hz (STMicroelectronics 2016b). The price of RuuviTag is around 23 euros when only one is bought and the price decreases when RuuviTags are bought in numbers.

Analog Devices produces also smart sensors (not wireless) more dedicated to vibration monitoring like the ADIS16223 and the ADIS16227. The ADIS16223 and the ADIS16227 both have a resonance frequency of 22 kHz, the bandwidth of 14.25 kHz, a maximum amplitude range of ± 70g, SPI output type, measuring in 3-axes, digital filters, a buffer, aluminium cover, programmable alarms, trigger launched data collection, a temperature sensor and digital power supply measurements (Analog Devices 2016b, Analog Devices 2016c). The ADIS16227 has a bit more features than the ADIS16223 like more signal processing features such as windowing options (Hanning, flat top, rectangular), FFT and FFT averaging, storage for FFT records and a higher sample rate of 100.2 ksps compared to the sample rate of 72.9 ksps of ADIS223 (Analog Devices 2016b, Analog Devices 2016c). The price of the ADIS16223 is 198.45 $ and the price of the ADIS16227 is 238.35 $ so they are higher in price than the earlier mentioned smart/wireless sensors.

There are also USB accelerometers that can be connected directly to computers through USB ports. For example, Digiducer has a product called 333D01 which has rugged packaging, 24-bit ADC, flat response up to 8 kHz, the maximum amplitude range of 20 g, the maximum sample rate of 48 kHz, the resonant frequency above 25 kHz and USB 2.0 (Digiducer Inc. 2016a, Digiducer Inc. 2016b). Unfortunately, these USB accelerometers can be pricy: the 333D01 costs 1039 $ (Digiducer Inc. 2016a). Also, Diagnostic Solutions have their own USB accelerometer which can be seen in Figure 19. The USB accelerometer of Diagnostic solutions has the following features: frequency range 2 Hz – 10 kHz, 16-bit ADC, a 2 kHz low-pass filter, envelope filters and the amplitude range of ± 50g (Diagnostic Solutions). The price of accelerometer alone could not be found but they sell the accelerometer with a handheld data acquisition device for 3392 € (Diagnostic Solutions 2016).

Figure 19. USB accelerometer from Diagnostic Solutions.

4.4 Single-board computers and microcontrollers

There are many different single-board microcontrollers (or prototyping/expansion/evaluation/development boards for microcontrollers) and single-board computers available (or prototyping/expansion/evaluation/development boards for microprocessors/systems on chips). The term single-board refers to the fact that those systems are made on one single small printed circuit board (PCB) and those boards have all the necessary hardware for a microcontroller or system on a chip/microprocessor to work. The difference between single-board microcontrollers (SBM) and single-board computer (SBC) is hard to define. The SBM is usually built around a microcontroller unit (MCU). They tend to have easier and better usability with external hardware and lower energy consumption than SBCs. On the other hand, the SBC is commonly built around a microprocessor or system on a chip (SoC) and has an operating system. SBCs usually have much more processing power and higher power consumption than the SBMs. As the name SBC says, they are computers and thus closer to a laptop than an SBM. The SBMs and SBCs could be used as platforms to connect sensors (provide power and input and output for sensor data) and to manipulate, store and transfer further the coming sensor data (McGrath, Scanaill 2013, p.53).

One common single-board microcontroller family is the family of Arduinos but there are also plenty of other microcontrollers like the STM32L-DISCOVERY and the STM32 Nucleo F401RE from STMicroelectronics, LaunchPads (Texas instruments), Beetle, Nanode, Pinguino PIC32, Ruggeduino, Gamebuino, Freescale Freedom, Teensy etc. Arduinos were developed in Italy 2005 for students who did not have any background in electronics to have an easy way to interact between the digital and the physical world (Arduino 2016). The software and the hardware of Arduinos are open-source so Arduinos are completely open-source (Arduino 2016). One good thing more about the Arduinos is that they have a huge user community so it is relatively easy to get information and help regarding projects with Arduinos and Arduinos themselves.

Common SBCs are found from the product line of Raspberry Pis. The newest version of Raspberries is the Raspberry Pi 3 that can be seen in Figure 20 (Raspberry Pi Foundation 2016c). There are also other options like Beaglebone, Banana Pi, Odroid-C1, UDOO and Firefly. Like the Arduino, the Raspberry Pi also has a big community behind it, which is useful if project examples or trouble-shooting help is needed. The Raspberry foundation was founded in 2008 for educational purposes to educate children and adults in the field of computers, computer science and related subjects (Raspberry Pi Foundation 2016b). A number of single-board computer models, their features, and prices can be found in appendix 5.

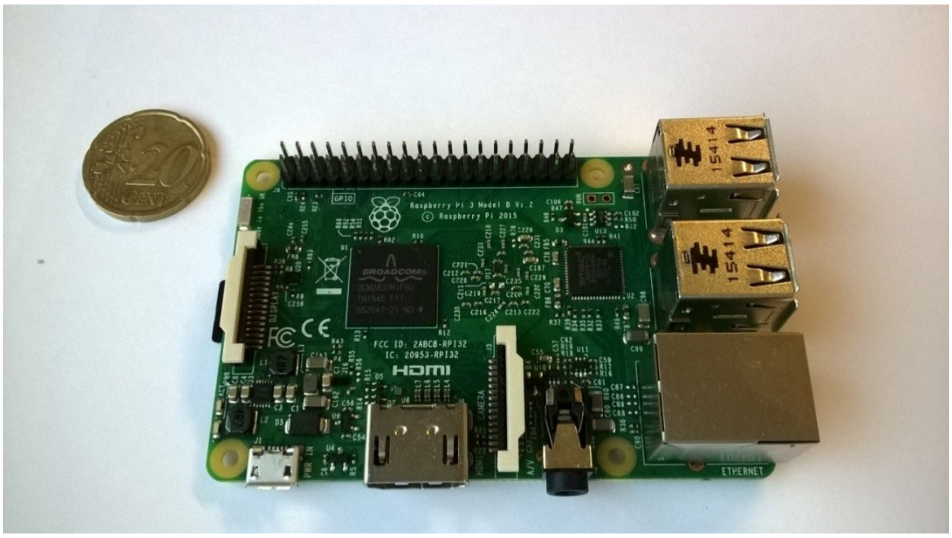

Figure 20. Single board computer Raspberry Pi 3 model B.

4.5 Evaluation boards for ADCs, filters and amplifiers

Like with microcontrollers, microprocessors and systems on chips there are also prototyping/expansion/evaluation/development boards for ADC ICs. A typical evaluation board for an ADC IC contains electronic components that are needed for using the ADC and they are usually attached to a single printed circuit board (PCB) following the prober printed circuit board design. Depending on the ADC evaluation board it might also have prober insulation, reference voltage, amplifiers, and filters attached to them making them more convenient for data acquisition. In other words, evaluation boards for ADC ICs form the analogue front end (AFE) for attached ADC ICs and the features/parameters of AFE depend on the ADC ICs that they are made for and on the amount of capabilities that the manufacturer has wanted to implement to the board. Maxim Integrated defines the AFE as “The analog portion of a circuit which precedes A/D conversion.” (Maxim Integrated 2016a). The used interfaces between the ADC evaluation boards and the processing units include parallel and serial (for example SPI, QSPI, Microwire) data interfaces among others. One conclusion made after studying multiple data sheets was that often the reachable sample rate is not so clearly stated. The term sample rate is used often but sometimes it is used for the total number of samples from all channels and sometimes it is used for the sample rate of one channel. It is difficult to know if the sample rate means the rate per channel or the complete rate of a system that has to be divided among channels to get the real rate per channel. This phenomenon of unclear sample rates is the same among all the systems/or components that include ADCs: ADC ICs, USB DAQs etc. Consequently the one who is searching for suitable ADCs must be careful when reading the data sheets.

One example of evaluation boards is the EVAL-AD7608SDZ, which has the previously mentioned AD7608 ADC attached to it. The EVAL-AD7608SDZ offers better accessibility to the AD7608 pins and also an extra reference voltage (Analog Devices 2016f). The EVAL-AD7608SDZ can be seen in Figure 21 with the EVAL-AD7609EDZ and the EVAL-AD7176-2. Some other evaluation boards for ADCs with their features can be found in appendix 6.

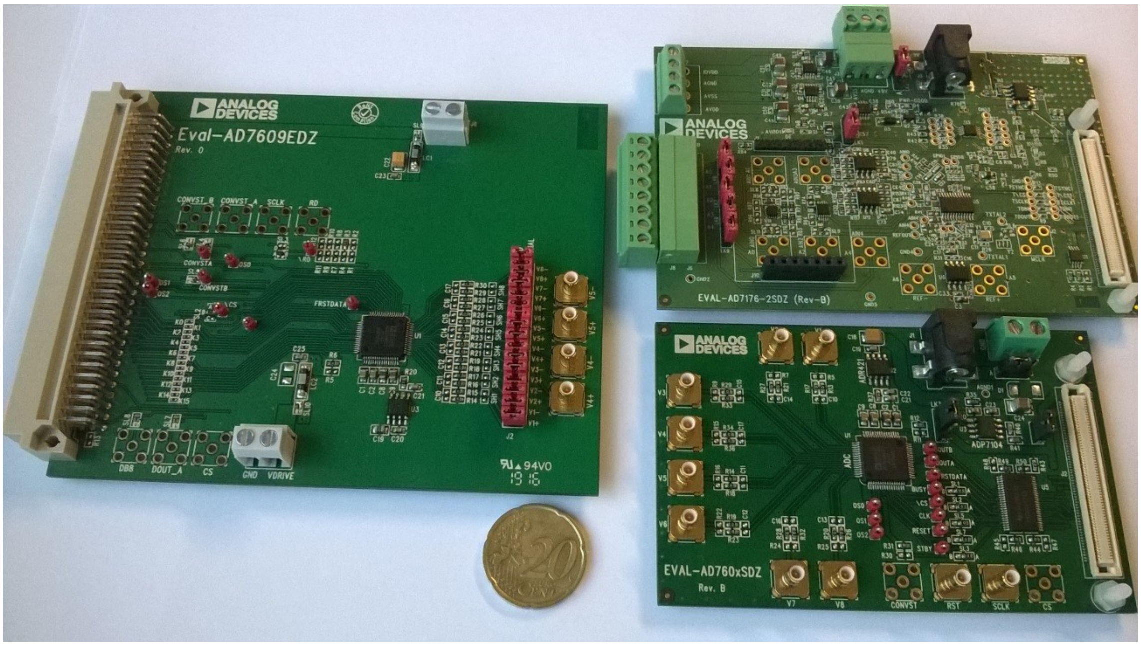

Figure 21. Evaluation boards for analogue-to-digital converters.

There are also printed circuit boards that have just amplification, filter or analogue front end properties without the ADC. For example Linear technology produces multiple different low-pass filtering boards like DC1251A-A, DC1304A-A, DC1304A-B, DC1418A-A, DC338A-A, DC338A-B, DC962A-A, DC962A-B, DC962A-E. The properties of these previously mentioned filter boards vary while the prices range from 50 € to 150 €. Some of them have amplifiers included, the order of the filter varies from 2nd order to 9th order, some have programmable low-pass filter, the number of channels varies from one to four and the cut-off frequencies go up to one megahertz with some of them (Linear Technology 2016). Another interesting filter board is a three pole Active Filter Board from Schmartboard. The filter board can be seen in Figure 22. The Active Filter Board can be easily configured for different cut frequencies and different filter types (Butterworth, Bessel, Chebyshev) by changing resistors and capacitors in the respective connectors (Schmartboard 2016).

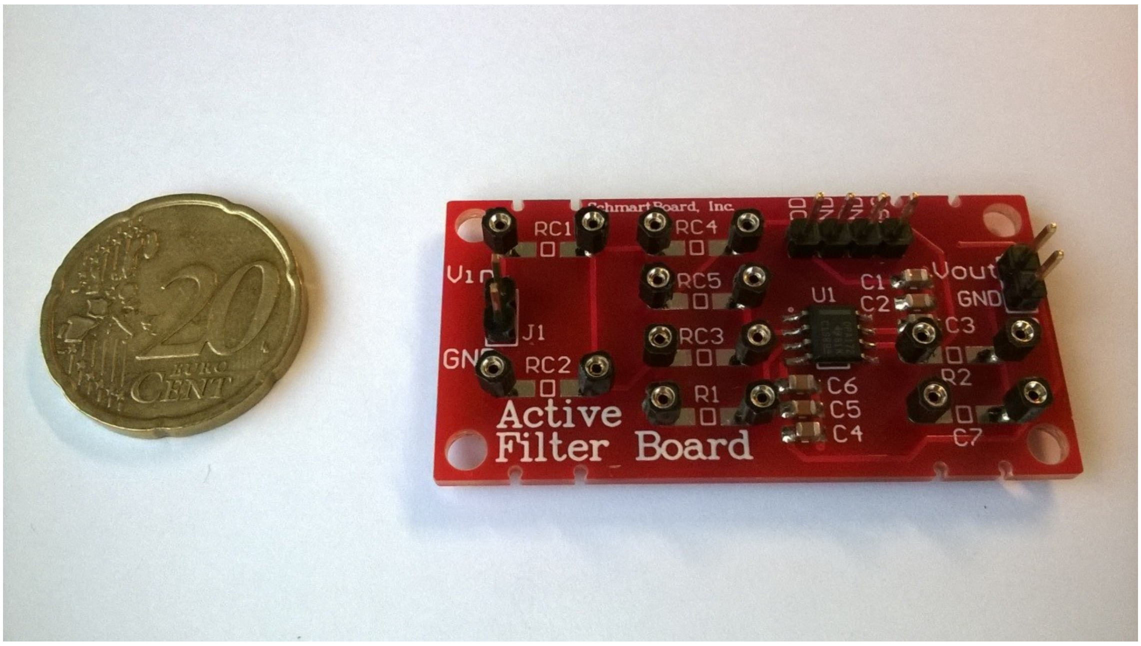

Figure 22. Active Filter Board from Schmartboard.

4.6 USB/Ethernet DAQs

Some data acquisition (DAQ) system manufacturers offer data logging devices that can be connected directly and easily to an USB or Ethernet port of a computer or a laptop and they are usually powered by the USB which make them more portable. The suitability to vibration monitoring or the quality and the price of USB/Ethernet DAQ devices varies. There are devices from 12-bit to 24-bit, sample rates from tens of hertz to few megahertz and with a price range from tens of euros to thousands of euros. There are also USB oscilloscopes that have high sample rates and can also be used for data acquisition purposes. Usually the USB DAQs/oscilloscopes that have the capability to measure 10 000 Hz signals and have a resolution from 16-bit upwards cost at minimum of hundreds of euros. Some well-known USB DAQ manufacturers are National Instruments, LabJack and Measurement Computing (MCC). Open DAQ [M] is the cheapest (200 €) USB DAQ found that just fulfils the requirements of 16-bit resolution and Nyquist theorem for 10 000 Hz. The PMD-1608FS from MCC costs 375 € and it goes further than just fulfilling the Nyquist theorem with its capability to sample 100 000 samples per second per channel. The PMD-1608FS can be seen in Figure 23. Appendix 7 describes some of the basic features of the USB DAQs and the USB oscilloscopes that were studied during the market review. Care should be taken when appendix 7 is used because often the highest sample rate and the highest resolution do not go hand in hand but rather the resolution decreases when the sample rate increases. It is recommended to check the manufacturers' data sheets if detailed information of the devices is needed.

Figure 23. USB data acquisition system from Measurement Computing.

One USB DAQ used at VTT for vibration measurements is the Quattro from Data Physics shown in Figure 24. The Quattro has 4 input channels, one trigger/tacho channel and two output/source channels. The bandwidth of the device is 40 kHz, the resolution is 24-bit and the sample rate goes up to 96 kHz. Also an anti-aliasing filter is integrated to the Quattro to in order to avoid aliasing. The casing of Quattro is made of metal to make it suitable for rough industrial environments (Data Physics 2016).

Figure 24. USB DAQ from Data Physics made for industrial measurements.

5 TESTS FOR LOW-COST EQUIPMENT

The Raspberry Pi with the EVAL-AD7609, the ADXL001, and the ACH 01 were chosen to further tests. The Raspberry Pi was chosen because of its popularity among hobbyists and others and because it has promising specifications: lot of processing power, the possibility for wireless connections and a number of different interfaces to connect sensors including 40 GPIO pins, SPI, UART, I2C and I2S. The EVAL-AD7609 was chosen because the Raspberry Pi needed an analogue to digital converter to check its capability to work with the ADC and analogue accelerometers. Also, the EVAL-AD7609 had attracting features including 200 ksps sample rate, 18-bit resolution, 8 channels and a reference voltage. The ADXL001 and the ACH 01 were chosen because of their relatively low price and interesting features like having high resonance frequencies thus making them capable to measure vibrations from a wide bandwidth up to 10 000 Hz and beyond.

5.1 Accelerometers

The ADXL001 and the ACH01 were calibrated using the Beran 475 calibrating equipment to verify their capabilities. Firstly, the new accelerometers were defined for the calibrating system by describing the basic parameters of the accelerometers from data sheets including interface, nominal sensitivity and the frequency of that sensitivity, operational range in m/s^2, mass and frequency range in Hz.

Secondly, all the mechanical and electrical connections were made. For both the ACH01 and the ADXL001 5V from Oltronix B202 power supply was provided. The voltages were checked with an oscilloscope and verified to be 5,003 V for the ADXL measurements and 5,013 for the ACH01 measurements. Variations in the voltages were within ±25mV. After the electrical connections were made, also mechanical connections had to be made between the ACH01/ADXL001 and the comparison accelerometer which was attached to the shaker. A few different solutions for connecting the accelerometers to the shaker including wax, instant glue and screws were tested. The used sensor cables were secured before the calibration by cable ties so that they did not introduce extra mass and distraction. The calibration arrangements can be seen in Figure 25 where the blue box is the power supply and black cylinder is a shaker on a sturdy base having the comparison accelerometer and the ACH01 attached.

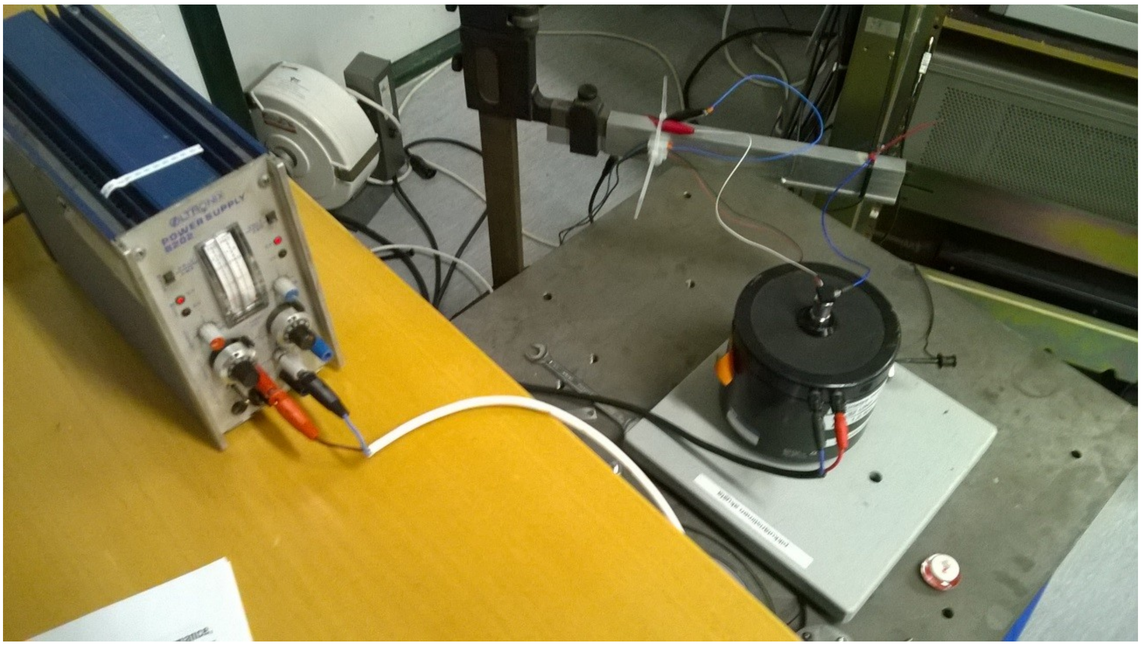

Figure 25. Calibration arrangements.

The comparison accelerometer to which all the other accelerometers were attached in these measurements was the 8305 from Brüel & Kjær, the used amplifier was Beran 801A for both the calibrating accelerometer and for the comparison accelerometer, the shaker/exciter was the 4824 from Brüel & Kjær and the Power Amplifier Type 2719 from Brüel & Kjær was used for the shaker.

There were a few different calibration programs to choose from with the Beran 475 like the frequency sweep and the amplitude linearity. The frequency sweep was chosen to reveal the acting of accelerometers at different frequencies but the complete calibration certificates including for example the phase and the amplitude steps can also be seen in appendices 8, 9, 10 and 11.

For comparison, the 4394 accelerometer from Brüel & Kjær (used at VTT for vibration measurements) was calibrated. The 4394 accelerometer was mounted to the comparison accelerometer using the accelerometer-mounting wax 32279 from Endevco. In Figure

26 can be seen the 4394 accelerometer attached to the comparison accelerometer. Also, the blue metal “hat” was screwed on top of the comparison accelerometer to prevent the wax from going to the threads of the comparison accelerometer. The result of the sweep from 10 Hz to 10 kHz can be seen in Figure 27 and Figure 29. The frequency step in Figure 28 shows the accelerometers acting at certain frequencies with ±5 % scale. The scale gives a more detailed perspective when compared to what is shown in Figure 27. In Figure 27 and Figure 28 the scaling displayed on the right side in percentage shows the difference between 4394 and comparison accelerometer. In Figure 29 the scale is shown in decibels. Figure 27 and Figure 29 have also black horizontal lines showing the ±5 % limit. The measured nominal sensitivity of 4394 is 1,007 mV/(m/s^2) and it seems to be almost all the way under the ±5 % limit. Just before 10 kHz the difference between the 4394 and the comparison accelerometer goes beyond ±5 % limit.

The ±5 % limit is seen as acceptable variation for the B&K 4394. The curves for the ADXL001 and the ACH01 with ±5 % scaling go beyond the scaling but they are still kept as shown because they reveal the acting of the ADXL001 in the the steady response frequency range, and they are more comparable to the B&K 4394 and to the ±5 % limit which is seen as a good qualifying limit. The curves are naturally presented with such a scaling that shows the curves fully.

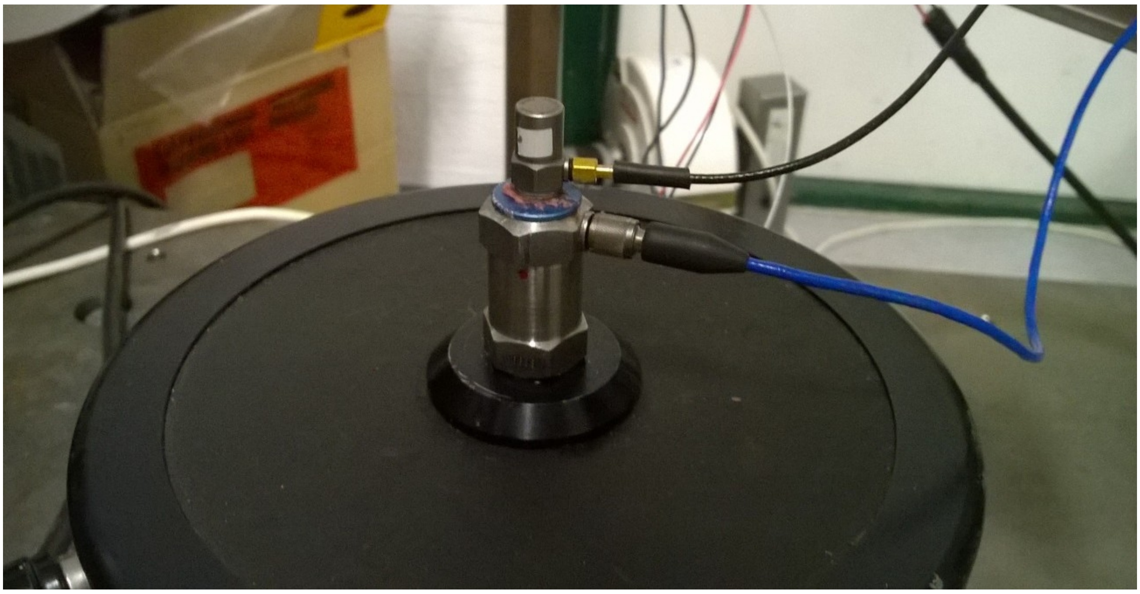

Figure 26. The Brüel & Kjær 4394 accelerometer attached to the comparison accelerometer.

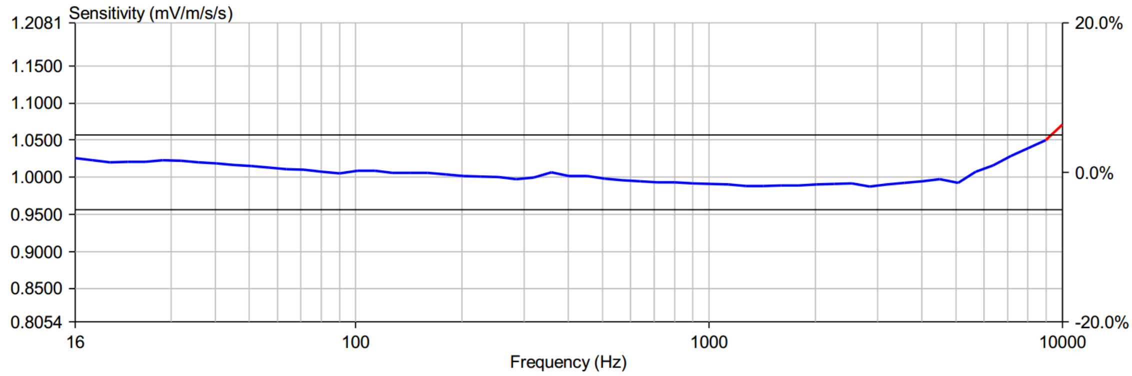

Figure 27. The Brüel & Kjær 4394 calibration (fsweep), installed with wax, ±20 % scale.

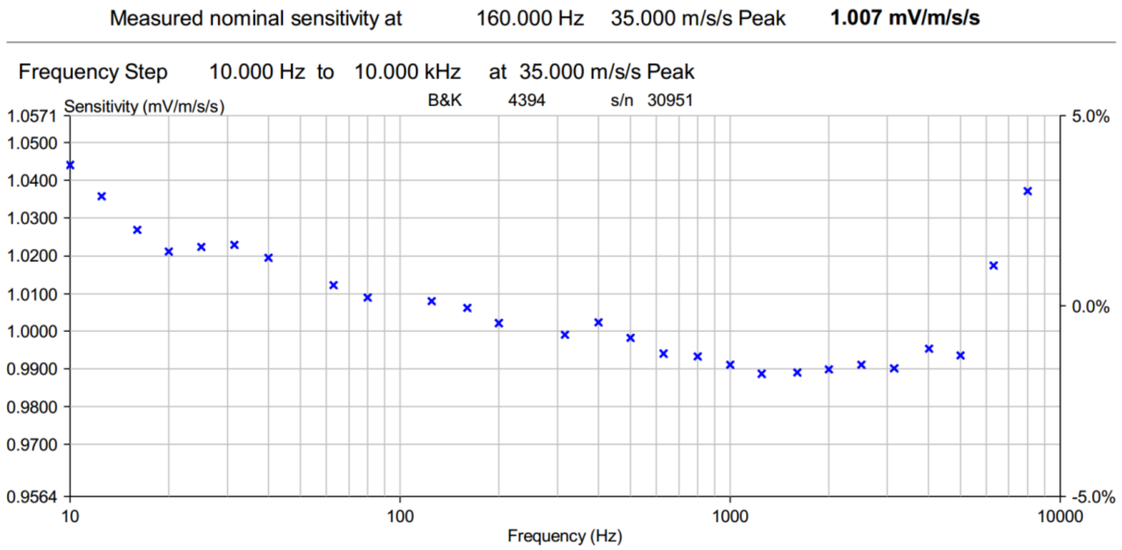

Figure 28. The Brüel & Kjær 4394 calibration (fstep), installed with wax, ±5 % scale.

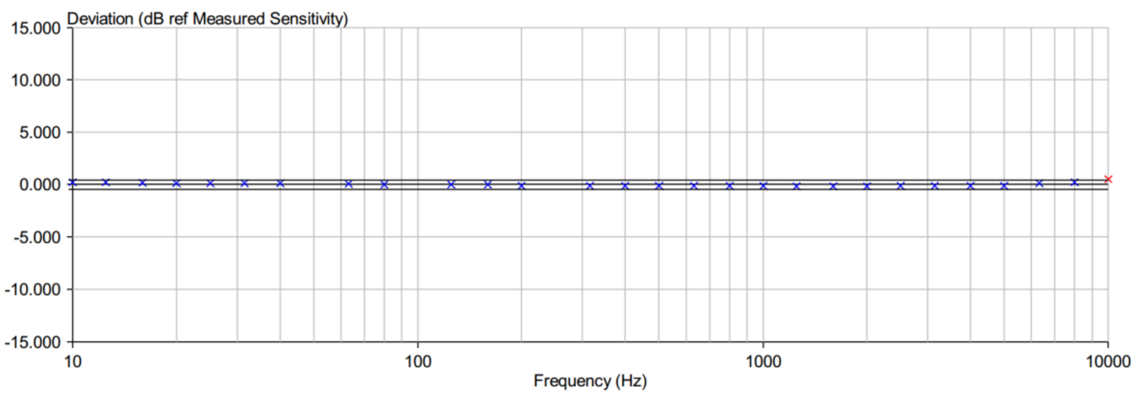

Figure 29. The Brüel & Kjær 4394 calibration, installed with wax, ±15 dB scale.

5.1.1 ACH 01

The calibration of the ACH01 followed the same procedure as with the 4394 accelerometer. The accelerometer was mounted on the top of the comparison accelerometer with the accelerometer mounting wax 32279 from Endevco and the frequency sweep and the nominal sensitivity measurement were done. The mounting of the ACH01 can be seen in Figure 30. The results compared with the 4394 are rather different as can be seen in Figure 31 and Figure 32. The measured nominal sensitivity differs also a lot when compared to the value of 1,091mV/(m/s^2) given by the manufacturer which was given with the accelerometer as the calibration result of that particular individual accelerometer.

The sensitivity of the ACH01 differs a lot at different frequencies as can be seen in Figure 32 (note ±50 dB scale). The ACH 01 is not stable at all and thus it is not good for vibration monitoring applications. Because the value of sensitivity varies quite a lot it is not possible to define the real value of acceleration.

The results are not in line with the specifications of ACH01 at all. The ACH-01 specification states that the ACH 01 has wide bandwidth (2Hz – 20Hz), excellent linearity (max 1 %) and the capability to be used in machine health monitoring (TE Connectivity 2016). There are possible solutions that explain the difference between the measured results and the data sheet: the specifications in the data sheet are not correct, this particular ACH 01 is poor in quality and/or the calibration was done in a wrong way. The calibration was done in the same way with the B&K 4394 and also with the ADXL001 and that calibration with the ADXL001 gave results that were more in line with the ADXL001 specification sheet. The 5 voltage power was fed into the ACH01 and it might be that the different voltages would generate different results but the ACH01 data sheet states that the voltages from 3V to 40V could be used with the ACH01.

Figure 30. The ACH01 attached to comparison the accelerometer for calibration.

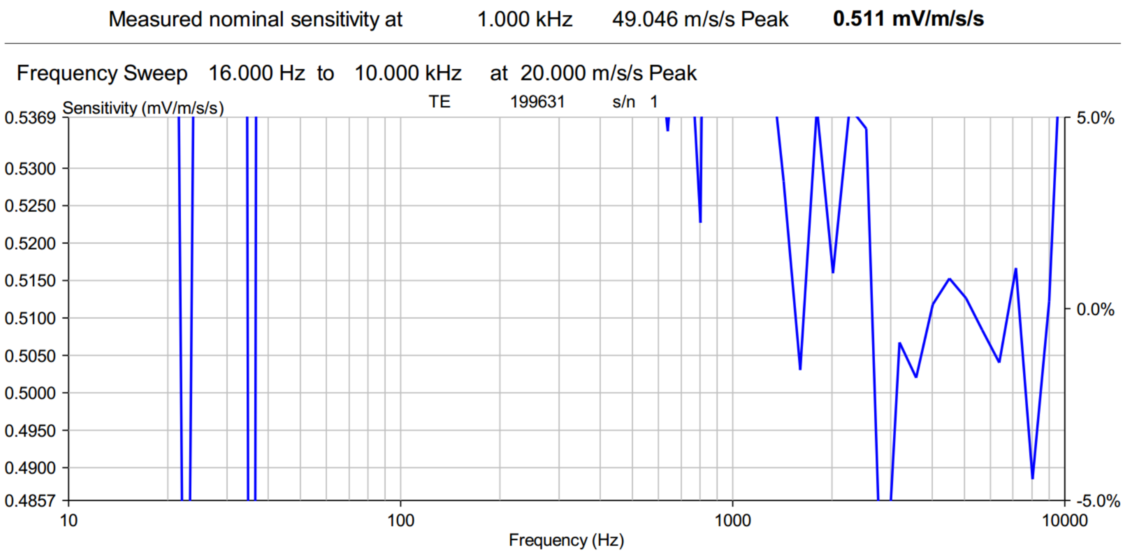

Figure 31. The ACH01 attached to comparison the accelerometer for calibration.

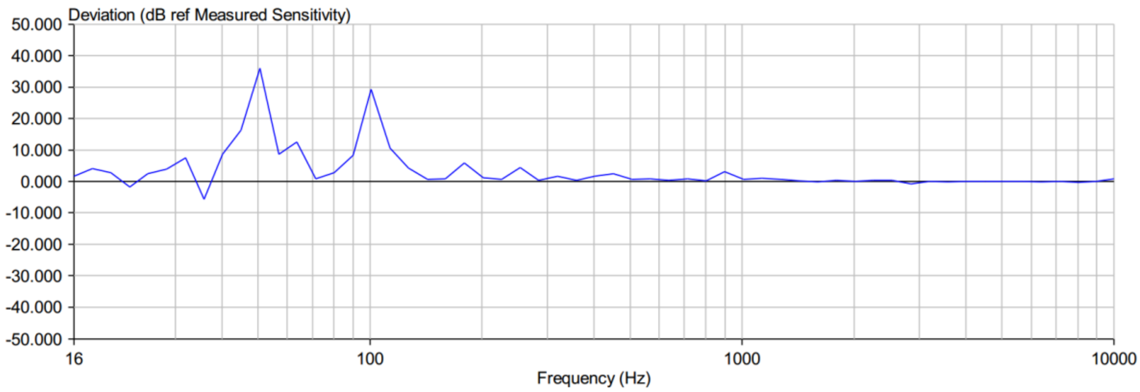

Figure 32. The ACH01 calibration, installed with wax, ±50 dB limits.

5.1.2 ADXL001

The ADXL001 was received from a company called Nome, which had made a prototype sensor system that included the ADXL001 and a temperature sensor in the same printed circuit board (Figure 33). According to Nome, the circuitry around the ADXL001 was constructed in a way that included a notch filter to flatten the frequency curve of the ADXL001 at high frequencies as advised by Analog Devices (Analog Devices 2016e, Analog Devices 2016d). The notch filter makes it easier to measure also high frequencies with the ADXL001.

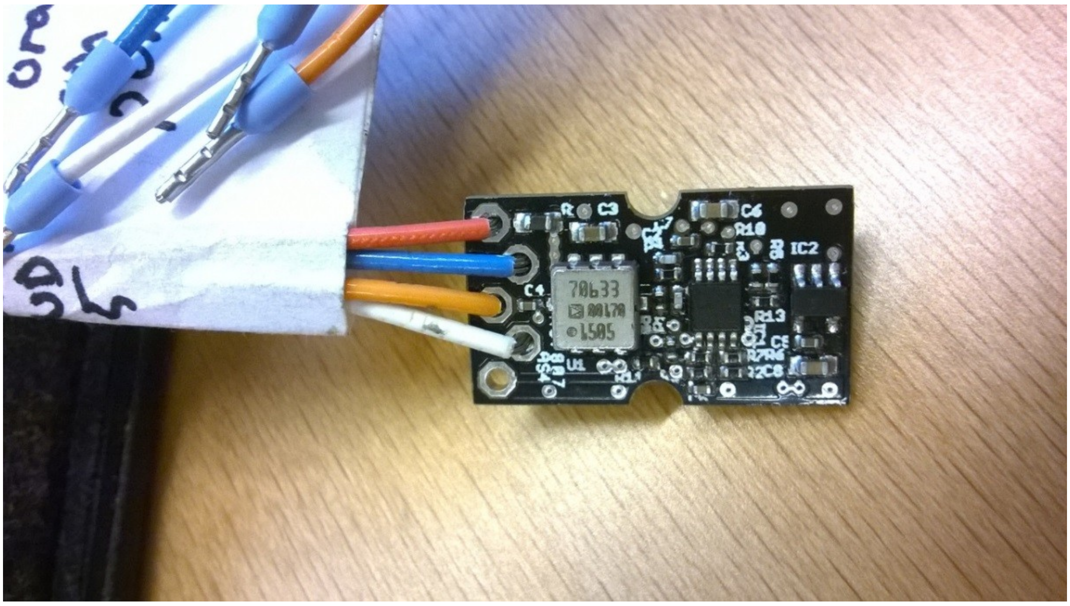

Figure 33. The ADXL001 attached to the PCB with the temperature sensor.

The calibration was done in the same way as for the ACH01 and the 4394 accelerometer: a frequency sweep was conducted and the nominal sensitivity was measured. Luckily, with this accelerometer there was enough time to try different mounting methods including instant glue, wax and screws. The wax and the instant glue did not differ significantly and thus the result of with the instant glue is only showed. Because of the sensitive axis of the ADXL the PCB had to be positioned in “standing” position and thus away from the centre axis of the comparison accelerometer as can be seen in Figure 34. The difference between the centre axes of the calibrating and the comparison accelerometer might have had a small effect on results. After some time from the first calibration with glue, a connection piece for the screw connection was made. The connection piece was made from available materials and available tools within a short time window which lead to the angle shape which is seen in Figure 35. Aluminium was chosen from the available materials to be as light as possible but still being stiff enough to be able to pass vibrations to the accelerometers from the shaker. Unfortunately, this shape led also to a situation where the centre axes of the calibration and the comparison accelerometer did not match. The positive side of being away from the centre axis of the comparison accelerometer was that the screw connection is more comparable to the glue connection because in both cases the ADXL001 is away from the centre axis of the comparison accelerometer. Some tape was used between the PCB and the metals to prevent from short circuits (seen red in Figure 35).

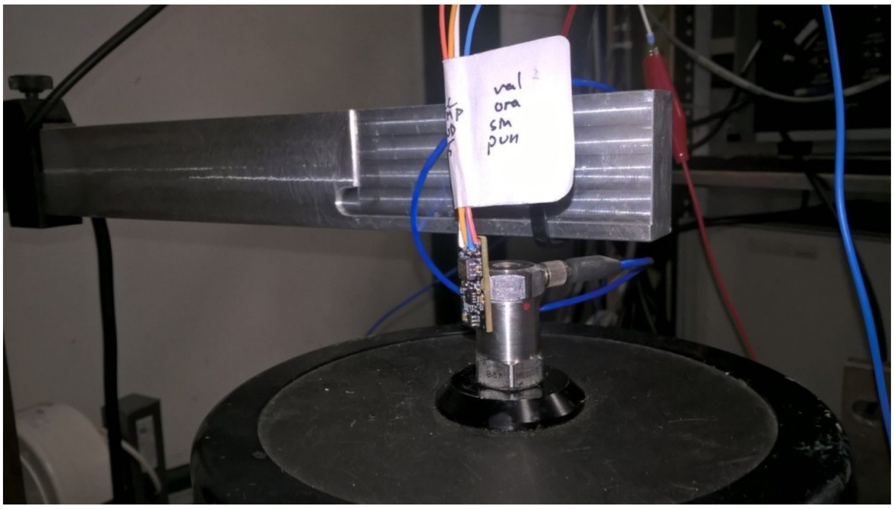

Figure 34. The ADXL PCB attached to comparison accelerometer with glue.

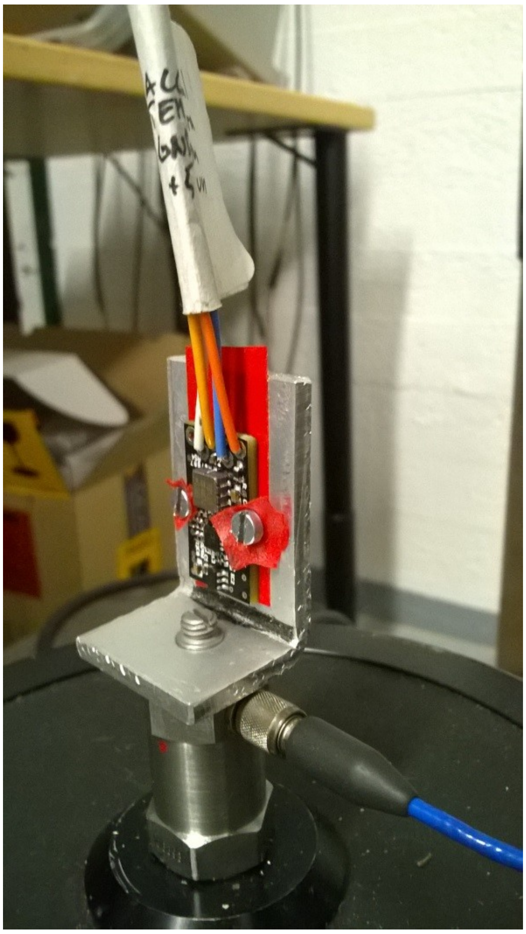

Figure 35. The ADXL PCB attached to the comparison accelerometer with screws.

When looking at the results in Figure 36 and in Figure 37 it is possible to see that the ADXL001 is acting quite in a stable way below 1000 Hz with the glue connection and in even more stable way with the screw connection. It could be said that the response of the ADXL001 is better than the response of the Brüel & Kjær 4394 below the frequency of 1000 Hz. The screw connection did not bring stableness to the high frequencies as was expected. The result in Figure 36 can be easily compared with the equal figure of the datasheet because they both have scaling in decibels and it can be seen that they are not similar (Analog Devices 2016e). Below 1000 Hz the results are similar with the datasheet but for higher frequencies, the test results do not follow a similar flat line as is shown in the datasheet, instead there are some instabilities. Again, there are multiple options why the figures do not match: the datasheet might have false information, this particular ADXL001 is faulty, the used printed circuit is faulty and/or the calibration has been done in a wrong way.

The used printed circuit board with its components might have a natural frequency somewhere between 1000 Hz and 10 000 Hz which affects to the sensitivity. Another option is that the given PCB does not have the circuitry/notch filter build in a proper way. The third option regarding to the influences caused by the PCB could be that the PCB does not pass the vibration well enough to the ADXL001 accelerometer. The Analog Devices sell the ADXL001 also connected to a PCB as seen in Figure 17. With Analog Devices' own PCB the results might be different.

There might have been also faults in the way the calibration process was carried out and especially in the mounting between the ADXL001 and the comparison accelerometer. As said before the axes did not match but also the tightness of screws and the used tape might have been a problem. Maybe the screws were not tightened enough because of the fear of breaking the PCB or the insulator tape had some small effect also to the tightness of the screws and the passing of vibration to the ADXL001. However, with these results it easy to say that the ADXL001 has a good frequency response below 1000 Hz and could be used for vibration monitoring up to that frequency.

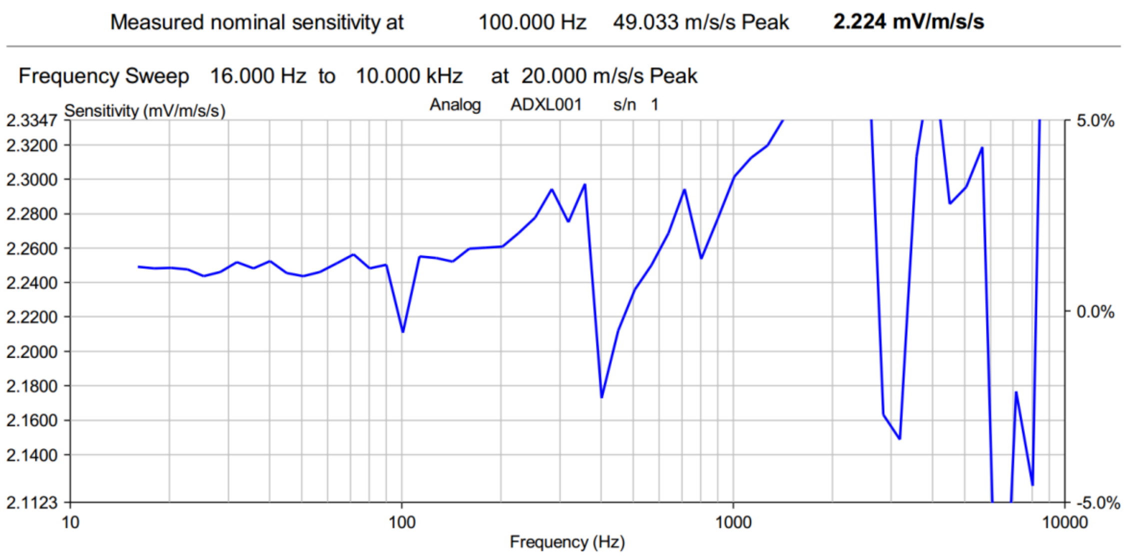

Figure 36. The ADXL001 calibration, installed with glue, ±5 % limits.

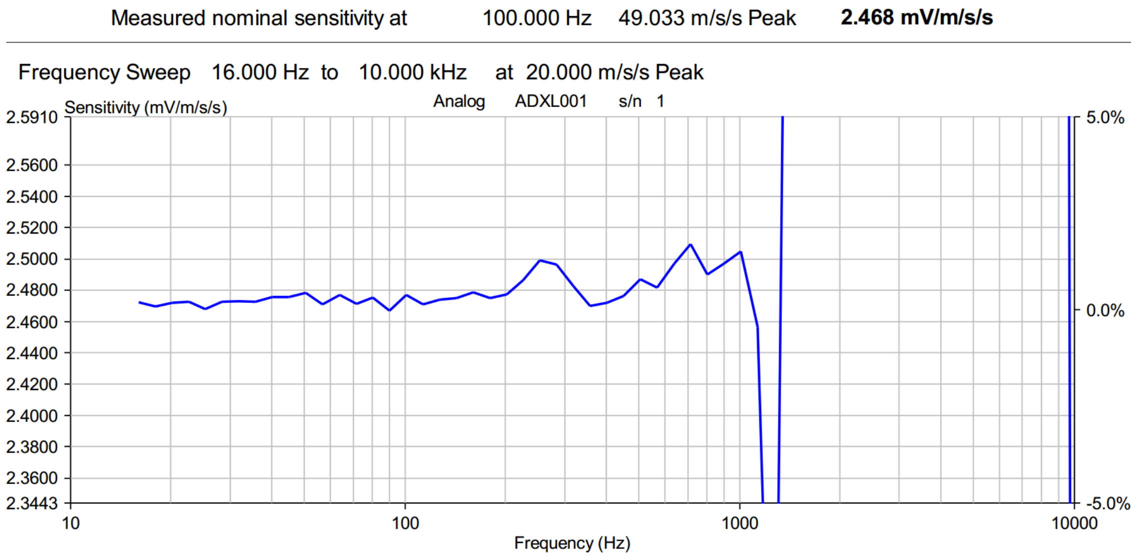

Figure 37. The ADXL001 calibration, installed with screws, ±5 % limits.

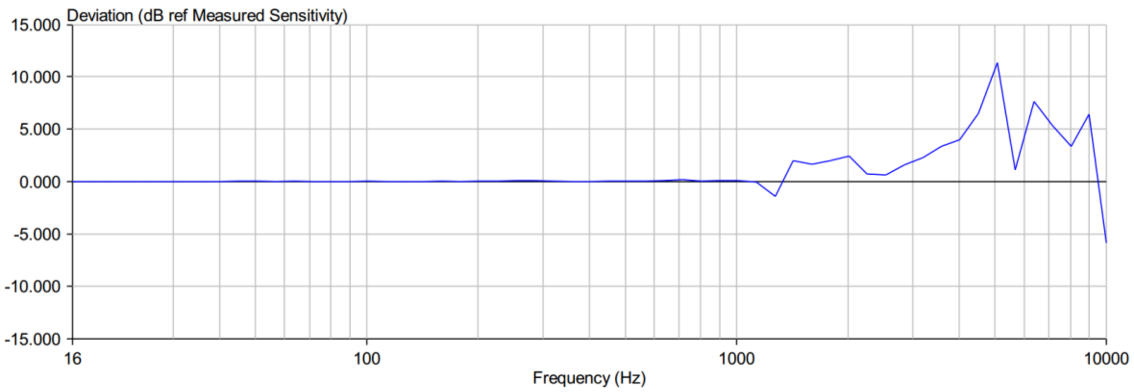

Figure 38. The ADXL001 calibration, installed with screws, ±15 dB limits.

5.2 Raspberry Pi 3 as a sensor platform

The Raspberry Pi3 model B was chosen as a sensor platform because it has reasonable price, good performance according to the specifications, Wi-Fi and Bluetooth for wireless communication enabling the possibility to be part of Internet of Things. The capability of being part of Internet of Things might be actually a big advantage because it is predicted that by 2020 there will be 50 billion Internet of Things devices (Evans 2011, p.3). Maybe, still the biggest driving factor towards to Raspberry was the large community of users. The Raspberry forum itself (https://www.raspberrypi.org/forums/) has 1 039 887 posts, 152 288 topics and 186 136 members (checked at 25.11.2016) but on top of that there are also other forums like the http://raspberrypi.stackexchange.com/. Also Arduino has a large user community which is revealed by the https://forum.arduino.cc/: 2 920 708 posts, 370 132 topics and 296 315 members (checked at 25.11.2016). The reason why Raspberry was chosen before Arduino was that the Raspberry Pi 3 has much more processing power than any of the Arduinos and that the processing power could be very useful in signal processing, data storing and sending data for further manipulation.

Even though the huge community is a big blessing, it is also a bit of a curse. Often there is not any verified information available (manuals, datasheets, guides etc.) and all the needed information has to be gathered from different forums. The forum post goodness has to be weighted somehow and the wanted information needs to be separated from the unnecessary and the false information. In addition, the writers of these forums might not have the best writing skills, language skills, correct terms or a unified way to express their answers/questions and thus it might be quite time consuming to find useful information. Because the Raspberry is so community based, many of the following references regarding to the Raspberry are from the Raspberry forums or from some websites and thus these references are, unfortunately, not so highly appreciated in the scientific world.

At first, before the Raspberry was purchased, it was roughly checked that the Raspberry would be able to reach the wanted sample rate when used for data acquisition. It was possible to find information that the previous Raspberry model has been used even as an oscilloscope to reach sample rates up to 10 mega samples per second (Pelikan 2014). This gave promising thoughts for the future and gave the courage to buy the Raspberry and to start further investigation.

5.2.1 Communication between Raspberry and external hardware

The Raspberry Pi 3 has 40 general-purpose input-output (GPIO) pins and multiple ways to communicate with external hardware like an ADC (MagPi 2016). The Raspberry Pi has numerous serial interfaces such as the universal asynchronous receiver/transmitter (UART), the serial peripheral interface (SPI), the inter-integrated circuit (I2C) and the inter-IC Sound (I2S) (Raspberry Pi Foundation 2016a). The parallel interface is also one way to communicate between the Raspberry and the external hardware. The SPI and the parallel interfaces were chosen for further investigation because of their wide usage in ADC to Raspberry connections and their high speed rates: the maximum speed of SPI is 8 megabits per second (Mbps) and in parallel mode it is possible to use it as an oscilloscope (10 mega samples per second) (Pelikan 2014, Abyz 2016a, Wootton 2016, p.335). Even though the SPI information page of the Raspberry Pi Foundation claims that the SPI has the maximum speed of 125 Mbps it is not reachable anymore when the signals reach the GPIO pins (Raspberry Pi Foundation 2016d, Raspberry Pi Foundation - Forum 2016e). The I2C is also widely used in projects that use the Raspberry Pi and the ADC but it has the maximum speed of 400 kilobits per second (kbps) and thus it is slower than the parallel interface or the SPI. The I2S might also have use in condition monitoring applications. The I2S is normally used in audio applications and it is able to reach a sample rate of ~200 kilo samples per second with the resolution of 24-bit when operating with the Raspberry Pi (Raspberry Pi Foundation - Forum 2016b).

The SPI was originally developed by Motorola but nowadays it is a bit loosely defined (McGrath, Scanaill 2013, p.63). Usually the SPI needs 4 wires to work: the slave select (SS) line to choose one of connected peripherals, the master-out slave-in (MOSI) to send data from the master device (for example CPU) to the slave device (for example ADC), the master-in slave-out (MISO) to receive data from the slave and the clock signal line (SCLK) to give the clock signal to the slave and to control the data stream (Wootton 2016, pp.335-336, McGrath, Scanaill 2013, p.63). The SPI works in full duplex mode meaning that the data is sent to the slave and received from the slave simultaneously (McGrath, Scanaill 2013, p.63). The data stream is controlled by the master device.

The parallel interface allows sending multiple bits at once but it also needs as many wires as it has bits to send and in addition a clock wire (Pelikan 2014, p.8). As described earlier, the parallel interface can reach even the speed of 10 mega samples per second with the Raspberry but there is also a problem: the system interrupts are disabled and thus sampling in this manner can be performed only for a millisecond or so without causing any interrupt related problems to the Linux operating system (Pelikan 2014, p.6). When the investigation of using the Raspberry as a sensor platform was carried, it was hoped that the parallel interface could also be an option for longer sampling times when the sample rate was slightly reduced.

5.2.2 Programming Raspberry

The Raspberry has a couple of text-editors (some have also features like colouring to make the programming easier) installed in advance that can be used for programming: Leafpad, IDLE, Nano and VI (Raspberry Pi Foundation 2016e). In addition, there are more text editors and integrated development environments (IDEs) that can be downloaded afterwards. For fast software applications, like fast ADC sampling, the programming language C is usually recommended over Python and that is the reason why it was chosen for this project (Raspberry Pi Foundation - Forum 2016f, Raspberry Pi Foundation - Forum 2016d, Raspberry Pi Foundation - Forum 2016c, Raspberry Pi Foundation - Forum 2016a). There are popular libraries to access the GPIOs of the Raspberry through the programming language C like PIGPIO, Wiring Pi and Mike McCauley's one (Abyz 2016b, Henderson 2016, McCauley 2016). The PIGPIO library was chosen for this project because Abyz seems to be an active member in the Raspberry Pi forums and is willing to help when problems occur.

5.2.3 Raspberry & EVAL-AD7609

The EVAL-AD7609 from Analog devices was chosen as the analogue interface because of its good features. The ADC used in the EVAL-AD7609 is the AD7609 having the same features as the AD7608 described in chapter *8.2 Measurement system from integrated circuits* added on the evaluation board which provides better access to the ADCs pins and an extra reference voltage. Without any previous programming or electronics background, it turned out to be quite time consuming and difficult to get the EVAL-AD7609 and the Raspberry to work together. Unfortunately, the time reserved for this thesis ended before this connection could be made to work properly.

The EVAL-AD7609 has the SPI and the parallel interfaces. The parallel interface was chosen at first after seeing the Raspberry used as an oscilloscope in the Pelikan's project and because of the basic concept of the parallel interface's capability to transfer multiple bits at once. The capability of the PIGPIO to read the GPIOs just every 5 microsecond leads to the maximum reading rate of 200 000 reads per second. The EVAL-AD7609 has 8 channels and a parallel interface that has to send bits in two sections per channel which leads to a sample rate of (200 000 sps / 8) / 2 = 12 500 sps. The poor performance of the parallel interface with the PIGPIO led to the change of the angle of the approach to use the SPI instead.

Ambitiously an option was searched to get all the power into use from the EVAL-AD7609 but unfortunately after long hours spent with the Raspberry and learning about the SPI, the PIGPIO, programming, and electronics a working solution was not found. Even though the SPI's maximum speed of 8 MHz is presented earlier in this thesis, it was not found in the early stage of attempts. The EVAL-AD7609 needs the SPI clock speed of 20 MHz to work in full speed and with 8 MHz SPI clock the full speed was not reached in this thesis. The clock signals of 1 MHz, 4 MHz, 8 MHz, 16 MHz, 31 MHz and 63 MHz are shown in Figure 40 - Figure 45 and it can be seen that the step like signal is transforming towards a sinusoidal signal when the frequency increases. The arrangements for the oscilloscope measurements can be seen in Figure 39.

With more time and with wider knowledge about programming and electronics, solutions to get the Raspberry Pi and the EVAL-AD7609 combination to work might be found. Also, the fact that the Raspberry Pi has been used successfully as an oscilloscope gives hope of success. The solution for this problem might be found from better programming or using the Raspberry without any operating system in a so-called bear metal mode.

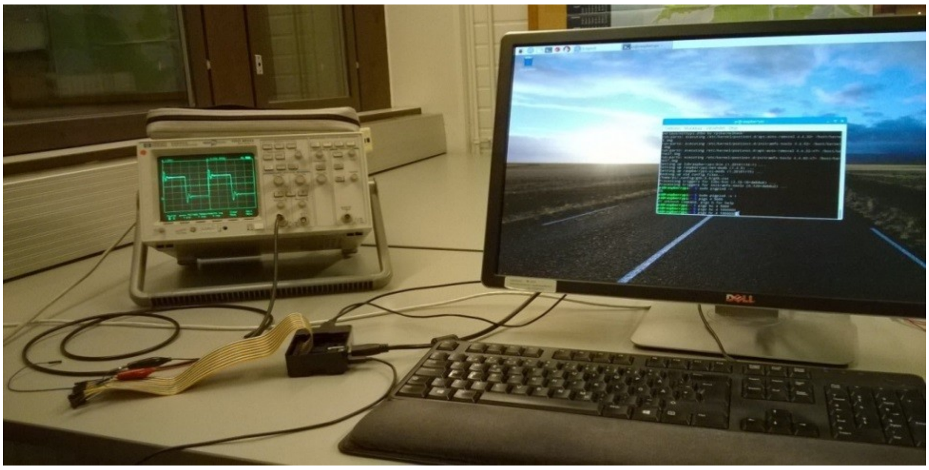

Figure 39. Arrangements for oscilloscope measurements with the Raspberry Pi.

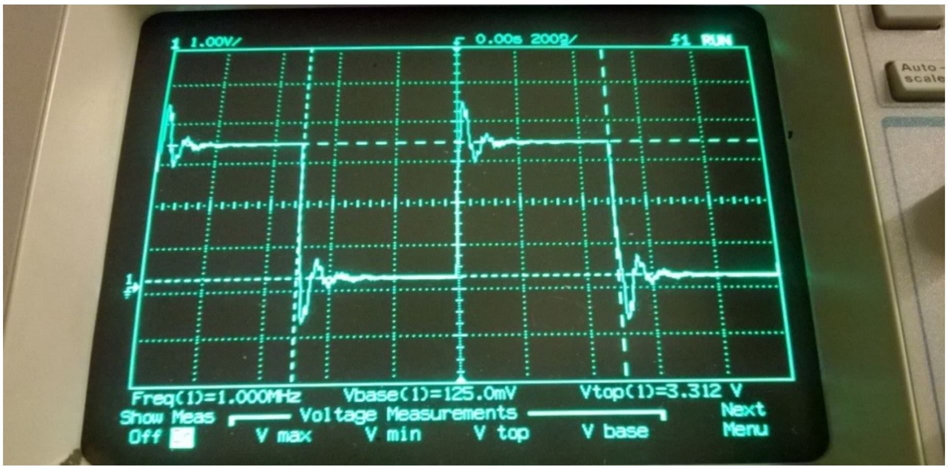

Figure 40. 1 MHz hardware clock signal from the Raspberry Pi.

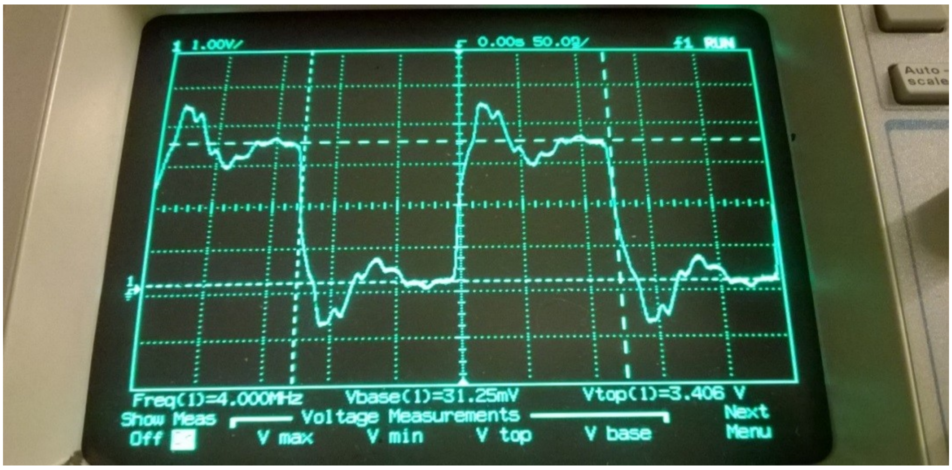

Figure 41. 4 MHz hardware clock signal from the Raspberry Pi.

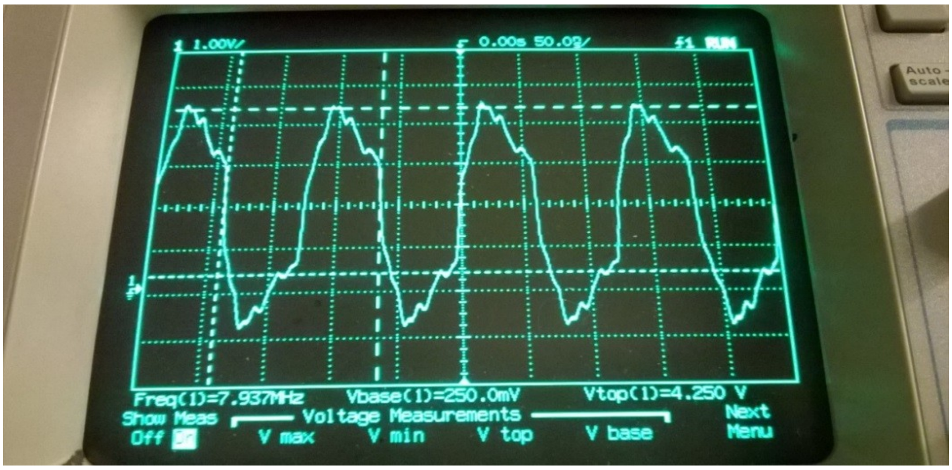

Figure 42. ~ 8 MHz hardware clock signal from the Raspberry Pi.

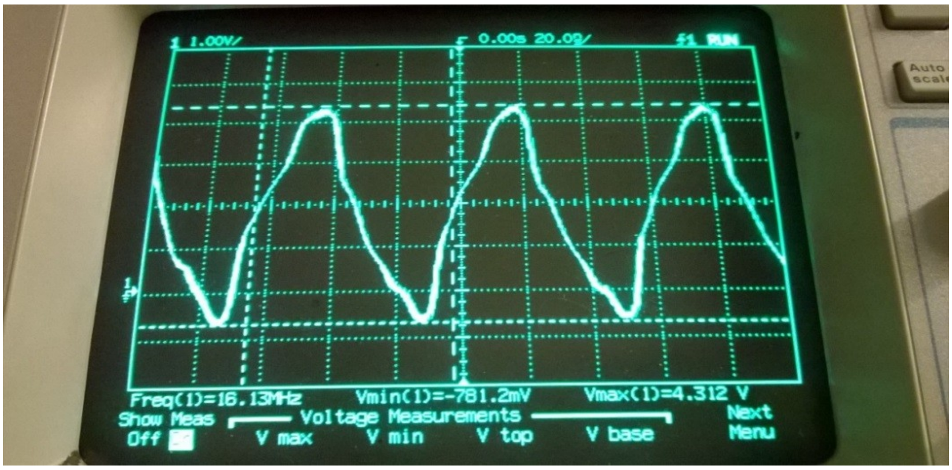

Figure 43. ~ 16 MHz hardware clock signal from the Raspberry Pi.

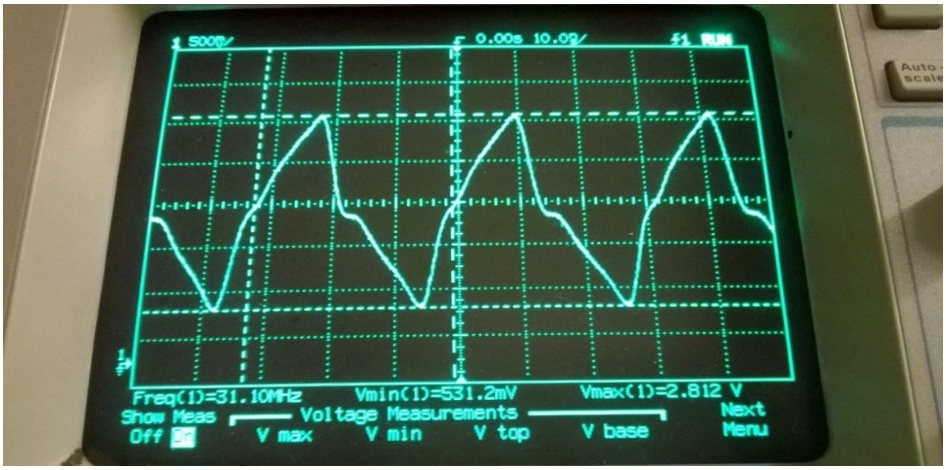

Figure 44. ~ 31 MHz hardware clock signal from the Raspberry Pi.

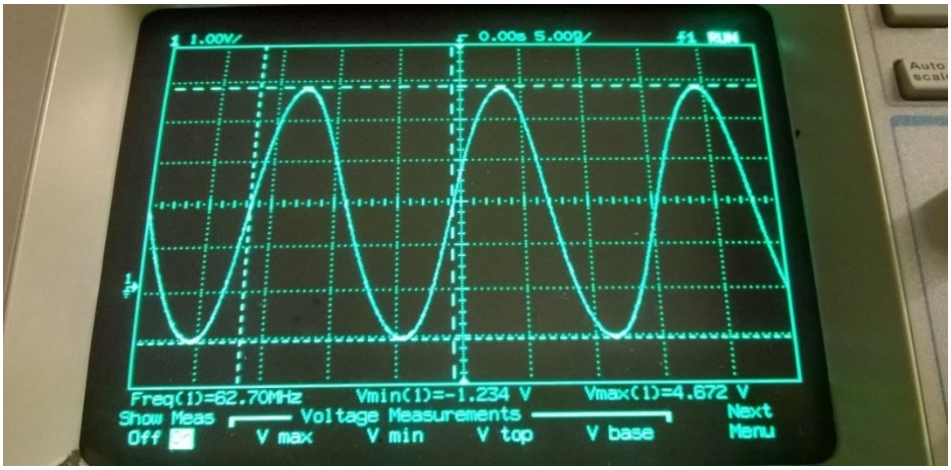

Figure 45. ~ 63 MHz hardware clock signal from the Raspberry Pi.

6 DISCUSSION

The budget of 100 € is too low for a complete vibration monitoring system that is capable to do bearing monitoring up to 10 000 Hz signals and to have 16-bit resolution. The only thinkable solution under 100 € was the system built from ICs. The IC component prices are well suited to the wanted limit of 100 € and the specifications of those components are also more than suitable to meet the criteria of being able to measure signals up to 10 000 Hz with the resolution of 16-bit. With 100 € it is possible to get a 24-bit ADC, with sample rate over 100 ksps, high order anti-aliasing filter, amplification, processor and even an accelerometer like ADXL001. The problem comes when these ICs are connected together: the programming, electronic circuit designing and connecting the electronic components might be time consuming (time is money). In addition, sometimes expensive tools maybe needed (like good soldering iron for small ICs) and electrical and programming knowledge should be high enough to be able to design non-noisy circuits and have effective and fast code which is able to sample fast enough and to do data manipulation. Luckily new ICs are coming that integrate many of the data-acquisition components to one chip like the AD7608 which has reference voltage, track-and-hold amplifiers, anti-alias filter and digital filter all integrated to one chip. The integration of the chips loosens the requirements for the needed wide knowledge about electronics and noise cancellation because many of the connections between components have already been taken care by the manufacturer.

Promising low-cost accelerometers were also found or at least promising specifications of accelerometers like the ACH 01 from Te Connectivity and the ADXL001 from Analog Devices. When these promising accelerometers were tested, the sensitivity of vibration monitoring was revealed. The ACH 01 did not follow at all its specification but with the ADXL001 the results were promising up to 1000 Hz. Most likely, it is possible to find the full potential of the ADXL001 in right conditions where the sensitivity of vibration monitoring is taken even more seriously: if the ADXL001 is connected to a PCB, the PCB has to be able to pass the vibration without affecting to it (for example the resonance frequency should be high enough for the PCB and it should not damp the vibration) and the connection of the ADXL001 or the ADXL001 and the

PCB to the measuring location should be made stiff enough and to an optimal point (the screw connection is usually the best and the accelerometer should be as near as possible to the measurement location without having any extra barriers in between). The few euro accelerometers were not able to reach the 10 000 Hz goal but they might be useful in other condition monitoring applications with lower frequencies. Though it have to be noted that many of the digital MEMS do not have an anti-aliasing filter build in. The lack of anti-aliasing filter has to be taken care of for example by using mechanical filters. Because of the low bandwidth they are not capable to measure defects from small bearings but might be usable with big bearings as the equation (1) shows.

The smart sensors form a class of their own when compact designs are needed or when multiple physical phenomena must be measured from the same location. Depending on the smart sensor, they can have many features included: multiple sensors in a single package, local data processing, wireless connection and so on. The Internet of Things is raising a lot of interest nowadays and the smart sensors with their wireless communication and local data processing are almost like made for IoT. The local data processing of a sensor minimises the amount of data transferred and reduces the needed storage space in the receiver device. The smart sensors with many features can be reasonable priced but when a smart sensor for bearing condition monitoring is wanted; the cost rises to hundreds of euros per accelerometer. The ADIS16227 is a good example of a smart sensor which is designed for vibration monitoring.

There are plenty of USB DAQs/oscilloscopes and ADC evaluation boards available for vibration monitoring up to 10 kHz but unfortunately, they are a bit too pricy as the price does not stay under 100 €. Under 200 € with the accelerometer and the processing unit might be feasible and also with the acceptable specifications reaching even 18-bit resolution, 200 ksps per second sample rate per channel and 8 channels if for example the EVAL-AD7609 is used. If easier connectivity is needed and a computer is available for data acquisition then the USB DAQ/oscilloscope might be the way to go. There are a wide variety of USB data acquisition devices available with varying features and costs. There are inexpensive and slow DAQ devices and also high end devices which cost thousands of euros. Often the USB DAQ/oscilloscope gets the electrical power from the USB port making them portable devices when connected for example to a laptop.

Unfortunately, the test of the Raspberry Pi 3 being used as a sensor platform and signal processing device with the EVAL-AD7609 did not work out in the time window reserved for the thesis. There is still hope that the Raspberry Pi 3 might work in high speed data acquisition. In the right hands, with more time and maybe with some external hardware it might be possible to get it working. There are also plenty of other single-board computers and microcontrollers that possibly could be used instead of the Raspberry Pi when sensor platform or processing unit is searched.

7 SUMMARY

An overall overview of data acquisition components for vibration based condition monitoring was carried out in this thesis. The different accelerometer types available including MEMS, piezofilm and piezoelectric accelerometers were studied. The importance of amplification and filtering were simulated: the amplification has an effect to the resolution of the sampled signal and with the filtering it is possible to avoid aliasing. The ADCs resolutions effect on the gathered data was also shown with simulation. Technical discussion of data vibration monitoring components has been carried out component by component: accelerometers, amplifiers, filters, ADCs and processors were covered. Consequently the third research question "*What kind of parameters do individual measurement device components have and what kind of meaning do they have related to the gathered vibration signal data?*" has been covered quite well.

Unfortunately, no complete low-cost system for bearing vibration monitoring costing under 100 € was found and thus this thesis does not offer any straight forward solution for low-cost bearing monitoring. Many different devices were studied but most likely there are still more devices to check out which leads to a suggestion for future work: even a wider market review could be possible. Also, the testing of other low-cost devices than tested in this thesis should be done due to the contradicting results between the specification sheets and the test results showed in the accelerometer testing. One thing that has to be noted is that the cheapest is not always the easiest option. In addition, the development time, which is used to make the cheap option to work, should be valued. Also, there might not be huge interest in companies to build their own devices for condition monitoring.

Technology is developing all the time which lowers the prices and that is the case with accelerometers also. With nowadays accelerometers costing less than 10 euros it might be already possible to do condition monitoring for large bearings but in the future it might be more of a rule than exception that bearings of all sizes are measured with the low-cost accelerometers. A suggestion for further work is to test these shown and upcoming low-cost accelerometers in real world applications.

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Appendix 1. Mathcad Prime 3 model of shock signal & ADC.

SHOCK SIGNAL & ADC

Shock signal

Introduction:

These shocks are made using a damped harmonic oscillator -equation and they imitate shocks that are generated by bearing defects (Barkova 1998, Mäkelä 2008, p,97, Nohynek, Lumme 2004, p.44). Shocks' time interval can be determined and also slight time variation between shocks. In this model shocks awake natural frequency of 3 000 Hz which means roughly a raceway natural frequency of 10 cm diameter steel bearing (El-Thalji 2016, pp.46-47).

Vibration equation:

$$v_2(x_2, t_2) := m_2 \cdot \frac{d^2}{dt_2^{\,2}} x_2(t_2) + c_2 \cdot \frac{d^1}{dt_2^{\,1}} x_2(t_2) + k_2 \cdot x_2(t_2)$$

$$v_2(x_2, t_2) := 0$$

Shock parameters:

- Amplitude = A_2 [V], phase = φ_2 [rad], damping ratio = ζ_2, frequency = f_2 [Hz], angular frequency = ω_2 [rad/s], signal length = t_{2l} [s], time = t_2 [s], time between shocks = t_s [s], shock's lastin time = t_{sl}, (+/-) time variation around the wanted interval = t_v [s], number of shocks = n

$A_2 := 0.05$ $\quad \varphi_2 := 0$ $\quad \zeta_2 := 0.1$ $\quad f_2 := 3000$ $\quad \omega_2 := 2 \cdot \pi \cdot f_2$ $\quad t_{2l} := 0.05$ $\quad t_2 := 0, 0.00001 .. t_{2l}$

$t_s := 0.01$ $\quad t_v := 0.000125$ $\quad t_{sl} := 0.002$ $\quad n := \left(\text{round}\left(\frac{t_{2l}}{t_s}, [0]\right)\right)_0 + 1 = 6$

(n is the maximum amount of shocks but real amount of shocks can change because variation;+1 comes because zero time has already 1 shock

Solution to vibration equation:

$$x_2(t_2) := A_2 \cdot e^{-\zeta_2 \cdot \omega_2 \cdot (t_2 - 1)} \cdot \cos\left(\sqrt[2]{1 - \zeta_2^{\,2}} \cdot \omega_2 \cdot (t_2 - 1) + \varphi_2\right)$$

Programs:

- Generating random numbers

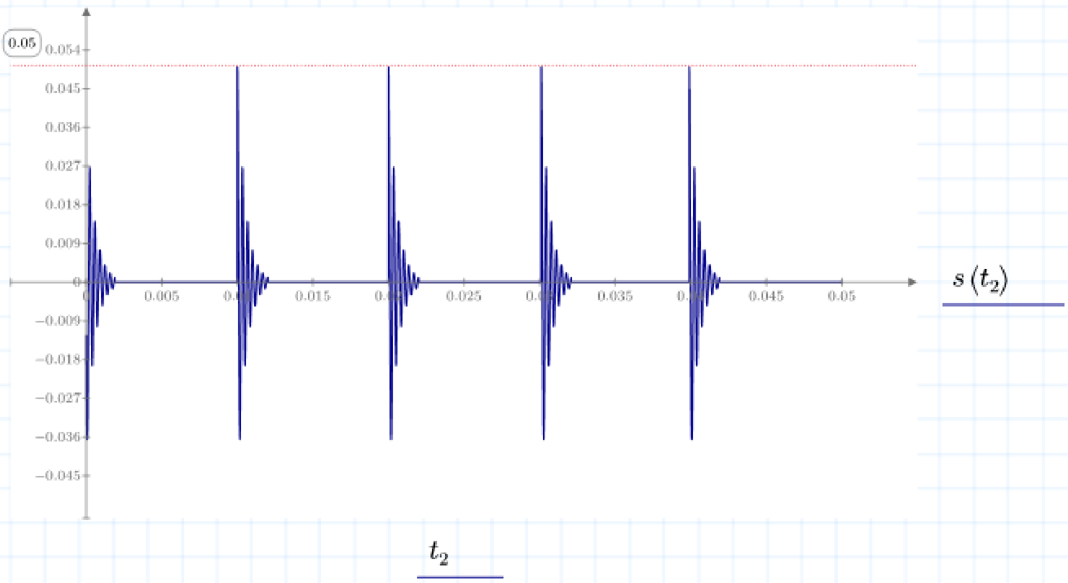
```
C := | for i ∈ 0 .. n − 1
     |   A^<i> ← round(runif(n, −t_v, t_v)_i, [4])
     | A
```

(runif(amount, min value, max value) round(number, [how many decimals]))

- Shock signal function:

$$s(t_2) := \begin{array}{l} \text{for } i \in 0..n-1 \\ \quad \text{if } i \cdot t_s + C_i \le t_2 \le i \cdot t_s + C_i + t_{sl} \\ \quad\quad s \leftarrow A_2 \cdot e^{-\zeta_2 \cdot \omega_2 \cdot \left(t_2 - \left(i \cdot t_s + C_i\right)\right)} \cdot \cos\left(\sqrt[2]{1 - {\zeta_2}^2} \cdot \omega_2 \cdot \left(t_2 - \left(i \cdot t_s + C_i\right)\right) + \varphi_2\right) \\ \quad\quad \text{break} \\ \quad \text{else} \\ \quad\quad s \leftarrow 0 \\ s \end{array}$$

- Plotted shock signal



(If shocks don't reach the same level it is because of plotting accuracy, it can be changed by changing t2)

Anologue-to-digital converters

Introduction:

Analogue-to-digital converter (ADC) is modelled following the ADC description found from handbook called: Kuntoon perustuva kunnossapito (Miettinen et al. 2009).

Transducer output signal:

- Transducer output parameters: minimum voltage = V_{tmin} [V], maximum voltage = V_{tmax} [V], voltage variation/range = V_t [V], amplitude = A [V], f = frequency [Hz], phase = φ [rad], time = t_2 [s], amplifier gain = G

$V_{tmin} := -5 \quad V_{tmax} := 5 \quad V_t := V_{tmax} - V_{tmin} = 10 \quad A := \frac{V_t}{40} \quad f := 30 \quad \varphi := 0$

$t_2 := 0, 0.0001 .. 0.05 \quad G := 10$

- Transducer output voltage signal:

$$y(t_2) := G \cdot (A \cdot \sin(2 \cdot \pi \cdot f \cdot t_2 + \varphi) + s(t_2))$$

Ad-converter spesifications:

- AD-parameters: resolution = bit, sample rate = sr [Hz], time = t_{AD}

$bit := 8 \quad sr := 20000 \quad t_{AD} := 0, \frac{1}{sr} .. 0.05$ *($t_2 \neq t_{AD}$ because plotting and sr)*

- ADC input parameters: minimum voltage = V_{imin} [V], maximum voltage = V_{imax} [V], voltage variation = V_i

$V_{imin} := -5 \quad V_{imax} := 5 \quad V_i := V_{imax} - V_{imin} = 10$

- Amount of steps/levels gained trough bits = st *(0 volt is already one step)*

$st := 2^{bit} = 256$

Ad-converter program:

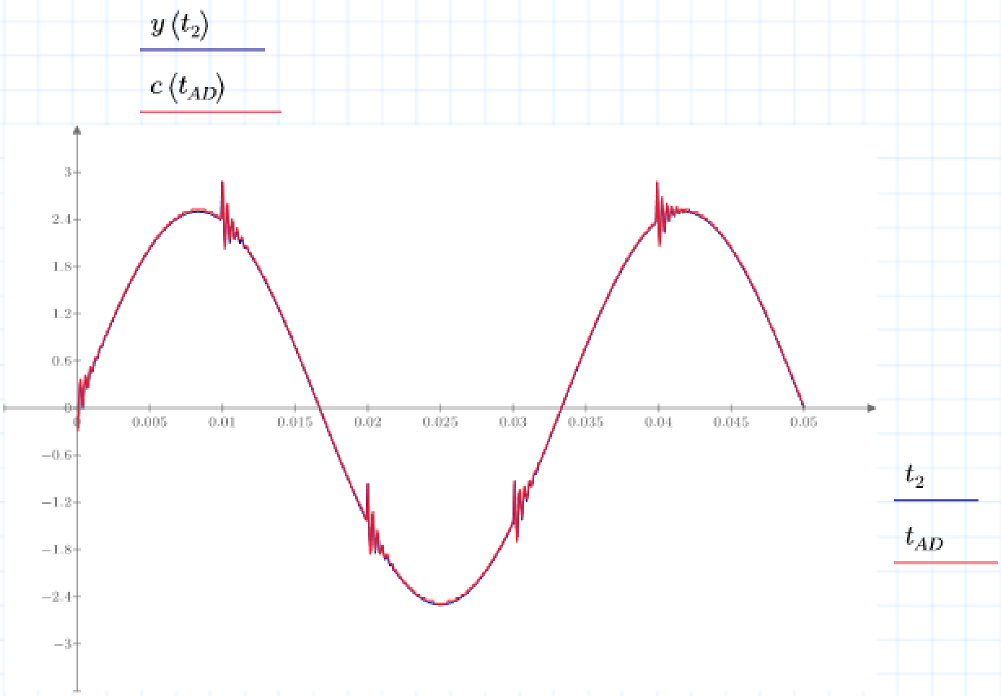
```
c(t_AD) := | st ← st
           | for n ∈ 0 .. st − 1
           |   | if y(t_AD) ≤ V_imin
           |   |   | s ← V_imin
           |   |   | break
           |   | else if V_imin + (n − 1) · V_i/(st − 1) < y(t_AD) ≤ V_imin + n · V_i/(st − 1)
           |   |   | s ← V_imin + n · V_i/(st − 1)
           |   |   | break
           |   | else if y(t_AD) ≥ V_imax
           |   |   | s ← V_imax
           |   |   | break
           | s
```

(NB

made for (-) clipping

Made for (+) clipping

if you want to see amount of steps put matrix [s ; n])



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Appendix 2. Basics of a signal path and processing modelled with Mathcad Prime 3.

BASICS OF A SIGNAL PATH & PROCESSING

Signal creation + sampling

- Let us do an example signal:

$f(t) := \sin(2\pi \cdot 1 \cdot t + 50) + \sin(2\pi \cdot 2 \cdot t + 90) + \sin(2\pi \cdot 3 \cdot t + 20)$

- Length of sample:

$t_l := 5$

- Amount of samples (has to be power of two because FFT):

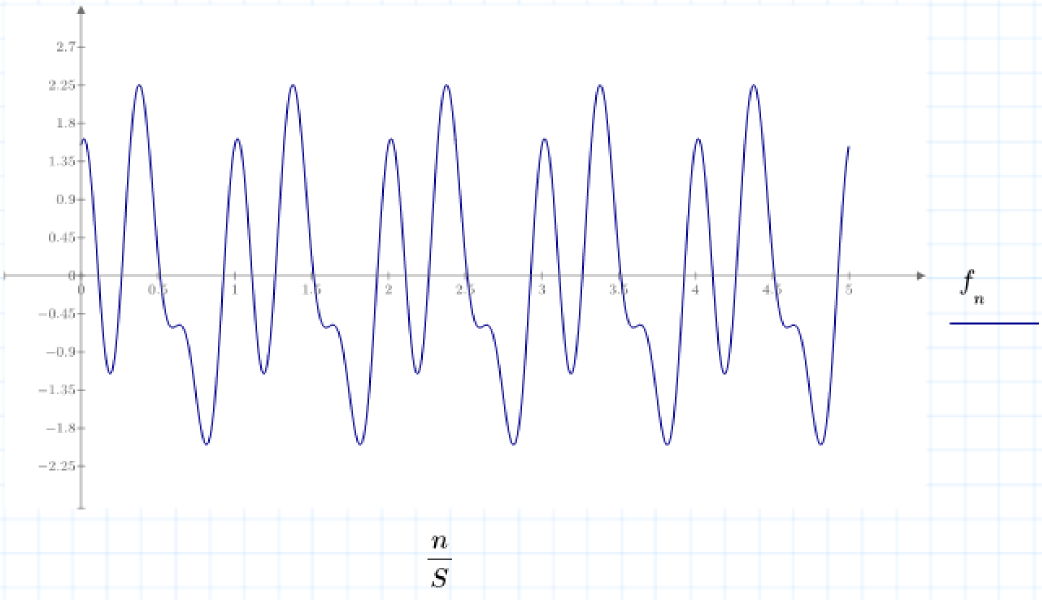
$m := 11 \qquad N := 2^m = 2.048 \cdot 10^3 \qquad n := 0..N-1$

- Sample rate

$S := \frac{N}{t_l} = 409.6$

- Sampling signal f (making vector out of it; f is also stored for later use):

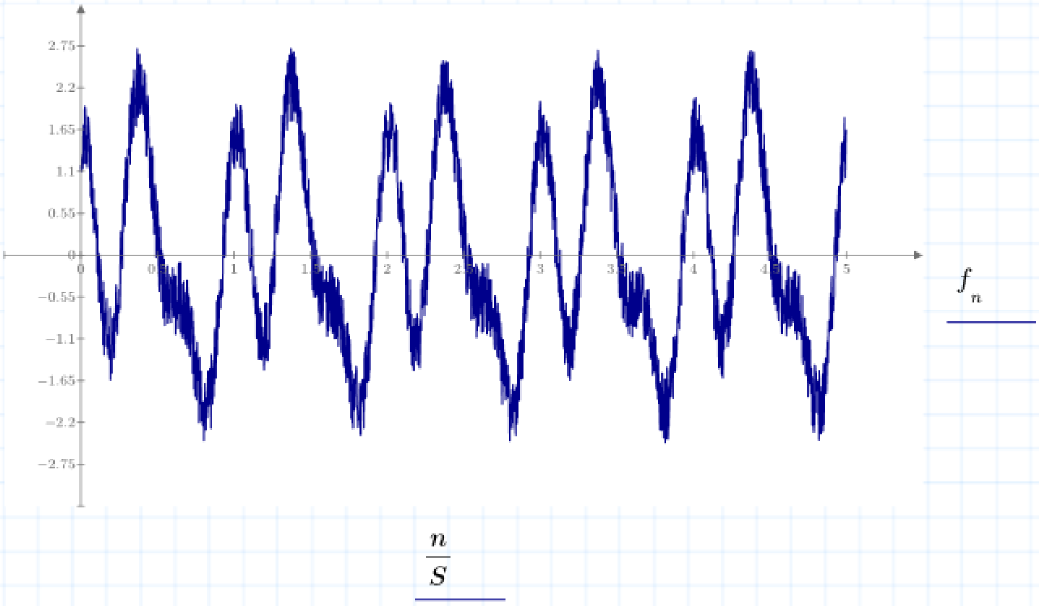
$f_n := f\left(\frac{n}{S}\right) \qquad f_y := f$



Intorducing noise to the signal

- Noise is generated by random number generator with maximum deviance of +- 0.5 (so called white noise). Electric components always introduce some amount of noise and thus noise is always presented in signal chain. Also f is stored to another variable to be used again later:

$f := f + \mathrm{runif}(N, -0.5, 0.5)$ $\quad f_x := f$

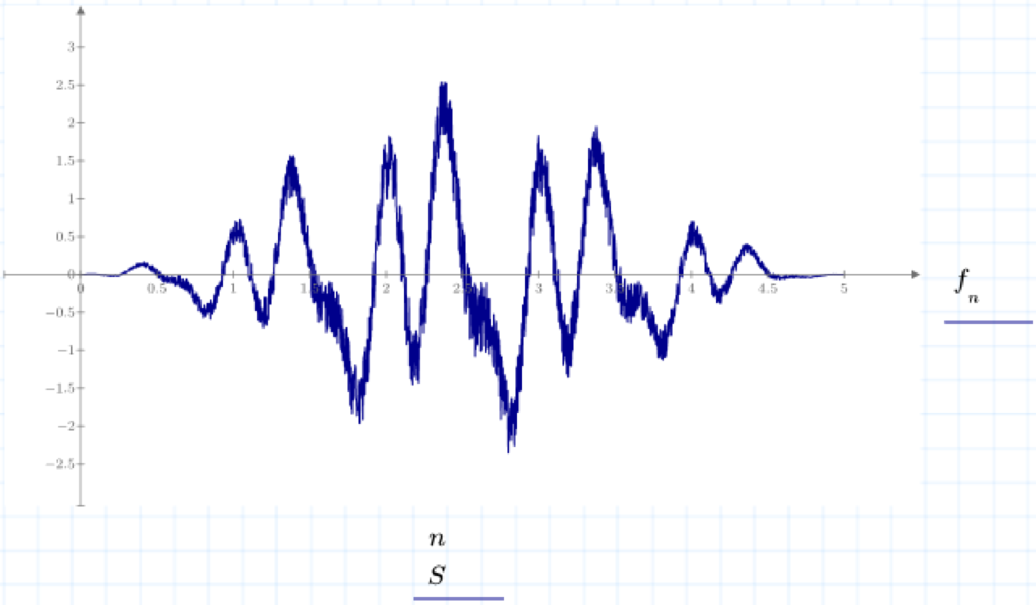


Hanning (windowing)

- Before FFT we use hanning window to the signal to improve the FFT result. More about windowing can be read for example from book *Application of B and K equipment to frequency analysis* (Randall-R-B 1977, pp.121-134).

- Built in hanning function of Mathcad and plotting the signal after hanning;

$hn := \text{hanning}(N)$ $\qquad f := \overrightarrow{f \cdot hn}$



Fast Fourier Transform (FFT) to signal

- Further below will be shown low-pass filtering and its effect to signal. Usually low-pass filtering is needed to prevent aliasing and it is done with analogue filter before sampling and FFT. FFT is done also to filtered signal and its result can be seen further below.

- Helper variables k (FFT or fft has 2^(m-1) + 1 elements) & freqk (turning k count to real frequencies). Also FFT resolution/step size is calculated:

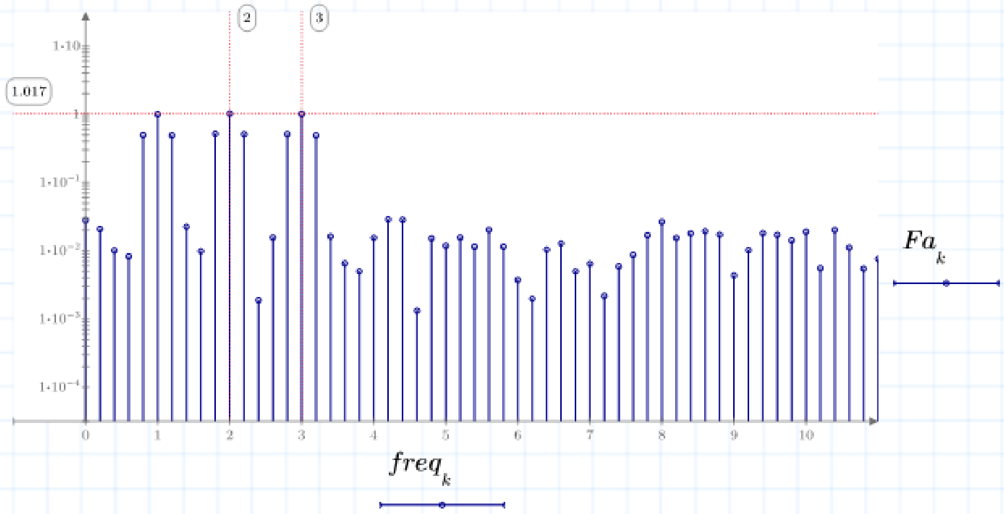
$k := 0 .. 2^{m-1}$ $\quad freq_k := \frac{k}{N} \cdot S$ $\quad freq_1 - freq_0 = 0.2$ (resolution/step (hz))

- Doing FFT & taking absolute values/moduluses/length of FFT elements and defining scaling factor s to match the FFT and orginal signal amplitudes (scaling is needed because of the nature of FFT and used hanning window before):

$s := 4$ $\quad F := \text{FFT}(f)$ $\quad Fa_k := s \cdot |F_k|$

- Finding max FFT value & defining help variables for markers

$mx := \max(Fa) = 1.017$ $\quad X := \frac{S}{N} \cdot \text{match}\left(\begin{bmatrix} mx - 0.01 \\ mx + 0.01 \end{bmatrix}, Fa, \text{"range"}\right) = \begin{bmatrix} 2 \\ 3 \end{bmatrix}$



- Low-pass filtering:

- Next will be showed different low-pass filters and effect of low-pass filter to a noisy signal.

- Filter order=OD, filter cutoff frequency=fc, proportion of cutoff frequency compared to sample frecuency=fpc, number of coefficients=N, ripple parameter= ε , scale factor to control gain at cutoff (needed with bessel) = scale:

$$OD:=8 \qquad f_c:=10 \qquad f_{pc}:=\frac{f_c}{S}=0.024 \qquad N=2.048\cdot 10^3 \qquad \varepsilon:=1$$

$$scale:=3.18$$

- Different filters; chebyshev type II = cheb, bessel=bes, butterworth=butt:

$$cheb:=\mathrm{iirlow}\left(\mathrm{cheby1}\left(OD,\varepsilon\right),f_{pc}\right)$$

$$bes:=\mathrm{iirlow}\left(\mathrm{bessel}\left(OD,scale\right),f_{pc}\right)$$

$$butt:=\mathrm{iirlow}\left(\mathrm{butter}\left(OD\right),f_{pc}\right)$$

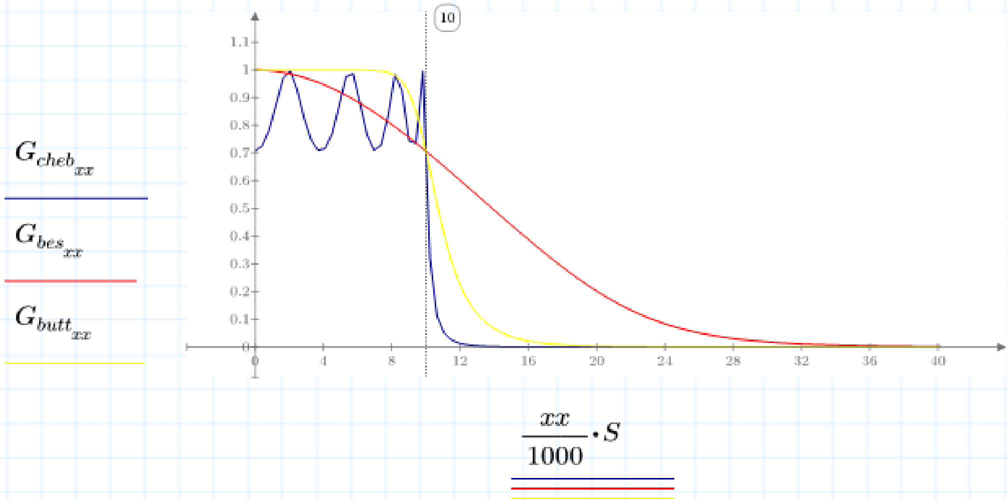
- Gain calculations, gain figures & calculated gains at cut frecuenies
(xx=helper variable):

$$xx:=0..500-1$$

$$G_{cheb_{xx}}:=\left|\mathrm{gain}\left(cheb,\frac{xx}{1000}\right)\right| \qquad \left|\mathrm{gain}\left(cheb,f_{pc}\right)\right|=0.707$$

$$G_{bes_{xx}}:=\left|\mathrm{gain}\left(bes,\frac{xx}{1000}\right)\right| \qquad \left|\mathrm{gain}\left(bes,f_{pc}\right)\right|=0.707$$

$$G_{butt_{xx}}:=\left|\mathrm{gain}\left(butt,\frac{xx}{1000}\right)\right| \qquad \left|\mathrm{gain}\left(butt,f_{pc}\right)\right|=0.707$$

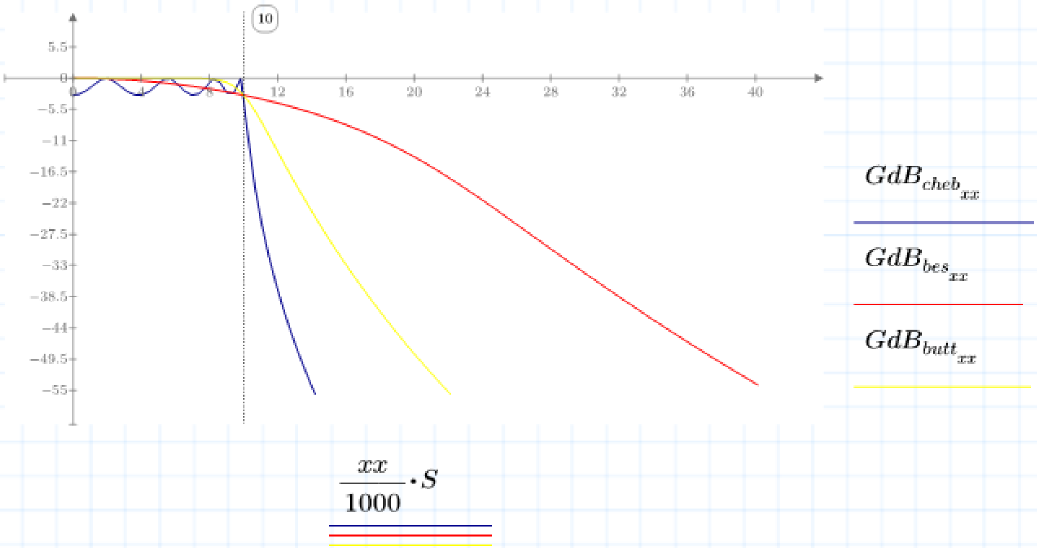


- Same gains in decibels:

$$GdB_{cheb_{xx}} := 20 \log\left(\left|\text{gain}\left(cheb, \frac{xx}{1000}\right)\right|\right) \qquad 20 \log\left(\left|\text{gain}\left(cheb, f_{pc}\right)\right|\right) = -3.01$$

$$GdB_{bes_{xx}} := 20 \log\left(\left|\text{gain}\left(bes, \frac{xx}{1000}\right)\right|\right) \qquad 20 \log\left(\left|\text{gain}\left(bes, f_{pc}\right)\right|\right) = -3.011$$

$$GdB_{butt_{xx}} := 20 \log\left(\left|\text{gain}\left(butt, \frac{xx}{1000}\right)\right|\right) \qquad 20 \log\left(\left|\text{gain}\left(butt, f_{pc}\right)\right|\right) = -3.01$$



- Let us use Butterworth for low-pass filtering the signal. First we add zeros to the end of gain vector to get as many elements as we have in FFT vector of the orginal signal:

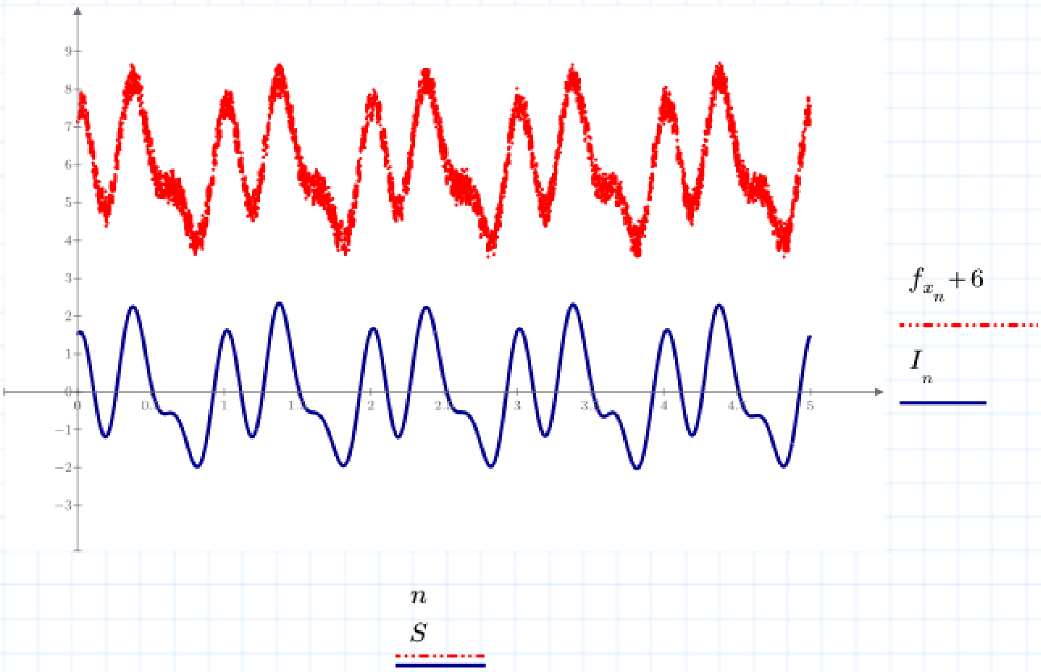
$$xxx := 0 .. \text{last}(Fa) \qquad M_{xxx} := 0 \qquad M_{xx} := G_{butt_{xx}}$$

- Then we multiple the FFT of orginal signal (without hanning) with filter gain values stored in vector M to filter the signal:

$$Fx := \text{FFT}(f_x) \qquad Faa := \overrightarrow{M \cdot Fx}$$

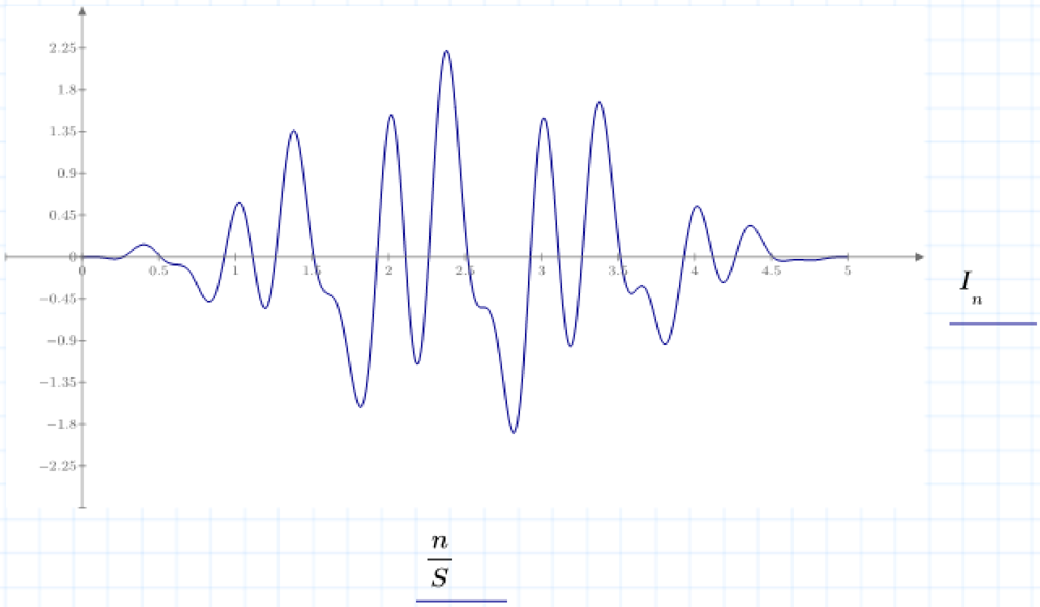
- Let as do inverse FFT and plot the filtered signal and orginal signal noisy signal:

$$I := \text{IFFT}(Faa)$$



- Let as do hanning in the same way as before:

$hn := \text{hanning}(N)$ $I := \overrightarrow{I \cdot hn}$

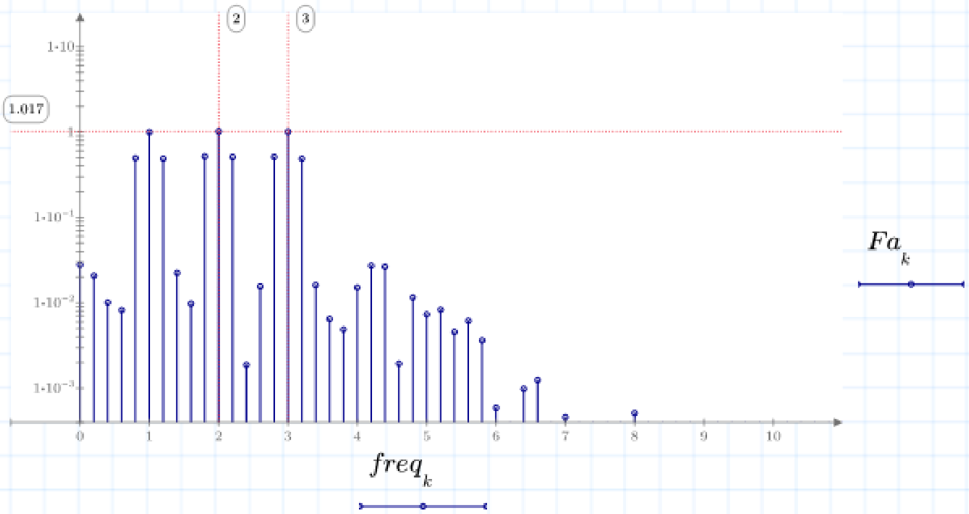


- Let as do FFT with same procedure as before:

$$s := 4 \qquad F := \mathrm{FFT}(I) \qquad Fa_k := s \cdot \left|F_k\right|$$

- Finding max FFT value & defining help variables for markers

$$mx := \max(Fa) = 1.017 \qquad X := \frac{S}{N} \cdot \mathrm{match}\left(\begin{bmatrix} mx - 0.01 \\ mx + 0.01 \end{bmatrix}, Fa, \text{“range”}\right) = \begin{bmatrix} 2 \\ 3 \end{bmatrix}$$



Accelerometers								
Manufacturer	Model	Type	Frequency BW (Hz)	Resonant Frequency (Hz)	Amplitude range (± g)	Resolution (bit)	Notes	Price (about)
Analog Devices	ADIS16227	Digital	14250	22000	1, 5, 20, 70	16	Measures in three direction, has signal processing in it (FFT [512 point], alarms, averaging [up to 256]), digital temperature and power supply measurement. Cost with board 340 €.	250,00 €
Analog Devices	ADXL001	Analogue	22000	22000	70 / 250 / 500		Electromechanical self-test, Evaluation board also available without soldering needs (77 €)	28,00 €
TE connectivity	ACH-01	Analogue	20000	35000	150		Made out of piezoelectric polymer film.	54,00 €
Kionix	KX122-1037	Digital	800	3500	2, 4, 8	16	Triaxis, self-test	2,44 €
ST	LIS2DS12	Digital	?	?	2, 4, 8, 16	16	Embedded temperature sensor, Self-test, 3-axis	3,28 €
ST	MIS2DH	Digital	?	?	2, 4, 8, 16	12	Embedded temperature sensor, Self-test, 3-axis	11,28 €
ST	LIS2DH	Digital	?	?	2, 4, 8, 16	12	Embedded temperature sensor, Self-test, 3-axis.	1,85 €

Appendix 4. ADC ICs.

IC ADC						
Manufacturer	**Model**	**ADC Type**	**Resolution (bit)**	**Channels**	**Max Sample Rate (Hz)/channel**	**Integrated Amp max Gain**
Analog Devices	AD1871YRSZ	ΣΔ	24	2 single-ended or differential	96000	
Analog Devices	AD7173-8BCPZ	ΣΔ	24	8 differential or 16 single-ended	31250	
Analog Devices	AD7175-2BRUZ	ΣΔ	24	2 differential or 4 single-ended	50000	
Analog Devices	AD7176-2	ΣΔ	24	2 fully differential or 4 pseudo differential	50000	
Analog Devices	AD7476	SAR	12	1- single-ended	1000000	
Analog Devices	AD7606BSTZ	SAR	16	8 single-ended	200000	
Analog Devices	AD7606BSTZ-4	SAR	16	4 single-ended	200000	
Analog Devices	AD7608	SAR	18	8 single-ended	200000	
Analog Devices	AD7609	SAR	18	8 differential	200000	
Analog Devices	AD7711ARZ	ΣΔ	24	1 differential and 1 single-ended	19500	128
Analog Devices	AD7760BSVZ	ΣΔ	24	1 differential	2500000	
Analog Devices	AD7765BRUZ	ΣΔ	24	1 differential	156000	
Analog Devices	AD7766BRUZ	SAR	24	1 differential	128000	
Analog Devices	AD7767BRUZ-2	SAR	24	1 differential	32000	
Analog Devices	ADAR7251	ΣΔ	16	4 differential	1800000	45 dB
Texas Instruments	ADS1251U	ΣΔ	24	1 differential	20000	
Texas Instruments	ADS1252U	ΣΔ	24	1 differential	40000	
Texas Instruments	ADS1255IDBT	ΣΔ	24	1 differential or two single-ended	30000	64
Texas Instruments	ADS1258IRTCTG4	ΣΔ	24	16 single-ended or 8 differential	23700	
Texas Instruments	ADS1271	ΣΔ	24	1 differential	105000	
Texas Instruments	ADS1274IPAPT	ΣΔ	24	4 differential	144000	
Texas Instruments	ADS1278IPAPT	ΣΔ	24	8 single-ended	144000	
Texas Instruments	ADS1294IPAG	ΣΔ	24	4 differential	32000	12
Texas Instruments	ADS131A04	ΣΔ	24	4 differential	128000	
Texas Instruments	ADS8344	SAR	16	8 single-ended or 4 differential	12500	
Texas Instruments	PCM1801U	ΣΔ	16	1 single-ended	48000	
Texas Instruments	PCM1803ADB	ΣΔ	24	1 Single-ended	96000	
Texas Instruments	PCM1808PWG4	ΣΔ	24	1 single-ended	96000	
Texas Instruments	PCM3500EG4	ΣΔ	16	1 single-ended	26000	
Texas Instruments	PCM4201	ΣΔ	24	1 differential	108000	
Texas Instruments	PCM4204PAPT	ΣΔ	24	4 differential	216000	
Texas Instruments	PCM4220PFB	ΣΔ	24	2 differential	216000	
NXP	UDA1361TS/N1	ΣΔ	24	1 single-ended	110000	

IC ADC							
Manufacturer	**Model**	**Integrated Filter Types**	**Low-pass Filter Cutoff Frequency - 3dB (Hz)**	**SNR [dB]**	**Data Interfaces**	**Price (about)**	**Data Sheet**
Analog Devices	AD1871YRSZ	digital low-pass		106	SPI®	9,40 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD1871.pdf
Analog Devices	AD7173-8BCPZ			?	SPI®; QSPI™; MICROWIRE™; DSP compatible	14,00 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7173-8.pdf
Analog Devices	AD7175-2BRUZ	Digital		?	SPI®; QSPI™; MICROWIRE™; DSP compatible	18,68 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7175-2.pdf
Analog Devices	AD7176-2	Digital filters (sinc 1, sinc 3, sinc 5)		?	SPI®; QSPI™; MICROWIRE™; DSP compatible	16,50 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7176-2.pdf
Analog Devices	AD7476			70	SPI®; QSPI™; MICROWIRE™; DSP compatible	7,50 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7476_7477_7478.pdf
Analog Devices	AD7606BSTZ	Anti-alias (2nd. Ord.), digital filter	15 000 or 22 000	95.5	SPI®; QSPI™; MICROWIRE™; DSP compatible	25,45 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7606_7606-6_7606-4.pdf
Analog Devices	AD7606BSTZ-4	Anti-alias (2nd. Ord.), digital filter	15 000 or 22 000	95.5	SPI®; QSPI™; MICROWIRE™; DSP compatible	16,95 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7606_7606-6_7606-4.pdf
Analog Devices	AD7608	Anti-alias (2nd. Ord.), digital filter	15 000 or 23 000	90.9	SPI®; QSPI™; MICROWIRE™; DSP compatible; Parallel	30,65 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7608.pdf
Analog Devices	AD7609	Low-pass Filter + Digital filter	23000 or 32000	91	SPI®; QSPI™; MICROWIRE™; DSP compatible; Parallel	33,48 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7609.pdf
Analog Devices	AD7711ARZ	Digital low-pass filter		?	Serial	30,19 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7711.pdf
Analog Devices	AD7760BSVZ	FIR low-pass		112	Parallel	45,49 €	http://www.analog.com/media/en/technical-documentation/data-sheets/ADAR7251.pdf
Analog Devices	AD7765BRUZ	FIR low-pass		107	SPI®	17,27 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7765.pdf
Analog Devices	AD7766BRUZ	FIR low-pass, Digital filter		108.5	Serial	10,80 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7766.pdf
Analog Devices	AD7767BRUZ-2	FIR low-pass		113.5	Serial	14,67 €	http://www.analog.com/media/en/technical-documentation/data-sheets/AD7767.pdf
Analog Devices	ADAR7251	Decimation filters, High-Pass filter		94	SPI®; Parallel	16,01 €	http://www.analog.com/media/en/technical-documentation/data-sheets/ADAR7251.pdf

IC ADC							
Manufacturer	**Model**	**Integrated Filter Types**	**Low-pass Filter Cutoff Frequency - 3dB (Hz)**	**SNR [dB]**	**Data Interfaces**	**Price (about)**	**Data Sheet**
Texas Instruments	ADS1251U			?	Serial	12,21 €	http://www.ti.com/lit/ds/symlink/ads1251.pdf
Texas Instruments	ADS1252U			?	Serial	13,30 €	http://www.ti.com/lit/ds/symlink/ads1251.pdf
Texas Instruments	ADS1255IDBT	digital low-pass		?	SPI®	12,90 €	http://www.ti.com/lit/ds/symlink/ads1255.pdf
Texas Instruments	ADS1258IRTCTG4	digital low-pass		?	SPI®	18,96 €	http://www.ti.com/lit/ds/symlink/ads1258.pdf
Texas Instruments	ADS1271	Digital FIR filter		106	SPI®; DSP compatible	13,00 €	http://www.ti.com/lit/ds/symlink/ads1271.pdf
Texas Instruments	ADS1274IPAPT	decimation		111	SPI®	23,54 €	http://www.ti.com/lit/ds/symlink/ads1274.pdf
Texas Instruments	ADS1278IPAPT	decimation		111	SPI®	38,90 €	http://www.ti.com/lit/ds/symlink/ads1278.pdf
Texas Instruments	ADS1294IPAG	decimation		112	SPI®	21,83 €	http://www.ti.com/lit/ds/symlink/ads1294.pdf
Texas Instruments	ADS131A04	digital decimation filters		111	SPI®	6,80 €	http://www.ti.com/lit/ds/symlink/ads131a04.pdf
Texas Instruments	ADS8344			?	SPI®	16,75 €	http://www.ti.com/lit/ds/symlink/ads8344.pdf
Texas Instruments	PCM1801U	Analogue Antialias, Decimation, High-pass	150 000	93	Left-Justified; I2S	5,62 €	http://www.ti.com/lit/ds/symlink/pcm1801.pdf
Texas Instruments	PCM1803ADB	Oversampling Decimation Filter (x64, x128), High-Pass Filter 0.84 Hz		103	Left-Justified; I2S; Right-Justified	1,80 €	http://www.ti.com/lit/ds/symlink/pcm1803a.pdf
Texas Instruments	PCM1808PWG4	Analogue anti-alias, Decimation, dig. High-pass	1 300 000	99	Left-Justified; I2S	2,71 €	http://www.ti.com/lit/ds/symlink/pcm1808.pdf
Texas Instruments	PCM3500EG4	Anti-alias, digital high pass,	60 000	88	Serial	9,41 €	http://www.ti.com/lit/ds/symlink/pcm3500.pdf
Texas Instruments	PCM4201	Digital high-pass filter		?	DSP compatible; Left-Justified	5,61 €	http://www.ti.com/lit/ds/symlink/pcm4201.pdf
Texas Instruments	PCM4204PAPT	decimation, digital high-pass		?	Left-Justified; I2S;	15,37 €	http://www.ti.com/lit/ds/symlink/pcm4204.pdf
Texas Instruments	PCM4220PFB	decimation. Dig high-pass		?	Left-Justified; I2S	13,30 €	http://www.ti.com/lit/ds/symlink/pcm4220.pdf
NXP	UDA1361TS/N1	IIR High-pass		100	I2S	1,90 €	http://www.nxp.com/documents/data_sheet/UDA1361TS.pdf

Appendix 5. Single-board computers.

SBCs									
Name	**SoC/ Processor**	**CPU Architecture**	**Cores**	**GPU**	**Clock Rate**	**Size RAM**	**PCIe**	**USB 2**	**USB 3**
armStoneA5	Freescale Vybrid VF6xx	ARM Cortex-A5 + ARM Cortex-M4	1		500 MHz	512	No	2	No
armStoneA8	Samsung S5PV210	ARM Cortex-A8	1	PowerVR SGX540	800 MHz	512 MB	No	1	No
armStoneA9	Freescale i.MX6 Quad	ARM Cortex-A9	4	Vivante GC2000 + GC335 + GC320	1.2 GHz	4 GB	1 mini	4	No
Arndale Board	Samsung Exynos 5	ARM Cortex-A15	2	Mali-T604MP4	1.7 GHz	2 GB	No	2	1
Banana Pi	Allwinner A20	ARM Cortex-A7	2	Mali-400MP2	1 GHz	1 GB	No	2	No
Banana Pi M2	Allwinner A31s	ARM-Cortex-A7	4	PowerVR SGX544MP	1 GHz	1 GB	No	2	No
Banana Pi M3	Allwinner A83T	ARM-Cortex-A7	8	PowerVR SGX544MP	1.8 GHz	2 GB	No	2	No
BeagleBoard	TI OMAP3530	ARM Cortex-A8	1	TMS320C64x @430 MHz, DSP	720 MHz	256 MB	No	1	No
BeagleBoard-xM	TI Sitara AM37x	ARM Cortex-A8	1	C64x, DSP	1 GHz	512 MB	No	4	No
BeagleBone	TI Sitara AM335x	ARM Cortex-A8	1	PowerVR SGX530	720 MHz	256 MB	No	1	No
BeagleBone Black	TI Sitara AM335x	ARM Cortex-A8	1	PowerVR SGX530	1 GHz	512 MB	No	1	No
Boardcon EM210	Samsung S5PV210	ARM Cortex-A8	1	PowerVR SGX540	800 MHz	512MB	No	2	No
Boardcon EM3288	Rockchip RK3288	ARM Cortex-A17	4	Mali-T764	1.8 GHz	2 GB	No	3	No
C.H.I.P.	Allwinner R8	ARM Cortex-A8	1	Mali 400	1 GHz	512 MB	No	2	No
CuBox-i2	Freescale i.MX6 Dual Lite	ARM Cortex-A9	2	Vivante GC880 + GC320	1 GHz	1 GB	No	2	No
CuBox-i2eX	Freescale i.MX6 Dual	ARM Cortex-A9	2	Vivante GC2000 + GC335 + GC320	1 GHz	1 GB	No	2	No
CuBox-i4Pro	Freescale i.MX6 Quad	ARM Cortex-A9	4	Vivante GC2000 + GC335 + GC320	1 GHz	2 GB	No	2	No
Dragonboard 410c	Qualcomm Snapdragon 410	ARM Cortex-A53	4	Qualcomm Adreno 306	1.2 GHz	1 GB	No	2	No
DreamPlug	Marvell Kirkwood 88F6281	ARM9E	1	N/A	1.2 GHz	512 MB	No	2	No
Graperain G4418 SBC	Samsung S5P4418	ARM Cortex-A9	4	Mali-400	1.4 GHz	1 GB	No	1	No
Graperain G6818 SBC	Samsung S5P6818	ARM Cortex-A53	8	Mali-400	1.4+ GHz	2 GB	No	1	No
HiKey	HiSilicon Kirin 620	ARM Cortex-A53	8	Mali-450 MP4	1.2 GHz	1 GB	No	2	No
HummingBoard-i2eX	Freescale i.MX6 Dual	ARM Cortex-A9	2	Vivante GC2000 + GC355 + GC320	1 GHz	1 GB	1 mini	2	No
Intel Galileo Gen 2	Intel Quark SoC X1000	x86 Quark	1	N/A	400 MHz	256 MB	1 mini	1	No
Inventami Entry	Freescale i.MX6 Dual	ARM Cortex-A9	2	Vivante GC2000 + GC335 + GC320	1 GHz	1 GB	1 mini	2 + 1 header	No

SBCs									
Name	SoC/ Processor	CPU Architecture	Cores	GPU	Clock Rate	Size RAM	PCIe	USB 2	USB 3
Inventami Full	Freescale i.MX6 Quad	ARM Cortex-A9	4	Vivante GC2000 + GC335 + GC320	1 GHz	1 GB	1 mini	2 + 1 header	No
MarsBoard RK3066	Rockchip RK3066	ARM Cortex-A9	2	Mali-400MP4	1.6 GHz	1-2 GB	No	4	No
MinnowBoard	Intel Atom E640	x86 Bonnell	1	Intel GMA600	1 GHz	1 GB	No	2	No
MIPS Creator CI20	Ingenic JZ4780	Ingenic XBurst (mips32 rev.2)	2	PowerVR SGX540	1.2 GHz	1 GB	No	2	No
MiraBox	Marvell Armada 370	ARMv7	1	N/A	1.2 GHz	1 GB	1 mini	1	3
MYIR MYD-AM335X	TI Sitara AM335x	ARM Cortex-A8	1	PowerVR SGX530 (optional)	800-1000 MHz	512 MB	No	4	No
NanoPC-T1	Samsung Exynos 4 (4412)	ARM Cortex-A9	4	Mali-400MP4	?	1 GB	No	2	No
NanoPi 2	Samsung S5P4418	ARM Cortex-A9	4	?	1.4 GHz	1 GB	No	1	No
NanoPi NEO	Allwinner H3	ARM Cortex-A7	4	ARM Mali-400 MP2	1.2 GHz	256 or 512 MB	No	1 + 2 on pads	No
Nitrogen6x	Freescale i.MX6 Quad	ARM Cortex-A9	4	Vivante GC2000 + GC355 + GC320	1 GHz	1 GB (2 GB option)	1 mini opt.[94]	2	No
Nvidia Jetson TK1	Nvidia Tegra K1	ARM Cortex-A15	5	Nvidia GK20A (192 CUDA cores) @950 MHz	2.3 GHz	2 GB	1 mini	1	1
ODROID-C2	Amlogic S905	ARM Cortex-A53	4	Mali-450MP3 +2VS @700 MHz	1.5 GHz	2 GB	No	4	No
ODROID-U3	Samsung Exynos 4 Quad	ARM Cortex-A9	4	Mali-400MP4 @440 MHz	1.7 GHz	2 GB	No	3	No
ODROID-W	Broadcom BCM2835	ARM11	1	Broadcom VideoCore IV	700 MHz	512 MB	No	Pads	No
ODROID-XU3	Samsung Exynos 5 Octa (5422)	ARM Cortex-A15 + ARM Cortex-A7	8	ARM Mali-T628 @695 MHz	2 GHz	2 GB	No	4	1
ODROID-XU3 Lite	Samsung Exynos 5 Octa (5422)	ARM Cortex-A15 + ARM Cortex-A7	8	ARM Mali-T628 @695 MHz	1.8 GHz	2 GB	No	4	1
ODROID-XU4	Samsung Exynos 5 Octa (5422)	ARM Cortex-A15 + ARM Cortex-A7	8	ARM Mali-T628 @695 MHz	2 GHz	2 GB	No	1	2
OLinuXino A10 LIME	Allwinner A10	ARM Cortex-A8	1	Mali-400	1 GHz	512 MB	No	2	No
OLinuXino A13 MICRO	Allwinner A13	ARM Cortex-A8	1	Mali-400	1 GHz	256 MB	No	1	No
OLinuXino A13 WIFI	Allwinner A13	ARM Cortex-A8	1	Mali-400	1 GHz	512 MB	No	3	No
OLinuXino A20 LIME	Allwinner A20	ARM Cortex-A7	2	Mali-400MP2	1 GHz	512 MB	No	2	No
OLinuXino A20 LIME2	Allwinner A20	ARM Cortex-A7	2	Mali-400MP2	1 GHz	1 GiB	No	2	No
OLinuXino A20 MICRO	Allwinner A20	ARM Cortex-A7	2	Mali-400MP2	1 GHz	1 GB	No	2	No
Orange Pi Lite	Allwinner H3	ARM Cortex-A7	4	ARM Mali-400 MP2 @600 MHz	1.2 GHz	512 MB	No	2	No
Orange Pi One	Allwinner H3	ARM Cortex-A7	4	ARM Mali-400 MP2 @600 MHz	1.2 GHz	512 MB	No	1	No

SBCs									
Name	SoC/ Processor	CPU Architecture	Cores	GPU	Clock Rate	Size RAM	PCIe	USB 2	USB 3
Orange Pi PC	Allwinner H3	ARM Cortex-A7	4	ARM Mali-400 MP2 @600 MHz	1.536 GHz	1 GB	No	3	No
Orange Pi PC Plus	Allwinner H3	ARM Cortex-A7	4	ARM Mali-400 MP2 @600 MHz	1.536 GHz	1 GB	No	3	No
Orange Pi Plus	Allwinner H3	ARM Cortex-A7	4	ARM Mali-400 MP2 @600 MHz	1.536 GHz	1 GB	No	4	No
Orange Pi Plus 2	Allwinner H3	ARM Cortex-A7	4	ARM Mali-400 MP2 @600 MHz	1.536 GHz	2 GB	No	4	No
Orange Pi Plus 2E	Allwinner H3	ARM Cortex-A7	4	ARM Mali-400 MP2 @600 MHz	1.536 GHz	2 GB	No	3	No
PandaBoard ES	TI OMAP4460	ARM Cortex-A9	2	PowerVR SGX540	1.2 GHz	1 GB	No	2	No
pcDuino Lite	Allwinner A10	ARM Cortex-A8	1	Mali-400	1 GHz	512 MB	No	2	No
pcDuino2	Allwinner A10	ARM Cortex-A8	1	Mali-400	1 GHz	1 GB	No	1	No
pcDuino3	Allwinner A20	ARM Cortex-A7	2	Mali-400MP2	1 GHz	1 GB	No	1	No
pcDuino3Nano	Allwinner A20	ARM Cortex-A7	2	Mali-400MP2	1 GHz	1 GB	No	2	No
phyBOARD-Mira	Freescale i.MX6	ARM Cortex-A9	4	N/A	1 GHz	1 GB	1 mini	2	No
phyBOARD-Wega	TI Sitara AM335x	ARM Cortex-A8	1	PowerVR SGX530	800 MHz	512 MB	No	2	No
PINE A64	Allwinner A64	ARM Cortex-A53	4	Mali-400MP2	1.2 GHz	2000MB	No	2	No
Radxa Rock Lite	Rockchip RK3188	ARM Cortex-A9	4	Mali-400MP4	1.6 GHz	1 GB	No	2	No
Radxa Rock Pro	Rockchip RK3188	ARM Cortex-A9	4	Mali-400MP4	1.6 GHz	2 GB	No	2	No
Raspberry Pi 2 Model B	Broadcom BCM2836	ARM Cortex-A7	4	Broadcom VideoCore IV	900 MHz	1 GB	No	4	No
Raspberry Pi 3 Model B	Broadcom BCM2837	ARM Cortex-A53	4	Broadcom VideoCore IV	1.2 GHz	1 GB	No	4	No
Raspberry Pi Zero	Broadcom BCM2835	ARM11	1	Broadcom VideoCore IV	1 GHz	512 MB	No	No	No
RIoTboard	Freescale i.MX6 Solo	ARM Cortex-A9	1	Vivante GC880 + GC320	1 GHz	1 GB	No	4	No
RouterBOARD RB450G	Qualcomm Atheros AR7161	MIPS 24K	1	N/A	680 MHz	256 MB	No	No	No
SBC8600B	TI Sitara AM3359	ARM Cortex-A8	1	PowerVR SGX530	720 MHz	512 MB	No	2	No
Supermicro E100-8Q	Intel® Quark™ SoC X1021	x86 Quark	1	N/A	400 MHz	512 MB	2 mini	2	No
TBS 2910 Matrix	Freescale i.MX6 Quad	ARM Cortex-A9	4	Vivante GC2000 + GC335 + GC320	1 GHz	2 GB	1 mini	3	No
UDOO Dual	Freescale i.MX6 Dual Lite +Atmel SAM3X8E	ARM Cortex-A9 ARM Cortex-M3	3	Vivante GC880 + GC320	1 GHz	1 GB	No	2+1	No
UDOO Dual Basic	Freescale i.MX6 Dual Lite + Atmel SAM3X8E	ARM Cortex-A9 ARM Cortex-M3	3	Vivante GC880 + GC320	1 GHz	1 GB	No	2+1	No
UDOO Quad	Freescale i.MX6 Quad + Atmel SAM3X8E	ARM Cortex-A9 +ARM Cortex-M3	5	Vivante GC2000 + GC355 + GC320	1 GHz	1 GB	No	2+1	No

SBCs									
Name	SoC/ Processor	CPU Architecture	Cores	GPU	Clock Rate	Size RAM	PCIe	USB 2	USB 3
UP	Intel x5-Z8350	x86-64	4	Intel® HD 400 Graphics, 12 EU GEN 8, up to 500 MHz	1.44 GHz	4 GB	No	4+2	1
Utilite Pro	Freescale i.MX6 Quad	ARM Cortex-A9	4	Vivante GC2000 + GC355 + GC320	1.2 GHz	2 GB	No	4	No
Utilite Standard	Freescale i.MX6 Dual	ARM Cortex-A9	2	Vivante GC2000 + GC355 + GC320	1 GHz	2 GB	No	4	No
Utilite Value	Freescale i.MX6 Solo	ARM Cortex-A9	1	Vivante GC880 + GC320	1 GHz	512 MB	No	4	No
Wandboard Dual	Freescale i.MX6 Dual	ARM Cortex-A9	2	Vivante GC880 + GC320	1 GHz	1 GB	No	1	No
Wandboard Quad	Freescale i.MX6 Quad	ARM Cortex-A9	4	Vivante GC2000 + GC355 + GC320	1 GHz	2 GB	No	1	No
Wandboard Solo	Freescale i.MX6 Solo	ARM Cortex-A9	1	Vivante GC880 + GC320	1 GHz	512 MB	No	1	No

SBCs													
Name	Onboard storage	Flash slots	SATA	Ethernet	Wifi	Blue - tooth	I2C	SPI	GPIO	Analog	Other interfaces	Web page	Price
armStoneA5	1GB Flash	µSD Slot	No	10/ 100	No	No	Yes	Yes	?	?	CAN, UART, Audio, Digital I/O, Touch Panel	https://www.fs-net.de/en/products/armstone/armstonea5/	179,00 €
armStoneA8	1GB Flash	No	No	10/ 100	No	No	Yes	Yes	?	?	CAN, Audio, Digital I/O, Touch Panel	https://www.fs-net.de/en/products/armstone/armstonea8/	?
armStoneA9	1GB Flash	SD	Yes	GbE	No	No	Yes	Yes	?	?	CAN, UART, Audio, Digital I/O, Touch Panel	https://www.fs-net.de/en/products/armstone/armstonea9/	299,00 €
Arndale Board	4GB eMMC	microSD	SATA 3.0	100	a/b/g/n (AR6003)	4.0 BR/EDR + BLE	?	?	OPt.	?	JTAG, RS232, MIPI DSI, Audio	http://www.arndaleboard.org/wiki/index.php/Main_Page	?
Banana Pi	No	SD	SATA 2.0	GbE	No	No	Yes	Yes	80	12-Bit-ADC	CSI, UART	http://www.bananapi.org/p/product.html	35 €
Banana Pi M2	No	microSD	No	GbE	a/b/g/n	No	Yes	Yes	40	12-Bit-ADC	CSI, UART	http://www.banana-pi.org/m2.html	60 €
Banana Pi M3	No	microSD	SATA 2.0	GbE	a/b/g/n	4.0	Yes	Yes	40	12-Bit-ADC	CSI, UART	http://www.banana-pi.org/m3.html	109,99 €
BeagleBoard	512MB Flash	SD	No	No	No	No	?	?	Yes	No		https://beagleboard.org/beagleboard	118,38 €
BeagleBoard-xM	?	SD	No	10/ 100	No	No	?	?	?	?	?	https://beagleboard.org/beagleboard-xm	141,11 €
BeagleBone	4GB Flash	microSD	No	10/ 100	No	No	Yes	Yes	66	12-Bit-ADC	CAN, UART	https://beagleboard.org/bone-original	84 €

SBCs

Name	Onboard storage	Flash slots	SATA	Ethernet	Wifi	Blue - tooth	I2C	SPI	GPIO	Analog	Other interfaces	Web page	Price
BeagleBone Black	4GB eMMC	microSD	No	10/100	No	No	Yes	Yes	66	12-bit ADC	CAN, UART	https://beagleboard.org/black	43 €
Boardcon EM210	4GB eMMC	microSD	No	10/100	b/g	No	Yes	Yes	Yes	ADCDAC PWM	UART, Audio, Digital I/O, Touch Panel, JTAG	http://www.boardcon.com/EM210/	?
Boardcon EM3288	8GB eMMC	microSD	Yes	GbE	b/g/n	4.0	Yes	Yes	Yes	ADC	UART, MIPI, I2S, Audio, Digital I/O, Touch Panel	http://www.boardcon.com/EM3288_SBC/	?
C.H.I.P.	4 GB	No	No	No	a/b/g/n	4.0	Yes	?	Yes	?	UART, PWM	https://getchip.com/pages/chip	8,5€
CuBox-i2	No	microSD	No	10/100	n opt.	Opt.	No	No	?	No	S/PDIF, CIR rx	https://www.solid-run.com/freescale-imx6-family/cubox-i/cubox-i-specifications/	103,50 €
CuBox-i2eX	No	microSD	eSATA 2.0	GbE	n opt.	Opt.	No	No	?	No	S/PDIF, CIR rx/tx	https://www.solid-run.com/freescale-imx6-family/cubox-i/cubox-i-specifications/	122,33 €
CuBox-i4Pro	No	microSD	E SATA 2.0	GbE	b/g/n (BCM 4329)	2.1 + EDR	No	No	?	No	S/PDIF, CIR rx/tx	https://www.solid-run.com/freescale-imx6-family/cubox-i/cubox-i-specifications/	131,74 €
Dragonboard 410c	8GB eMMC	microSD	No	No	a/b/g/n (2.4 GHz)	4.1	Yes	Yes	12	No	UART, I2S, 2-lane + 4-lane CSI, USB (expansion), GPS (onboard antenna)	https://developer.qualcomm.com/hardware/dragonboard-410c	71 €
DreamPlug	4GB microSD	microSD	eSATA 2.0	2x GbE	b/g/n (88W 8787)	3.0 + HS	No	No	7	No	JTAG, UART	https://www.globalscaletechnologies.com/p-54-dreamplug-devkit.aspx	149,63 €
Graperain G4418 SBC	8GB eMMC	2x TF	No	GbE	b/g/n (RTL8723BU) (2.4 GHz)	4.0 + LE (RTL8723BU)	Yes	Yes	Yes	PWM	UART	https://www.graperain.com/ARM-Embedded-S5P4418-Single-Board-Computer/	?
Graperain G6818 SBC	8GB eMMC	2x TF	No	GbE	b/g/n (RTL8723BU) (2.4 GHz)	4.0 + LE (RTL8723BU)	Yes	Yes	Yes	PWM	UART	https://www.graperain.com/ARM-Embedded-S5P6818-Single-Board-Computer/	?
HiKey	4GB eMMC	microSD	No	No	a/b/g/n	4.0	Yes	Yes	12	No	UART, USB (expansion)	http://www.96boards.org/product/hikey/	71 €
HummingBoard-i2eX	No	microSD (UHS)	mSATA	GbE	No	No	Yes	Yes	8	No	CIR rx, CSI-2, FlexCAN, UART	https://www.solid-run.com/product/hummingboard-carrier-pro/#configuration	79 €
Intel Galileo Gen 2	8MB Flash + 8 KB EEPROM	SD	No	10/100	No	No	Yes	Yes	20	12-bit ADC, 6 PWM	Arduino 1.0 headers, JTAG, 6x UART	http://www.intel.com/content/www/us/en/embedded/products/galileo/galileo-overview.html	64 €
Inventami Entry	4GB eMMC	microSD	mSATA	GbE	No	No	Yes	Yes	46	No	FPGA ETH, FPGA GPIO, CAN, UART, RS-232, LVDS+Touch Panel	http://www.inventami.com/	?
Inventami Full	16GB eMMC	microSD	mSATA	GbE	No	No	Yes	Yes	50	No	FPGA ETH, FPGA GPIO, FPGA SerDes, CAN, UART, RS-232, LVDS+Touch Panel	http://www.inventami.com/	?

SBCs

Name	Onboard storage	Flash slots	SATA	Ethernet	Wifi	Blue - tooth	I2C	SPI	GPIO	Analog	Other interfaces	Web page	Price
MarsBoard RK3066	4GB Flash	microSD	No	10/ 100	b/g/n (RTL8 188)	No	No	No	?	No	CIF, UART	http://www.marsboard.com/marsboard_rk3066_feature.html	55 €
MinnowBoard	No	microSD	Yes	GbE	No	No	No	No	14	No	JTAG	http://wiki.minnowboard.org/MinnowBoard_Wiki_Home	?
MIPS Creator CI20	8GB Flash	SD	No	10/ 100	b/g/n (BCM 4330)	4.0 (BCM4330)	Yes	Yes	25	ADC	UART, JTAG	http://creatordev.io/ci20	72 €
MiraBox	1GB Flash	microSD	No	2x GbE	b/g/n (88W 8787)	3.0	No	No	40	No	JTAG	https://www.globalscaletechnologies.com/p-58-mirabox-development-kit.aspx	140,22 €
MYIR MYD-AM335X	512MB Flash	SD	No	2x GbE	No	No	Yes	Yes	No	ADCPWM	CAN, 2x RS-232, RS-485	http://www.myirtech.com/list.asp?id=466	131,64 €
NanoPC-T1	8GB eMMC	SD	No	10/100	No	No	No	No	?	No	CIF, UART	http://www.nanopc.org/NanoPC-T1_Feature.html	?
NanoPi 2	No	2x microSD	No	No	b/g/n (AP62 12)	4.0 + LE (AP6212)	Yes	Yes	Yes	PWM	UART	http://nanopi.io/nanopi2.html	30 €
NanoPi NEO	No	microSD	No	10/100	No	No	Yes	Yes	Yes	PWM	UART	http://nanopi.io/nanopi-neo.html	?
Nitrogen6x	No	2x microSD	SATA	GbE	b/g/n (WL1 271)	Opt.	Yes	No	?	No	CAN-2, JTAG, extra USB header	https://boundarydevices.com/product/nitrogen6x-board-imx6-arm-cortex-a9-sbc/	211,74 €
Nvidia Jetson TK1	16GB eMMC	SD	Yes	GbE	No	No	Yes	Yes	7	No	CSI-2, HSIC, JTAG, RS-232, UART	http://www.nvidia.com/object/jetson-tk1-embedded-dev-kit.html	181,83 €
ODROID-C2	eMMC module opt.	microSD	No	10 / 100 / 1000	No	No	Yes	Yes	32	2x 12-bit ADC PWM	UART, IR, Real-time clock battery connector	http://www.hardkernel.com/main/products/prdt_info.php?g_code=G145457216438	40 €
ODROID-U3	eMMC module opt.	microSD	No	10/ 100	No	No	Yes	No	Yes	No	UART, Real-time clock battery connector	http://www.hardkernel.com/main/products/prdt_info.php?g_code=g138745696275	65 €
ODROID-W	eMMC module opt.	microSD	No	No	No	No	Yes	Yes	32	2x 12-bit ADC PWM	Real-time clock battery connector, LiPo battery connector	http://www.hardkernel.com/main/products/prdt_info.php?g_code=g140610189490	28 €
ODROID-XU3	eMMC module opt.	microSD	No	10/ 100 (LAN9514)	No	No	Yes	Yes	Yes	ADC	UART, Real-time clock battery connector	http://www.hardkernel.com/main/products/prdt_info.php?g_code=g140448267127	169,51 €
ODROID-XU3 Lite	eMMC module opt.	microSD	No	10/ 100 (LAN9514)	No	No	Yes	Yes	Yes	ADC	UART, Real-time clock battery connector	http://www.hardkernel.com/main/products/prdt_info.php?g_code=G141351880955	94 €
ODROID-XU4	eMMC module opt.	microSD	No	10 / 100 / 1000 (LAN9514)	No	No	Yes	Yes	Yes	ADC	UART, Real-time clock battery connector	http://www.hardkernel.com/main/products/prdt_info.php?g_code=G143452239825	70 €
OLinuXino A10 LIME	No	microSD	Yes	100	No	No	Yes	Yes	134	PWM	6x UART	https://www.olimex.com/Products/OLinuXino/A10/A10-OLinuXino-LIME/open-source-hardware	30 €

SBCs													
Name	**Onboard storage**	**Flash slots**	**SATA**	**Ethernet**	**Wifi**	**Blue - tooth**	**I2C**	**SPI**	**GPIO**	**Analog**	**Other interfaces**	**Web page**	**Price**
OLinuXino A13 MICRO	No	microSD	No	No	No	No	?	?	142	No	?	https://www.olimex.com/Products/OLinuXino/A13/A13-OLinuXino-MICRO/open-source-hardware	35 €
OLinuXino A13 WIFI	4GB Flash	microSD	No	No	b/g/n (RTL8188)	No	?	?	142	No	?	https://www.olimex.com/Products/OLinuXino/A13/A13-OLinuXino-WIFI/open-source-hardware	55 €
OLinuXino A20 LIME	4GB Flash opt.	microSD	Yes	100	No	No	?	?	160	No	UART, UEXT	https://www.olimex.com/Products/OLinuXino/A20/A20-OLinuXino-LIME/open-source-hardware	33 €
OLinuXino A20 LIME2	4GB Flash opt.	microSD	Yes	1000	No	No	?	?	160	No	UART, UEXT	https://www.olimex.com/Products/OLinuXino/A20/A20-OLinuXIno-LIME2/open-source-hardware	45 €
OLinuXino A20 MICRO	4GB Flash opt.	microSD, SD	Yes	100	No	No	?	?	160	No	UART, UEXT	https://www.olimex.com/Products/OLinuXino/A20/A20-OLinuXino-MICRO/open-source-hardware	55 €
Orange Pi Lite	No	microSD	No	No	b/g/n (RTL8189FTV)	No	Yes	Yes	Yes	?	CSI, IR, UART	http://www.orangepi.org/orangepilite/	11 €
Orange Pi One	No	microSD	No	10/ 100	No	No	Yes	Yes	Yes	?	CSI, UART	http://www.orangepi.org/orangepione/	9,5 €
Orange Pi PC	No	microSD	No	10/ 100	No	No	Yes	Yes	Yes	?	CSI, IR, UART	http://www.orangepi.org/orangepipc/	14 €
Orange Pi PC Plus	8GB Flash	microSD	No	10/ 100	b/g/n (RTL8189FTV)	No	Yes	Yes	Yes	?	CSI, IR, UART	http://www.orangepi.org/orangepipcplus/	19 €
Orange Pi Plus	8GB Flash	microSD	SATA 2.0	GbE	b/g/n (RTL8189ETV)	No	Yes	Yes	Yes	?	CSI, IR, UART	http://www.orangepi.org/	19 €
Orange Pi Plus 2	16GB eMMC	microSD	SATA 2.0	GbE	b/g/n (RTL8189ETV)	No	Yes	Yes	Yes	?	CSI, IR, UART	http://www.orangepi.org/orangepiplus2/	46 €
Orange Pi Plus 2E	16GB eMMC	microSD	No	GbE	b/g/n (RTL8189FTV)	No	Yes	Yes	Yes	?	CSI, IR, UART	http://www.orangepi.org/orangepiplus2e/	33 €
PandaBoard ES	No	SDHC	No	10/ 100	b/g/n (WL1271)	2.1 + EDR	Yes	No	Yes	No	JTAG, RS-232, UART	http://pandaboard.org/content/pandaboard-es	190,92 €
pcDuino Lite	No	microSD	No	10/ 100	No	No	Yes	Yes	22	ADC PWM	Arduino 1.0 headers	http://www.linksprite.com/linksprite-pcduino-lite/	28 €
pcDuino2	4GB Flash	microSD	No	10/ 100	b/g/n (RTL8188)	No	Yes	Yes	22	ADC PWM	Arduino 1.0 headers	http://www.linksprite.com/linksprite-pcduino2/	46 €
pcDuino3	4GB Flash	microSD	Yes	10/ 100	b/g/n (RTL8188)	No	Yes	Yes	22	ADC PWM	Arduino 1.0 headers	http://www.linksprite.com/linksprite-pcduino3/	47 €

SBCs													
Name	**Onboard storage**	**Flash slots**	**SATA**	**Ethernet**	**Wifi**	**Blue - tooth**	**I2C**	**SPI**	**GPIO**	**Analog**	**Other interfaces**	**Web page**	**Price**
pcDuino3Nano	4GB Flash	microSD	Yes	GbE	No	No	Yes	Yes	22	ADC PWM	Arduino 1.0 headers	http://www.linksprite.com/linksprite-pcduino3-nano/	38 €
phyBOARD-Mira	1GB Flash, 4 kB EEPROM	microSD	Yes	GbE	Yes	No	Yes	Yes	Yes	PWM	CAN, RS232, Digital I/O, Audio, Camera, UART, JTAG	http://www.phytec.de/produkt/single-board-computer/phyboard-mira/	166,00 €
phyBOARD-Wega	512MB Flash,4 kB EEPROM	microSD	No	10/ 100	No	No	Yes	Yes	Yes	ADC PWM	CAN, RS232, Audio, UART, JTAG, MMC	http://www.phytec.eu/product/single-board-computer/phyboard-wega/	130,00 €
PINE A64	No	microSD	No	10/ 100	Opt.	Opt.	Yes	Yes	46	No		https://www.pine64.org/	28 €
Radxa Rock Lite	4GB Flash	microSD (SDXC)	No	10/ 100	b/g/n (RTL8188)	No	Yes	Yes	80	ADC PWM	UART	http://wiki.radxa.com/Rock/specification	76 €
Radxa Rock Pro	8GB Flash	microSD (SDXC)	No	10/ 100	b/g/n (RTL8723)	4.0 (Works on android but not on linux)	Yes	Yes	80	ADC PWM	UART	http://wiki.radxa.com/Rock/specification	?
Raspberry Pi 2 Model B	No	microSD	No	10/ 100	No	No	Yes	Yes	17	No	UART, CSI, DSI	https://www.raspberrypi.org/products/raspberry-pi-2-model-b/	34 €
Raspberry Pi 3 Model B	No	microSD	No	10/ 100	b/g/n	4.1	Yes	Yes	17	No	UART, CSI, DSI	https://www.raspberrypi.org/products/raspberry-pi-3-model-b/	35 €
Raspberry Pi Zero	No	microSD	No	No	No	No	Yes	Yes	17	No	UART, DSI (only newer versions)	https://www.raspberrypi.org/products/pi-zero/	4,7 €
RIoTboard	4GB Flash	microSD and SD	No	GbE	No	No	Yes	Yes	10	PWM	CSI, UART	http://riotboard.org/	73 €
RouterBOARD RB450G	512MB Flash	microSD	No	5x GbE (AR8316)	No	No	No	No	No	No	JTAG, RS-232	https://routerboard.com/RB450G	94 €
SBC8600B	512MB Flash	microSD	No	2x GbE	No	No	No	Yes	Yes	12-bit ADC	CAN-2, RS-232, RS-485	http://www.ti.com/devnet/docs/catalog/endequipmentproductfolder.tsp?actionPerformed=productFolder&productId=21120	136,46 €
Supermicro E100-8Q	No	microSDHC	No	2 x 10/ 100	No	No	No	No	No	No	RS232 (DB9), RS285 (screw terminal), ZigBee module socket	http://www.supermicro.com/products/system/Compact/IoT/SYS-E100-8Q.cfm	?
TBS 2910 Matrix	16GB eMMC	microSD and SD	SATA 2.0	GbE	b/g/n	No	Yes	No	No	Yes	UART	http://www.tbsdtv.com/products/tbs2910-matrix-arm-mini-pc.html	142,04 €
UDOO Dual	No	microSD	No	GbE	n (RT5370)	No	Yes	Yes	76	10-bit ADC PWM	Arduino 1.0 headers	http://www.udoo.org/udoo-dual-and-quad/	105,91 €
UDOO Dual Basic	No	microSD	No	No	No	No	Yes	Yes	76	10-bit ADC PWM	Arduino 1.0 headers	http://shop.udoo.org/eu/quad-dual/udoo-dual-basic.html	94 €
UDOO Quad	No	microSD	SATA	GbE	n (RT5370)	No	Yes	Yes	76	10-bit ADC PWM	Arduino 1.0 headers	http://www.udoo.org/udoo-dual-and-quad/	127,85 €
UP	16/32/64 GB eMMC	No	No	GbE	No	No	Yes	Yes	Yes	No	40-pin GP-bus	http://www.up-board.org/up/	122,17 €

SBCs													
Name	**Onboard storage**	**Flash slots**	**SATA**	**Ethernet**	**Wifi**	**Blue - tooth**	**I2C**	**SPI**	**GPIO**	**Analog**	**Other interfaces**	**Web page**	**Price**
Utilite Pro	32GB mSATA	microSD (SDXC)	m SATA	2x GbE	b/g/n (88W 8787)	3.0	No	No	No	No	2x RS-232	http://www.compulab.co.il/utilite-computer/web/utilite-models	242,44 €
Utilite Standard	8GB microSD	microSD (SDXC)	m SATA	2x GbE	b/g/n (88W 8787)	3.0	No	No	No	No	2x RS-232	http://www.compulab.co.il/utilite-computer/web/utilite-models	188,46 €
Utilite Value	4GB microSD	microSD (SDXC)	m SATA	GbE	No	No	No	No	No	No	2x RS-232	http://www.compulab.co.il/utilite-computer/web/utilite-models	126,90 €
Wandboard Dual	No	2x microSD	No	GbE	n (BCM 4329)	Yes	Yes	Yes	10	No	UART	http://www.wandboard.org/	94 €
Wandboard Quad	No	2x microSD	Yes	GbE	n (BCM 4329)	Yes	Yes	Yes	10	No	UART	http://www.wandboard.org/	122,17 €
Wandboard Solo	No	2x microSD	No	GbE	No	No	Yes	Yes	10	No	UART	http://www.wandboard.org/	75 €

Appendix 6. Evaluation boards for IC ADCs

PCB ADC													
Manufacturer	Model	ADC IC Model	ADC Type	Max Resolution (bit)	Channels	Max Sample Rate (Hz)/channel	Integrated Amp max Gain	Integrated Filter Types	Antialiasing Filter Cut Frequency (Hz)	Data Interface	Data Sheet	Price (about)
Linear Technology	DC2289A	LTC2368-24	SAR	24	1 pseudo-differential	1000000		Digital averaging filter		Parallel	http://cds.linear.com/docs/en/demo-board-manual/dc2289afa.pdf	187,66 €
Analog Devices	EVAL-CN0225-SDPZ-ND	AD7687	SAR	16	1 differential	250000				Serial	http://www.analog.com/media/en/reference-design-documentation/reference-designs/CN0225.pdf	64 €
Microchip	ADM00499	MCP3912	ΣΔ	24	4 differential	31250	32	Sinc filters		USB	http://ww1.microchip.com/downloads/en/DeviceDoc/50002308A.pdf	116,85 €
Analog Devices	EVAL-CN0261-SDPZ-ND	AD7691	SAR	18	1 differential	250000				Serial	http://www.analog.com/media/en/reference-design-documentation/reference-designs/CN0261.pdf	77 €
Microchip	ADM00573	MCP3919	ΣΔ	24	3 differential	31250	32	Sinc filters		USB	http://ww1.microchip.com/downloads/en/DeviceDoc/50002309A.pdf	116,85 €
Texas Instruments	ADS131E08EVM-PDK	ADS131E08	ΣΔ	24	8 differential	64000	12	Sinc filters		SPI®	http://www.ti.com/lit/ug/sbau200b/sbau200b.pdf	180,28 €
Texas Instruments	ADS1271EVM	ADS1271	ΣΔ	24	2 differential	105000		Digital FIR filter		SPI®	http://www.ti.com/lit/ug/sbau107c/sbau107c.pdf	44 €
Zeal electronics	RPIADC ISOL	MCP3913	ΣΔ	24	6 differential	125000	32	Digital filters		SPI®	http://www.zeal-electronics.co.uk/rpi16in-16out-adcisol-instructionmanual-c2013-16ss-systems-v112.pdf	131,00 €
Analog Devices	EVAL-AD7606-4EDZ	AD7606-4	SAR	16	4 single-ended	200000		Anti-alias (2nd. Ord.)	15000 or 22000	SPI®; Paral-lel	http://www.analog.com/media/en/technical-documentation/user-guides/EVAL-AD7605-4SDZ_7606SDZ_7606-6SDZ_7606-4SDZ_7607SDZ_7608SDZ.pdf	83 €
Analog Devices	EVAL-AD7606-6EDZ	AD7606-6	SAR	16	6 single-ended	200000		Anti-alias (2nd. Ord.)	15000 or 22000	SPI®; Paral-lel	http://www.analog.com/media/en/technical-documentation/user-guides/EVAL-AD7605-4SDZ_7606SDZ_7606-6SDZ_7606-4SDZ_7607SDZ_7608SDZ.pdf	88 €

PCB ADC												
Manufacturer	**Model**	**ADC IC Model**	**ADC Type**	**Max Resolution (bit)**	**Channels**	**Max Sample Rate (Hz)/channel**	**Integrated Amp max Gain**	**Integrated Filter Types**	**Antialiasing Filter Cut Frequency (Hz)**	**Data Interface**	**Data Sheet**	**Price (about)**
Analog Devices	EVAL-AD7606SDZ	AD7606	SAR	16	8 single-ended	200000		Anti-alias (2nd. Ord.)	15000 or 22000	SPI®; Paral-lel	http://www.analog.com/media/en/technical-documentation/user-guides/EVAL-AD7605-4SDZ_7606SDZ_7606-6SDZ_7606-4SDZ_7607SDZ_7608SDZ.pdf	55 €
Analog Devices	EVAL-CN0303	AD7476	SAR	12	1 single-ended	1000000				SPI®	http://www.analog.com/media/en/reference-design-documentation/reference-designs/CN0303.pdf	70 €
Analog Devices	EVAL-AD7609	AD7609	SAR	18	8 differential	200000		Amalog low pass	23000 or 32000	SPI®; QSPI™; MICRO-WIRE™; DSP compa-tible; Paral-lel	http://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/EVAL-AD7609.html#eb-overview	130,00 €
Analog Devices	EVAL-AD7176-2	AD7176-2	ΣΔ	24	2 differential	50000		Digital filters		SPI®; QSPI™; MICRO-WIRE™; DSP compa-tible	http://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/eval-ad7176-2.html#eb-overview	76 €
Analog Devices	EVAL-AD7608	AD7608	SAR	18	8 single-ended	200000		Analog low pass	15000 or 23000	SPI®; QSPI™; MICRO-WIRE™; DSP compa-tible; Paral-lel	http://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/EVAL-AD7608.html#eb-overview	67 €
Waveshare	Raspberry Pi High-Precision AD/DA Expansion Board	ADS1256	ΣΔ	24	8 single-ended or 4 differential	4000	64	Digital filter (5th order sinc)		SPI®	http://www.waveshare.com/High-Precision-AD-DA-Board.htm	28 €
Analog Devices	EVAL-CN0254-SDPZ	AD7689	SAR	16	8 single-ended or differential	250000		Selectable one-pole low-pass filter		SPI®	http://www.analog.com/media/en/reference-design-documentation/reference-designs/CN0254.pdf	74 €
Analog Devices	EVAL-CN0269-SDPZ	AD7984	SAR	18	16 single-ended or 8 differential	250000				Serial	http://www.analog.com/media/en/reference-design-documentation/reference-designs/CN0269.pdf	98 €

USB DAQs/oscilloscopes									
Manufacturer	Model	Type	Max Resolution (bit)	Channels	Max Sample Rate (Hz)/ch	Integrated Amp max Gain	Data Interfaces	Price (about)	Data Sheet
LabJack	U6	DAQ	18	14 single-ended or diffe-rential	50000	1000	SPI®; USB; I2C	281,24 €	https://labjack.com/sites/default/files/LabJack-U6-Datasheet-Export-20161024.pdf
LabJack	T7	DAQ	16	14 single-ended or diffe-rential	100000	1000	SPI®; USB; I2C; Wi-Fi; Ethernet	375,31 €	https://labjack.com/sites/default/files/LabJack-T7-Datasheet-Export-20161024.pdf
Open DAQ	[M]	DAQ	16	8 single-ended or diffe-rential	20000	100	USB	200,00 €	https://www.open-daq.com/productos/opendaq-m
USB-DUX	D	DAQ	12	8 single-ended	8000		USB	59,15 €	http://www.linux-usb-daq.co.uk/tech2_usbdux/
USB-DUX	Fast	DAQ	12	16 single-ended	3000000		USB	59,15 €	http://www.linux-usb-daq.co.uk/tech2_duxfast/
USB-DUX	Sigma	DAQ	24	16 single-ended	4000		USB	118,30€	http://www.linux-usb-daq.co.uk/tech2_duxsigma/
Data Transla-tion	DT9816	DAQ	16	6 single-ended	50000	2	USB	454,58€	http://www.datatranslation.com/Products/Low-Cost-DAQ/DT9816
Bitscope	BS05	Sco-pe	12	2 single-ended	20000000		USB	136,31 €	http://www.bitscope.com/product/BS05/?p=specs
Bitscope	BS10	Sco-pe	12	2 single-ended	20000000		USB	231,18 €	http://www.bitscope.com/product/BS10/?p=specs
NI	NI USB-6210	DAQ	16	16 single-ended or 8 diffe-rential	250000		USB	720,00 €	http://www.ni.com/pdf/manuals/375194c.pdf
MC	USB-1608FS-Plus	DAQ	16	8 single-ended	100000		USB	375,23 €	http://www.mccdaq.com/PDFs/specs/USB-1608FS-Series-data.pdf

Appendix 8. Certificate of calibration (wax mounting): B&K 4394.

CERTIFICATE OF CALIBRATION

Transducer serial number: **30951**

Calibration date: 28.11.2016

The sensitivity of the transducer under test was determined by comparison with the output from a single-ended reference grade accelerometer. The calibration of reference accelerometer, conducted by SIRA Test & Certification Ltd, is traceable, via the Euromet agreement, to the German national standard held by Physikalisch-Technische Bundesanstalt.

Transducer under test:

Manufacturer:	**B&K**
Transducer type:	**4394**
Serial number:	**30951**
Mounting method:	wax
Amplifier:	Beran 801A/ch2
Exciter:	Bruel&Kjaer 4824

Reference:

B&K 8305 s/n 1068937

Amplifier: Beran 801A s/n B008 / ch1

Nominal laboratory conditions:

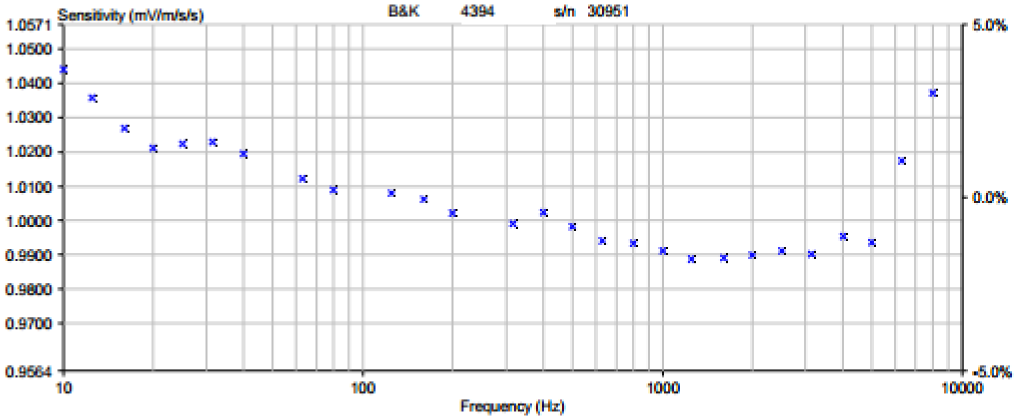
Temperature

Humidity 68%

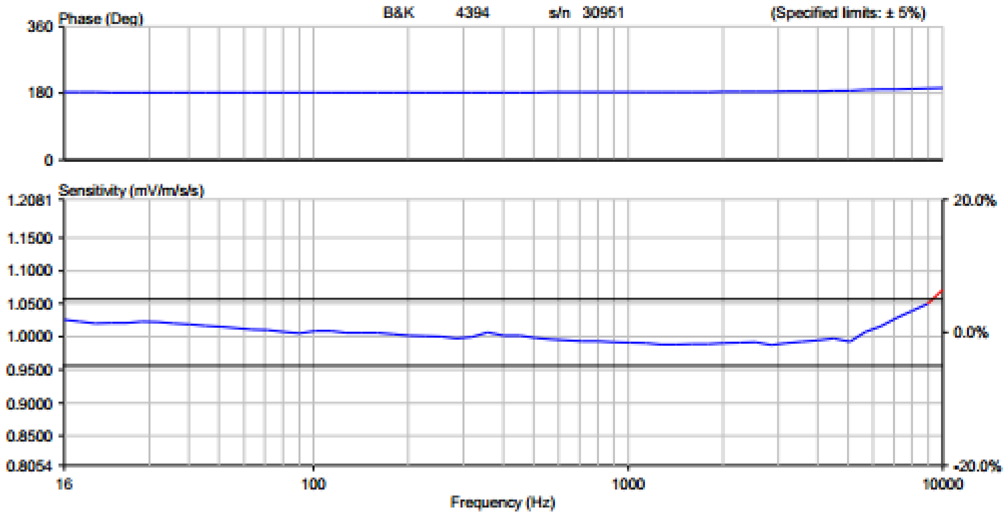
Additional information:

Measured nominal sensitivity at 160.000 Hz 35.000 m/s/s Peak **1.007 mV/m/s/s**

Frequency Step 10.000 Hz to 10.000 kHz at 35.000 m/s/s Peak



Frequency Sweep 16.000 Hz to 10.000 kHz at 35.000 m/s/s Peak



CAUTION: The frequency points measured in this sweep are not traceable, and therefore the curve is guidance only

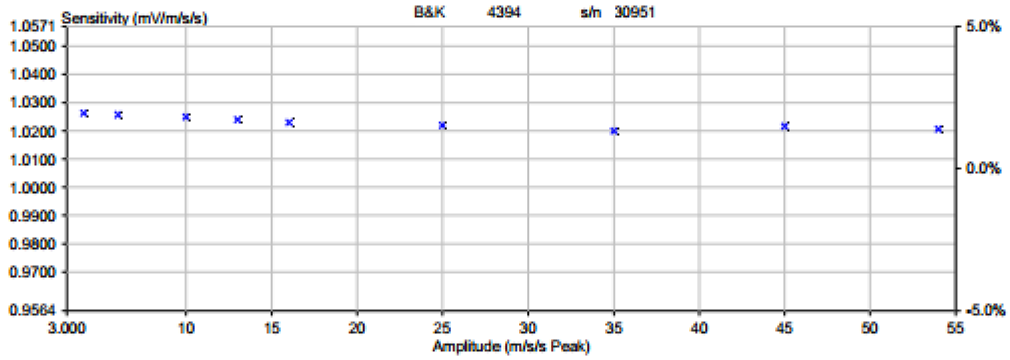
* Results that are Not Traceable - Reference Not Calibrated at These Points
† Results that are Outside of Specification

CERTIFICATE OF CALIBRATION

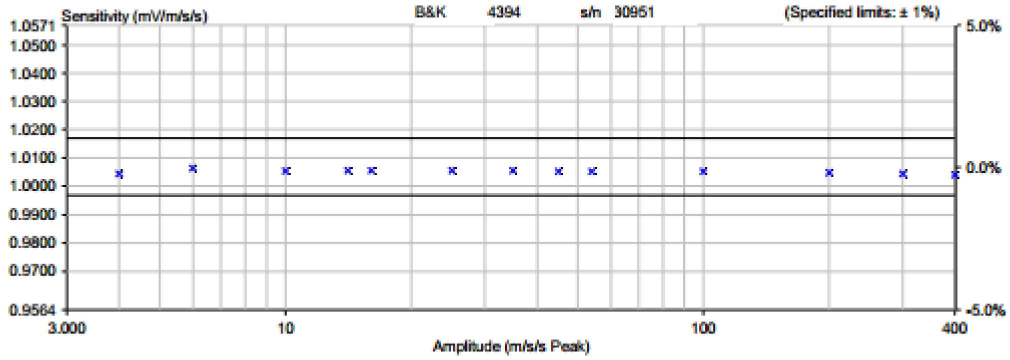
Transducer serial number: **30951**

Calibration date: 28.11.2016

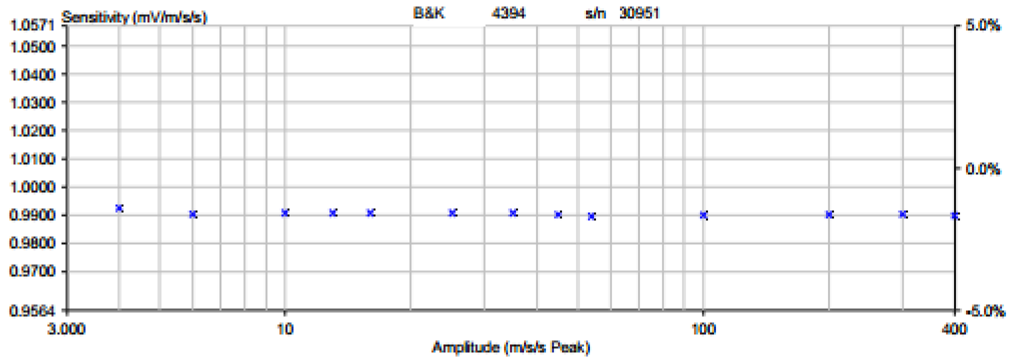
Amplitude linearity at 20.000 Hz



Amplitude linearity at 160.000 Hz



Amplitude linearity at 1.000 kHz



Measurement uncertainties at a confidence probability of 95%:

4Hz ≤ f < 20Hz:	2,9%
20Hz ≤ f ≤ 4kHz:	1,0%
4kHz < f ≤ 10kHz:	3,0%

The reported expanded uncertainty is based on a standard uncertainty multipled by a coverage factor k=2, providing a level of confidence of approximately 95%. The uncertainty evaluation has been carried out in accordance with UKAS requirements.

* Results that are Not Traceable - Reference Not Calibrated at These Points
† Results that are Outside of Specification

Frequency Step at 35.000 m/s/s Peak

Frequency Hz	Amplitude m/s/s Peak	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg	Frequency Hz	Amplitude m/s/s Peak	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg
10.00	14.00	1.0440	3.70		182.59	800.00	35.00	0.9933	-1.34		181.75
12.50	20.00	1.0358	2.89		182.30	1000.00	35.00	0.9912	-1.55		181.97
16.00	35.00	1.0268	1.99		181.96	1250.00	35.00	0.9887	-1.79		182.26
20.00	35.00	1.0211	1.42		181.64	1600.00	35.00	0.9892	-1.75		182.73
25.00	35.00	1.0223	1.54		181.39	2000.00	35.00	0.9900	-1.67		183.19
31.50	35.00	1.0228	1.59		181.36	2500.00	35.00	0.9913	-1.54		183.80
40.00	35.00	1.0195	1.27		181.30	3150.00	35.00	0.9903	-1.64		184.58
63.00	35.00	1.0122	0.54		181.17	4000.00	35.00	0.9954	-1.13		185.85
80.00	35.00	1.0089	0.21		181.13	5000.00	35.00	0.9937	-1.30		187.22
125.00	35.00	1.0080	0.12		181.02	6300.00	35.00	1.0173	1.04		188.84
160.00	35.00	1.0062	-0.06		181.10	8000.00	35.00	1.0371	3.01		190.58
200.00	35.00	1.0021	-0.46		181.12	10000.00	35.00	1.0713	6.41	†	193.97
315.00	35.00	0.9991	-0.76		180.76						
400.00	35.00	1.0023	-0.44		181.28						
500.00	35.00	0.9984	-0.83		181.47						
630.00	35.00	0.9942	-1.25		181.60						

Frequency Sweep at 35.000 m/s/s Peak

Frequency Hz	Amplitude m/s/s Peak	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg	Frequency Hz	Amplitude m/s/s Peak	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg
16.00	35.00	1.0258	1.89		181.96	284.52	35.00	0.9975	-0.92	*	181.04
17.95	35.00	1.0227	1.59	*	181.79	319.24	35.00	0.9996	-0.71	*	180.72
20.14	35.00	1.0204	1.35	*	181.59	358.20	35.00	1.0068	0.00	*	181.06
22.60	35.00	1.0209	1.41	*	181.45	401.90	35.00	1.0020	-0.47	*	181.28
25.36	35.00	1.0214	1.45	*	181.38	450.94	35.00	1.0014	-0.54	*	181.35
28.45	35.00	1.0225	1.56	*	181.38	505.96	35.00	0.9982	-0.85	*	181.46
31.92	35.00	1.0220	1.51	*	181.37	567.70	35.00	0.9962	-1.05	*	181.56
35.82	35.00	1.0201	1.32	*	181.33	636.97	35.00	0.9940	-1.27	*	181.60
40.19	35.00	1.0184	1.16	*	181.30	714.69	35.00	0.9936	-1.30	*	181.65
45.09	35.00	1.0166	0.98	*	181.24	801.90	35.00	0.9930	-1.37	*	181.75
50.60	35.00	1.0147	0.79	*	181.22	899.75	35.00	0.9919	-1.48	*	181.87
56.77	35.00	1.0129	0.61	*	181.18	1009.53	35.00	0.9913	-1.54	*	181.98
63.70	35.00	1.0112	0.44	*	181.15	1132.71	35.00	0.9902	-1.65	*	182.14
71.47	35.00	1.0098	0.30	*	181.13	1270.93	35.00	0.9887	-1.80	*	182.27
80.19	35.00	1.0078	0.10	*	181.09	1426.00	35.00	0.9887	-1.80	*	182.45
89.97	35.00	1.0054	-0.14	*	180.96	1600.00	35.00	0.9891	-1.76		182.72
100.95	35.00	1.0084	0.16	*	180.81	1795.23	35.00	0.9895	-1.72	*	182.94
113.27	35.00	1.0081	0.13	*	181.00	2014.28	35.00	0.9900	-1.66	*	183.20
127.09	35.00	1.0061	-0.07	*	181.02	2260.06	35.00	0.9906	-1.61	*	183.51
142.60	35.00	1.0063	-0.05	*	181.03	2535.83	35.00	0.9914	-1.52	*	183.84
160.00	35.00	1.0059	-0.09		181.09	2845.25	35.00	0.9878	-1.89	*	184.31
179.52	35.00	1.0038	-0.30	*	181.10	3192.42	35.00	0.9901	-1.66	*	184.71
201.43	35.00	1.0018	-0.49	*	181.11	3581.95	35.00	0.9923	-1.44	*	184.99
226.01	35.00	1.0012	-0.56	*	181.07	4019.02	35.00	0.9946	-1.21	*	185.87
253.58	35.00	1.0004	-0.63	*	181.08	...	...	...	...	...	...

Amplitude Step at 20.000 Hz

Amplitude m/s/s Peak	Frequency Hz	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg	Amplitude m/s/s Peak	Frequency Hz	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg
4.00	20.00	1.0263	1.94	*†	181.72	45.00	20.00	1.0216	1.47	†	181.71
6.00	20.00	1.0257	1.88	*†	181.79	54.00	20.00	1.0206	1.37	†	181.68
10.00	20.00	1.0249	1.80	*†	181.83						
13.00	20.00	1.0239	1.70	*†	181.77						
16.00	20.00	1.0229	1.60	†	181.75						
25.00	20.00	1.0220	1.51	†	181.74						
35.00	20.00	1.0203	1.34	†	181.63						

Amplitude Step at 160.000 Hz

Amplitude m/s/s Peak	Frequency Hz	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg	Amplitude m/s/s Peak	Frequency Hz	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg
4.00	160.00	1.0044	-0.23	*	180.97	45.00	160.00	1.0051	-0.17		181.09
6.00	160.00	1.0063	-0.05	*	181.07	54.00	160.00	1.0052	-0.16		181.10
10.00	160.00	1.0053	-0.15	*	181.08	100.00	160.00	1.0050	-0.17	*	181.09
14.10	160.00	1.0057	-0.10	*	181.07	200.00	160.00	1.0047	-0.21	*	181.09
16.00	160.00	1.0056	-0.12		181.08	300.00	160.00	1.0044	-0.24	*	181.08
25.00	160.00	1.0056	-0.12		181.08	400.00	160.00	1.0039	-0.29	*	181.03
35.00	160.00	1.0056	-0.12		181.09						

Amplitude Step at 1.000 kHz

Amplitude m/s/s Peak	Frequency Hz	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg	Amplitude m/s/s Peak	Frequency Hz	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg
4.000	1000.000	0.9927	-1.399	*†	181.927	45.000	1000.000	0.9902	-1.647	†	182.025
6.000	1000.000	0.9907	-1.602	*†	181.989	54.000	1000.000	0.9897	-1.694	†	182.019
10.000	1000.000	0.9908	-1.584	*†	181.990	100.000	1000.000	0.9900	-1.667	*†	182.004
13.000	1000.000	0.9908	-1.585	*†	181.983	200.000	1000.000	0.9903	-1.639	*†	181.991
16.000	1000.000	0.9908	-1.591	†	181.991	300.000	1000.000	0.9904	-1.629	*†	181.986
25.000	1000.000	0.9907	-1.595	†	181.984	400.000	1000.000	0.9898	-1.688	*†	182.005
35.000	1000.000	0.9907	-1.594	†	181.985						

Calibrated by: Jarno Junnola

* Results that are Not Traceable - Reference Not Calibrated at These Points
† Results that are Outside of Specification

Appendix 9. Certificate of calibration (wax mounting): Te Connectivity ACH 01

CERTIFICATE OF CALIBRATION

Transducer Under Test

Manufacturer: TE Connectivity

Model Number: 199631

Serial Number: 1

Calibration Period: 0 Months

Manufacturer Specifications

Nominal Sensitivity: 1.091mV/m/s/s

Frequency Response: 2.000 Hz to 20.000 kHz

Test equipment used

Calibration System: Beran Instruments 485 Calibration System

Analyser: 475, Serial Number: 182463 Firmware: 3.2.1

Exciter model: Bruel&Kjaer 4809 /with cooling

Reference:

Manufacturer: B&K

Model Number: 8305

Serial number: 1068937

Nominal Laboratory Condition

Temperature

Humidity 68%

Air Pressure

Results:

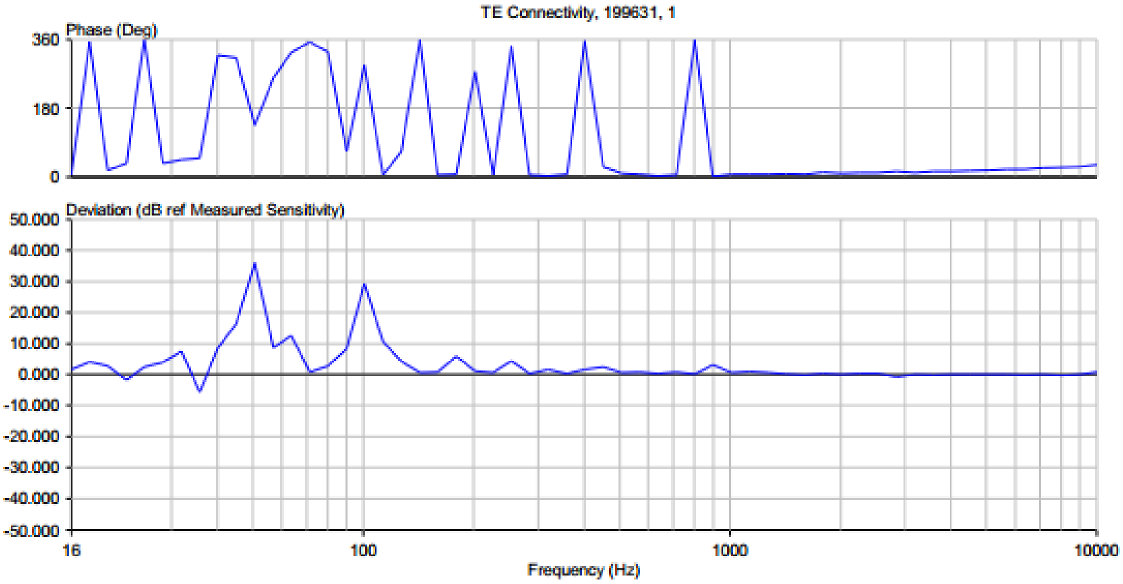
Measured Nom Sensitivity: 0.511 mV/m/s/s 358.556 Deg at 1.000 kHz 34.681 m/s/s RMS

* Results that are Not Traceable - Reference Not Calibrated at These Points
† Results that are Outside of Specification

Test Profile: F_sweep_AnalogDev_MEMS

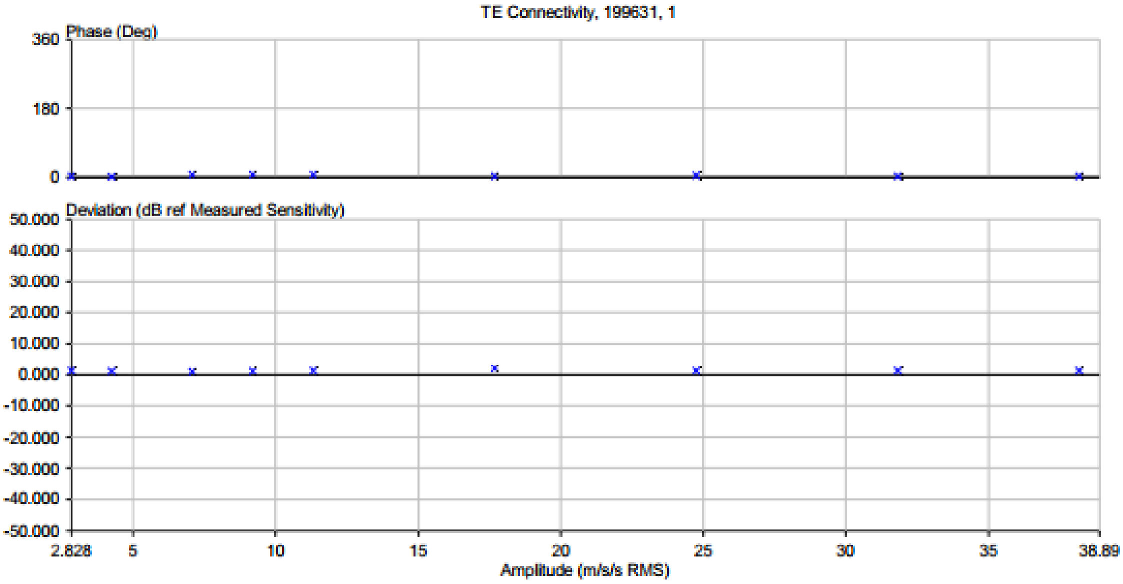
Frequency Hz	Amplitude m/s/s RMS	Sensitivity mV/m/s/s	Deviation dB Meas		Phase Deg
16.000	14.142	0.610	1.536	†	3.270
17.952	14.142	0.821	4.109	*†	354.646
20.143	14.142	0.692	2.630	*†	15.935
22.601	14.142	0.419	-1.729	*†	35.454
25.358	14.142	0.685	2.543	*†	357.887
28.452	14.142	0.802	3.910	*†	35.110
31.924	14.142	1.199	7.404	*†	44.612
35.820	14.142	0.266	-5.690	*†	47.564
40.190	14.142	1.386	8.659	*†	317.975
45.094	14.142	3.371	16.381	*†	312.138
50.596	14.142	31.912	35.906	*†	133.993
56.770	14.142	1.379	8.617	*†	258.515
63.697	14.142	2.164	12.532	*†	325.383
71.469	14.142	0.556	0.730	*†	353.153
80.190	14.142	0.698	2.701	*†	325.959
89.975	14.142	1.326	8.275	*†	64.781
100.953	14.142	14.685	29.164	*†	292.432
113.271	14.142	1.733	10.602	*†	3.861
127.093	14.142	0.825	4.155	*†	64.866
142.600	14.142	0.550	0.641	*†	358.572
160.000	14.142	0.564	0.846	†	3.597
179.523	14.142	0.989	5.728	*†	5.692
201.428	14.142	0.581	1.103	*†	275.021
226.006	14.142	0.546	0.565	*†	3.858
253.583	14.142	0.853	4.441	*†	342.524
284.525	14.142	0.540	0.473	*†	3.729
319.242	14.142	0.615	1.599	*†	1.601
358.195	14.142	0.540	0.476	*†	6.139
401.902	14.142	0.607	1.496	*†	356.228
450.941	14.142	0.680	2.477	*†	25.114
505.964	14.142	0.550	0.640	*†	7.873
567.701	14.142	0.558	0.759	*†	5.529
636.971	14.142	0.535	0.393	*†	2.981
714.694	14.142	0.563	0.838	*†	4.161
801.900	14.142	0.523	0.192	*†	358.316
899.746	14.142	0.732	3.117	*†	1.562
1009.532	14.142	0.551	0.642	*†	4.922
1132.713	14.142	0.573	0.986	*†	4.837
1270.925	14.142	0.549	0.623	*†	5.851
1426.002	14.142	0.528	0.284	*†	7.565
1600.000	14.142	0.503	-0.141	†	5.643
1795.230	14.142	0.538	0.443	*†	12.241
2014.281	14.142	0.516	0.079	*	9.035
2260.060	14.142	0.538	0.444	*†	10.247
2535.829	14.142	0.535	0.398	*†	9.917
2845.247	14.142	0.466	-0.802	*†	13.290
3192.420	14.142	0.507	-0.078	*	10.466
3581.954	14.142	0.502	-0.158	*†	13.066
4019.018	14.142	0.512	0.008	*	13.995
4509.413	14.142	0.515	0.067	*	15.485
5059.644	14.142	0.513	0.023	*	16.573
5677.014	14.142	0.508	-0.048	*	19.804
6369.715	14.142	0.504	-0.124	*†	20.171
7146.937	14.142	0.517	0.090	*†	22.000
8018.996	14.142	0.489	-0.395	*†	24.389
8997.461	14.142	0.512	0.016	*	26.078
10000.000	14.142	0.559	0.769	†	30.638

* Results that are Not Traceable - Reference Not Calibrated at These Points
† Results that are Outside of Specification



Test Profile: A_stepB&K_20

Amplitude m/s/s RMS	Frequency Hz	Sensitivity mV/m/s/s	Deviation dB Meas		Phase Deg
2.828	20.000	0.617	1.630	*†	2.818
4.243	20.000	0.583	1.139	*†	1.083
7.071	20.000	0.574	1.011	*†	6.083
9.192	20.000	0.587	1.198	*†	6.157
11.314	20.000	0.597	1.344	†	6.167
17.678	20.000	0.646	2.034	†	2.636
24.749	20.000	0.592	1.274	†	3.343
31.820	20.000	0.602	1.423	†	2.896
38.184	20.000	0.601	1.403	†	3.035



* Results that are Not Traceable - Reference Not Calibrated at These Points
† Results that are Outside of Specification

Appendix 10. Certificate of calibration (glue mounting): Analog devices ADXL001

CERTIFICATE OF CALIBRATION

Page 1(3)

Transducer serial number: **1**

Calibration date: 21.10.2016

The sensitivity of the transducer under test was determined by comparison with the output from a single-ended reference grade accelerometer. The calibration of reference accelerometer, conducted by SIRA Test & Certification Ltd, is traceable, via the Euromet agreement, to the German national standard held by Physikalisch-Technische Bundesanstalt.

Transducer under test:

Manufacturer: **Analog Devices**
Transducer type: **ADXL001**
Serial number: **1**

Mounting method:

Amplifier:
Exciter: Bruel&Kjaer 4809 /with cooling

Reference:

B&K 8305 s/n 1068937
Amplifier: Beran 801A s/n B008 / ch1

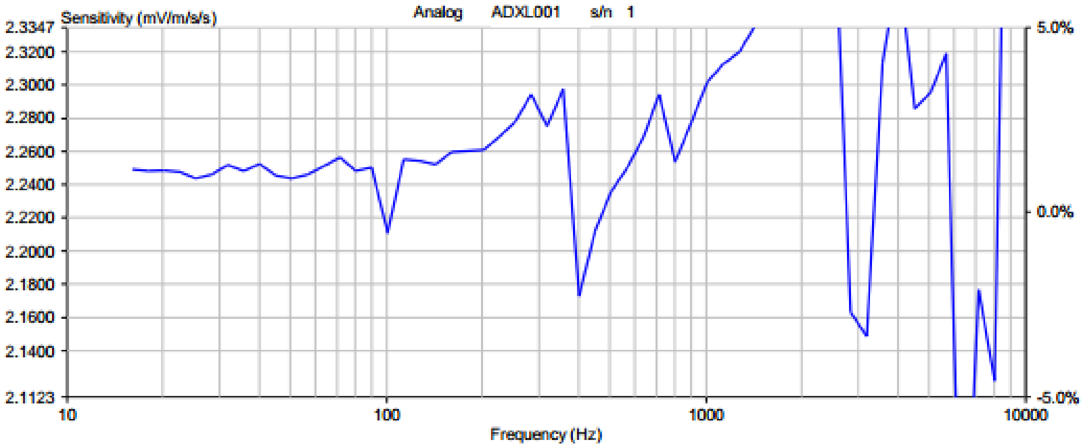
Nominal laboratory conditions:

Temperature
Humidity 68%

Additional information:

Measured nominal sensitivity at 100.000 Hz 49.033 m/s/s Peak **2.224 mV/m/s/s**

Frequency Sweep 16.000 Hz to 10.000 kHz at 20.000 m/s/s Peak



Frequency Sweep 16.000 Hz to 10.000 kHz at 20.000 m/s/s Peak

Analog ADXL001 s/n 1 (Specified limits: ± 5%)

CAUTION: The frequency points measured in this sweep are not traceable, and therefore the curve is guidance only

* Results that are Not Traceable - Reference Not Calibrated at These Points
† Results that are Outside of Specification

CERTIFICATE OF CALIBRATION

Transducer serial number: **1**

Calibration date: 21.10.2016

Frequency Sweep at 20.000 m/s/s Peak

Frequency Hz	Amplitude m/s/s Peak	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg	Frequency Hz	Amplitude m/s/s Peak	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg
16.00	20.00	2.2488	1.14		182.00	100.95	20.00	2.2108	-0.57	*	181.09
17.95	20.00	2.2484	1.12	*	181.73	113.27	20.00	2.2551	1.42	*	180.92
20.14	20.00	2.2488	1.14	*	181.60	127.09	20.00	2.2543	1.38	*	180.94
22.60	20.00	2.2476	1.08	*	181.42	142.60	20.00	2.2521	1.28	*	181.22
25.36	20.00	2.2436	0.90	*	181.30	160.00	20.00	2.2597	1.63		181.18
28.45	20.00	2.2463	1.02	*	181.27	179.52	20.00	2.2605	1.66	*	181.41
31.92	20.00	2.2517	1.27	*	181.10	201.43	20.00	2.2609	1.68	*	181.67
35.82	20.00	2.2483	1.11	*	181.15	226.01	20.00	2.2685	2.02	*	181.67
40.19	20.00	2.2526	1.31	*	180.99	253.58	20.00	2.2780	2.45	*	181.94
45.09	20.00	2.2456	0.99	*	180.78	284.52	20.00	2.2944	3.19	*	182.31
50.60	20.00	2.2436	0.90	*	180.66	319.24	20.00	2.2751	2.32	*	183.22
56.77	20.00	2.2463	1.02	*	180.76	358.20	20.00	2.2974	3.32	*	185.26
63.70	20.00	2.2513	1.25	*	180.91	401.90	20.00	2.1726	-2.29	*	183.33
71.47	20.00	2.2566	1.49	*	180.50	450.94	20.00	2.2119	-0.52	*	182.44
80.19	20.00	2.2482	1.11	*	180.80	505.96	20.00	2.2358	0.55	*	182.79
89.97	20.00	2.2503	1.21	*	181.01	...	...	...	...	...	...

Appendix 11. Certificate of calibration (screw mounting): Analog devices ADXL001

CERTIFICATE OF CALIBRATION

Transducer Under Test

Manufacturer: Analog Devices

Model Number: ADXL001

Serial Number: 1

Calibration Period: 0 Months

Manufacturer Specifications

Nominal Sensitivity: 2.468mV/m/s/s

Frequency Response: 1.000 Hz to 15.000 kHz

Test equipment used

Calibration System: Beran Instruments 485 Calibration System

Analyser: 475, Serial Number: 182463 Firmware: 3.2.1

Exciter model: Bruel&Kjaer 4809 /with cooling

Reference:

Manufacturer: B&K

Model Number: 8305

Serial number: 1068937

Nominal Laboratory Condition

Temperature

Humidity 68%

Air Pressure

Results:

Measured Nom Sensitivity: 2.468 mV/m/s/s 180.878 Deg at 100.000 Hz 34.672 m/s/s RMS

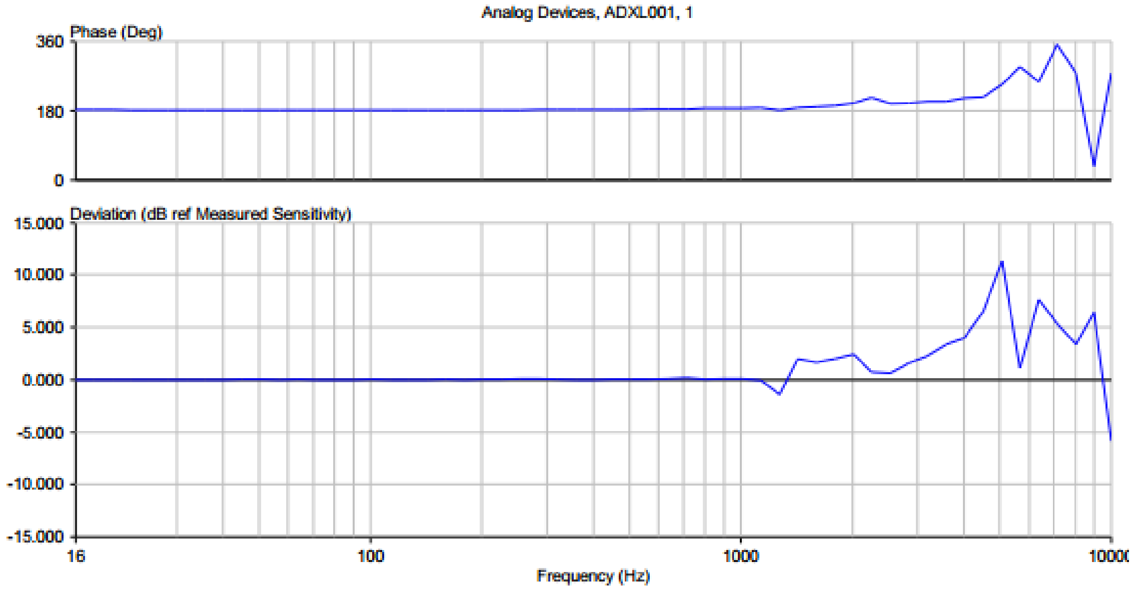
* Results that are Not Traceable - Reference Not Calibrated at These Points

† Results that are Outside of Specification

Test Profile: F_sweep_AnalogDev_MEMS

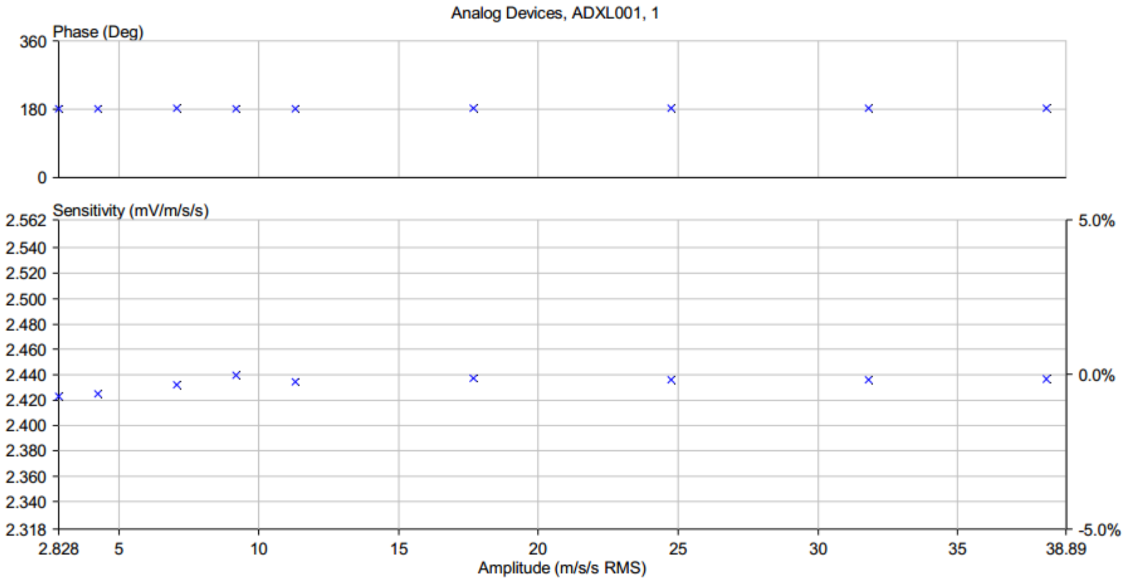
Frequency Hz	Amplitude m/s/s RMS	Sensitivity mV/m/s/s	Deviation dB Meas		Phase Deg
16.000	14.142	2.472	0.016		181.955
17.952	14.142	2.470	0.007	*	181.858
20.143	14.142	2.472	0.015	*	181.717
22.601	14.142	2.473	0.017	*	181.528
25.358	14.142	2.468	0.000	*	181.372
28.452	14.142	2.473	0.018	*	181.214
31.924	14.142	2.473	0.019	*	181.147
35.820	14.142	2.472	0.017	*	181.011
40.190	14.142	2.476	0.028	*	180.886
45.094	14.142	2.476	0.029	*	180.926
50.596	14.142	2.478	0.037	*	180.799
56.770	14.142	2.471	0.012	*	180.920
63.697	14.142	2.477	0.032	*	180.720
71.469	14.142	2.472	0.014	*	180.700
80.190	14.142	2.475	0.027	*	180.707
89.975	14.142	2.467	-0.002	*	180.868
100.953	14.142	2.477	0.033	*	180.838
113.271	14.142	2.471	0.012	*	180.714
127.093	14.142	2.474	0.022	*	180.801
142.600	14.142	2.475	0.026	*	181.021
160.000	14.142	2.479	0.038		181.068
179.523	14.142	2.475	0.026	*	181.107
201.428	14.142	2.478	0.035	*	181.199
226.006	14.142	2.486	0.065	*	181.379
253.583	14.142	2.499	0.110	*	181.531
284.525	14.142	2.496	0.101	*	182.745
319.242	14.142	2.482	0.051	*	182.305
358.195	14.142	2.470	0.008	*	182.388
401.902	14.142	2.472	0.015	*	182.411
450.941	14.142	2.476	0.030	*	182.655
505.964	14.142	2.487	0.067	*	182.815
567.701	14.142	2.482	0.049	*	183.439
636.971	14.142	2.497	0.103	*	183.607
714.694	14.142	2.509	0.145	*	184.269
801.900	14.142	2.490	0.078	*	184.730
899.746	14.142	2.497	0.104	*	185.207
1009.532	14.142	2.505	0.130	*	186.110
1132.713	14.142	2.456	-0.040	*	186.561
1270.925	14.142	2.095	-1.424	*†	180.973
1426.002	14.142	3.107	2.002	*†	186.555
1600.000	14.142	3.000	1.696	†	189.847
1795.230	14.142	3.103	1.990	*†	192.879
2014.281	14.142	3.258	2.412	*†	198.901
2260.060	14.142	2.690	0.750	*†	213.791
2535.829	14.142	2.656	0.637	*†	198.184
2845.247	14.142	2.976	1.628	*†	199.598
3192.420	14.142	3.227	2.330	*†	202.728
3581.954	14.142	3.620	3.328	*†	203.079
4019.018	14.142	3.906	3.990	*†	211.553
4509.413	14.142	5.222	6.510	*†	214.608
5059.644	14.142	9.085	11.321	*†	248.160
5677.014	14.142	2.793	1.076	*†	293.131
6369.715	14.142	5.967	7.669	*†	253.930
7146.937	14.142	4.560	5.333	*†	351.907
8018.996	14.142	3.632	3.356	*†	275.828
8997.461	14.142	5.175	6.432	*†	36.082
10000.000	14.142	1.251	-5.902	†	277.940

* Results that are Not Traceable - Reference Not Calibrated at These Points
† Results that are Outside of Specification



Test Profile: A_stepB&K_20

Amplitude m/s/s RMS	Frequency Hz	Sensitivity mV/m/s/s	Deviation (%) Meas		Phase Deg
2.828	20.000	2.423	-0.702	*	181.547
4.243	20.000	2.425	-0.627	*	181.267
7.071	20.000	2.432	-0.351	*	181.746
9.192	20.000	2.440	-0.029	*	181.519
11.314	20.000	2.434	-0.244		181.509
17.678	20.000	2.437	-0.129		181.663
24.749	20.000	2.436	-0.166		181.617
31.820	20.000	2.436	-0.175		181.656
38.184	20.000	2.437	-0.147		181.646



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† Results that are Outside of Specification