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Vibration Analysis for Predictive Maintenance Purpose

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This final year project's purpose was to investigate vibrations with three different vibration sensors integrated with a low-cost ready-made bundle and analyze them with a custom-built LabView application. This study was done in cooperation with BeGo Solutions specializing in data business and sensors.

The study began with a research into vibrations and what kind of vibration sensor are commonly used. The study then focused on using three pre-selected vibration sensors and BeGo Solution company's guidelines to set criteria for more sensors for future development purposes. After the market survey, the LabView application was built for three pre-selected sensors. In later stages the company decided to concentrate on one vibration sensor, contact microphone, to increase data accuracy and reliability. The built application for three sensors was put on hold for future development and a new application for the contact microphone was designed and tested with BeGo Solutions' ready-made bundle in several test cases. The vibration data was obtained using contact microphone that measured heart pulses and a water-filtering pump with water and water-dirt mixture, and finally, the pump was knocked for additional data.

The survey found few sensors that can be integrated with the company's bundle but also showed that this kind of system is not readily available on the market. The custom-built LabView application has two versions. The first option that was not tested follows the initial plan of using three different sensors, whereas, the second option that was tested was built according to the contact microphone. It was found that using BeGo Solutions' bundle it is possible to build a low-cost vibration measuring and analyzing system. According to the company, this kind of solution has a growing market share in the upcoming years and, therefore, will be improved.

Keywords	Vibrations, Fast Fourier Transform, Market survey, LabView

Contents

List of Abbreviations

FFT	Fast Fourier Transform, used in mathematics to analyze vibrations, also used in NI LabView for analysis.
NI	National Instruments, company who provides the software used in this study.
PS	Power spectrum analysis in LabView. Provides results in decibels.

1 Introduction

Vibrations, also referred to as motions and oscillations, occur simultaneously everywhere. Some are visible, whereas, others can only be felt and some vibrations are detectable only with measurement devices. Measuring vibrations and analyzing them is very important because it offers an insight on how those influence the surroundings, such as machines and people and what are the likely results of motions. Measuring and analyzing vibrations are done in several ways that are explained in this thesis. How vibrations are measured in industrial world, what sensors are used, how those sensors function, how is the data analyzed are questions. However, the details about the vibration analysis programs are business secrets. This study aims to find out if it is possible to and build an entry-level application in LabView and use a low-cost ready-made bundle to measure and analyze vibration data with Fast Fourier transform.

To mimic an effectively working application, the analysis program should provide a sufficient overview of the oscillations and at the same time the program should be simple, low-cost and as universal as possible.

The idea originates from a company called BeGo Solutions that sells data patterns, data, sensor hardware and analytics. This study is a potential use case for the company because the idea tested in this study is not available on the market. The practical parts, as well as the analyzing method were set by BeGo Solutions and extended by the author of this study with the theoretical background.

In addition to the vibration analysis program, to further enlarge the theme and to integrate the idea with an undergoing project in BeGo Solutions, the thesis includes market survey based on pre-selected sensors.

2 Vibrations Background

The scope of this work is to analyze vibrations, also referred as motions and oscillations, using a custom-built application with Fast Fourier Transform method. However, in order to measure and analyze vibrations the theory on how vibrations occur must be known.

2.1 Theory of Vibrations

Although, there are several sources of vibrations, they all share the same theory. Vibrations occur in a periodic motion during a time interval where the motion repeats after certain length of time. The simplest form of vibration is harmonic motion illustrated in figure 1.

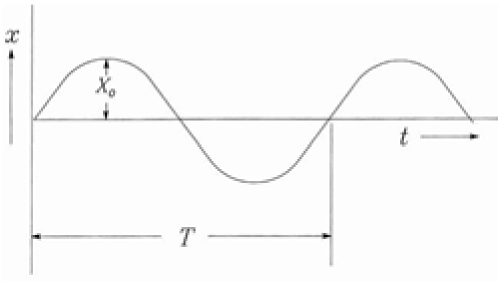

Figure 1. Harmonic motion of a simple pendulum.

In figure 1, X_0 signifies the amplitude of the vibration signal, T which is measured in seconds, is the period in which the signal does not repeat itself and t is time often measured in seconds.

However, in reality, vibrations are complex graphs that consist of several signals. A more real-life example from a vibration signal is shown in figure 2 where the vibration signal consist of the vibrations of a rotating element and the supporting structure of its turbine.

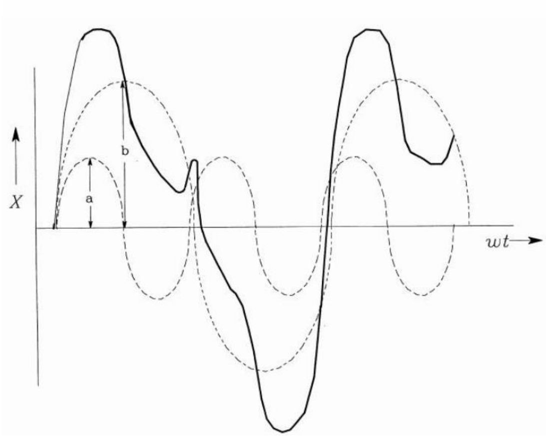

Figure 2. Vibration graph consisting the vibrations of a turbine structure and the rotating element on it.

In figure 2, the capital X signifies the amplitude, ωt means the circular frequency. Because in this example, the object is rotating, the dotted line with an amplitude of a is the rotating vibration, whereas, the amplitude b indicates the vibration wave of the supporting structure. As those waves with amplitudes a and b are summed, the result is the black vibration waveform in figure 2. The summed waveform in figure 2 was determined by a French physicist and mathematician Jean Fourier. He found that nonharmonic functions in the time-domain vibration profile, illustrated in figure 2, are the mathematical sum of simple harmonic waves such as shown in figure 1. [1.]

The four most important measured components of a vibration are frequency, displacement (amplitude), velocity and acceleration. Velocity and displacement are common in motor analysis, whereas, frequency and acceleration more in every-day analysis, such as heart condition or passing train influence to nearby offices for example. Frequency indicates the number of repetitions of a certain vibration component over a certain amount of time, which is very important in terms of the influences on human body. In addition, frequency provides an option to forecast the failure tendency because some failures happen at specific frequencies. The amplitude provides the vibrations peak-value – the maximum value of the signal measured from zero to the maximum peak of a signal. Peak value can be associated with velocity or acceleration. Displacement is the difference in position of a vibrating object relative to its reference point (point of origin). Velocity shows how quickly a vibrating object is moving and finally, acceleration indicates the time rate of change of velocity. Usually, acceleration is computed with the gravitation force g, which is often shown in datasheets for accelerometers. [3.; 4.]

2.2 Origins of Vibrations

The sources of motions determine how significant the influence on nearby surroundings is. It is important to measure and study vibrations because all motions influence nearby objects and people, which have consequences to nearby people and equipment.

The necessity of analyzing vibrations is unique to each process and equipment. Vibrations are categorized in a variety of ways, for example, vibrations originating from equipment and processes can be categorized into three parts: centrifugal, reciprocating and continuous processes. Centrifugal equipment are blowers, fans, mills and generators – machines that function by the force being equal or opposite to the centripetal force which ultimately increases the distance between the moving object and the center of rotation.

The centripetal force itself is the process in which an object is pushed towards the center of rotation in smooth curve like parabolas or logarithmic curves. Reciprocating objects are in an engine cylinder that output unequal force within the cylinder that result in vibrations and noise in the engine and to its surroundings. These kinds of devices are gasoline and diesel engines, compressors and cylinders. Continuous processes are systems consisting of several machines and lines, such as paper machines, plating and can manufacturing lines but also printing and chemical production lines. From human perspective, vibrations could be divided into the following parts: slow and visible, invisible and sensible by touching, and insensible by touching yet sensible by hearing via audible sounds. Low frequency and visible can be ground and piping vibration, water flow, invisible and sensible by touching is misbalance or misalignment of objects and sensible by hearing via audible sounds can be abnormal noise such as originating from a laptop or from an older refrigerator, as it turns of cooling or from gears which are dependent on the number of gear teeth. [3.; 4.]

2.3 Importance of Measuring and Analyzing Vibrations

Analyzing vibration data provides answers how to optimize maintenance and improve efficiency. For instance, vibration measuring and analyzing are used to detect leaks, analyze fluid flow through pipes or to conduct nondestructive testing functions increasing the reliability of critical plant systems, for example. Vibrations cause disturbances also to electronic devices. The main failures are cut cable cords, defects in welding points, broken component outputs, short circuits, functional failure of components and misalignment of optical circuits. Although, the list is significantly longer, the named problems caused by vibrations indicate how carefully components and devices must be designed and how vital vibration analysis is.

The usage of measurement and analyzation data can be divided into the following categories: predictive maintenance, acceptance testing, quality control, loose or foreign parts detection, noise control, leak detection and machine design and engineering. Predictive maintenance is used with rotating elements where the motion is predictable and vibrations can be forecasted. This enables to forecast and detect catastrophic failure. Acceptance testing is another effective method to detect their operating characteristics. It is done at the factory where theoretical test results are compared with measurement data. This method enables to detect design problems, possible damage during shipping as well as installation and reduce the occurrence of unexpected repair costs and long-term damage. In quality control, vibration data provides excellent insight into the correlation between manufacturing devices, and manufactured devices. For instance, in paper industry, if rolling mills equipment is nearing their life cycle, it can be detected from vibration analysis and thus the chances of manufacturing products with failures caused by manufacturing equipment are reduced. Loose and foreign parts detection method is used in nuclear plants because diagnosing vibrations from incorrectly installed and wrong parts increases the safety of nuclear power plants. Leakage detection offers great overview about the possible leaks in oil industries, for example, where many valves are used. Leakage offers vibration data which is analyzed to detect whether the flow in a tube or a valve is within limits. Accelerometers are efficient sensors for this kind of method. In machine design and engineering, analyzing vibration data from similar devices provide a strong base to form a preliminary design thus increasing the quality of the final design. Noise control is used in correlation with government regulations that require noise levels not to exceed certain points. Noise control provides data about the engines, generators, production lines and how their sound vibrations travel in space and ultimately, how those effect human body. [1.; 3.; 4.; 6.]

Due to the vibration effects on people, governments have passed regulations drawing limits to what kind of vibration levels humans can be exposed to in work environments. The international standard ISO 2631, first published 1974, was a first of a kind which gave the numerical limits of vibration exposure to the human body. The standard was revised three times in years 1978, 1982 and 1985. Currently, the standard is called "Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration" and consist of four parts. First part is the general information which states the human response to vibration is strongly frequency-dependent. The table 1 about ISO 2631 gives the general limitations of levels of comfort for different vibration levels.

Table 1. Vibration levels and their influence on human body. Copied from The effect of vibration on human performance and health: A review of recent literature. [5, 5]

Less than 0.315 m/s^2	Not comfortable
0.315 to 0.63 m/s^2	A little uncomfortable
0.5 to 1 m/s^2	Fairly comfortable
0.8 to 1.6 m/s^2	Uncomfortable
1.25 to 2.5 m/s^2	Very uncomfortable
> 2 m/s^2	Extremely uncomfortable

The standard explains that a long-term strong vibration level exposure to the human body may lead to risk of injury to the lumbar spine and its nervous system. In addition, the effects on female reproductive organs, digestive systems and blood vessels are briefly discussed. Oddly, there is no information about the correlation between the human health and the vibration intensity, meaning that it is not known, for example, if a certain level of vibration is experienced for 30 days then how much the lumbar spine is affected. [5.]

2.4 Mathematical Backround of Vibrations

As mentioned in theory part, the vibration wave consist of summed waves determined by Jean Fourier. In this part, the mathematical side of vibrations and the mathematical method used to analyze vibrations in this study are explained.

The measured vibration signal consist of several signals. To simplify the theory, the figure 2 shall be taken as a basis of explanation. The thickest wave in figure 2 is the sum of two dotted lines with amplitudes a and b, X_1 and X_2 accordingly. Those vibrations or oscillations can be presented as:

$$X_1 = \mathrm{asin}(\omega_1 t). \tag{1}$$

$$X_2 = \mathrm{bsin}(\omega_2 t). \tag{2}$$

Where $\omega_x t$ is the frequency of a single sine wave.

As Jean Fourier determined, the vibration black-colored wave is the sum of all nonharmonic vibrations that is calculated by:

$$X = X_1 + X_2 = \mathrm{a}\sin(\omega_1 t) + b sin(\omega_2 t). \quad (3)$$

This gives the graphical representation of the black colored wave which is no longer simple. Furthermore, Fourier added the amplitudes as well as the phase angles of each oscillation resulting in the following formula:

$$f(t) = A_0 + A_1 \sin(\omega t + \varphi_1) + A_2 \sin(2\omega t + \varphi_2) + A_3 \sin(3\omega t + \varphi_3) + \cdots . \quad (4)$$

In this infinitely long equation, the $f(t)$ represents the entire Fourier series function in relation with time. The equation is that long as the vibration is recorded. The capital A represents the amplitude/displacement value of each vibration wave and φ is the vibration phase angle which is the difference at zero amplitude of two oscillating motions. Because the length of vibrations is unknown and can be infinite, thus three dots are added to the end. [1.]

2.5 Fast Fourier Transform

In this study the method for analyzing vibrations is Fast Fourier Transform, also referred to as FFT which is derived from first Fourier series and then Fourier Transform, a closer look into the Fourier Transform first must be taken to clarify the computational process.

The explanations above regarding Fourier series are correct, yet more precise representation of the calculus side of Fourier series and Transform that include sums and integrals is also explained to further deepen the understanding. In calculus, the Fourier series is illustrated as given in formula 5:

$$f(t) = \sum_{n=-\infty}^{n=\infty} C_n e^{jn\omega_0 t}. \quad (5)$$

Where Sigma indicates the entire sum of all functions, capital C represents the integral of the summed vibration function and two small n-s indicate the number of samples, time is within the interval from 0 seconds to 0 seconds plus period of measurement. Capital C is the vibration's function which is further written as shown below:

$$C_n = \frac{1}{T} \sum_{t_0}^{t_0+T} f(t) e^{-jn\omega_0 t} dt. \qquad (6)$$

The summed vibration signal is the $f(t)$ which includes three parts seen below:

$$f(t) = \sum_{n=1}^{n=\infty} (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t). \qquad (7)$$

The small a represents the amplitude, the same amplitude as shown by formula 4. In this function, new term cos is introduced, although, Fourier did not come up with this – it was added later, the addition of cos originates from the equation:

$$e^{in\theta} = \cos n\theta + i \sin n\theta. \qquad (8)$$

The addition of this equation introduces the complex term which becomes necessary when calculating power spectral density which is used to analyze random vibrations which are motions at several frequencies at the same time, for instance, during transporting goods. Using FFT to analyze random motions does not provide sufficient data. [28.]

Continuing with the explanations, the FFT can be further written as:

$$F(j\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt. \qquad (9)$$

This is the Fourier transform of a vibration signal where all the signals are located. In this case, the Fourier transform includes both real and imaginary points of a signal, the $f(t)$ is the vibration function itself and the limits are from negative infinite to infinite. This was the first part of obtaining the FFT, the following is changing the Fourier transform into a Discrete Fourier Transform that results in the following formula:

$$F(j\omega) = \sum_{k=0}^{N-1} f[k] e^{-j\omega kT}. \qquad (10)$$

Where N is the number of samples in every period marked as capital T, k can be from zero to infinite and is a part of one function meaning function at the point of N. This is the

Discrete Fourier Transform. However, the method used to analyze vibrations is Fast Fourier Transform.

The necessity of FFT hides in the power of the computer performing the calculations. The DFT has multiplications of N^2. In order to have sufficient overview, often the N is chosen to be 256, however, this will become a problem since 256^2 is a very large number for computers. The FFT is expressed as:

$$F[\mathrm{n}] = \sum_{k=0}^{N-1} f[k]e^{-\frac{j2\pi}{N}nk} \; as \; F[n] = \sum_{k=0}^{N-1} f[k]W_N^{nk} \, . \tag{11}$$

The $j\omega$ term has been substituted with the term n and exponential term e with W. This enables the FFT to have significantly less operations. Therefore, in simplified form the formula the computer uses can be written as such:

$$F[n] = \sum_{k=0}^{N-1} f[k]N\log_2(N). \tag{12}$$

Meaning, if the signal length is 1024, the DFT would need 1048576 operations, whereas, the FFT method would need 10240 calculations, drastically reducing the computing power and increasing the speed of calculations. [29.; 30.]

2.6 Types of Common Vibration Sensors

Measuring vibrations can be done in several ways with different sensors. Some sensors must be attached to the measured object, whereas, others measure vibrations through free space. Despite the fact that there are many several vibration sensors, there are few most common and most effective sensors: displacement, velocity and acceleration.

Displacement sensors are commonly placed near generators to measure shaft motion and internal clearances. Those proximity sensors, as shown in figure 3, detect vibrations through other structures supporting the measurable object. The data comes in as vibration that is relative to the structure that supports or is a part of the vibrating device. The measurable frequency is very low, about 1-100 Hz and at those frequencies, the low-amplitude displacement can be found. For instance, those are used in sleeve-bearing machines which are large industrial turbo-machines like turbines. In those machines the oil is distributed to the connection points. Displacement sensors can also be piezoelectric that are used with rolling element-bearing machines, which can only roll along one axis that are used in electric motors and conveyer systems. Displacement sensors can be either non-contact using magnetic fields or light and contact sensors installed on objects.

Figure 3. Example of contact displacement sensors. [34]

The next most common sensors used for vibrations are velocity sensors, illustrated in figure 4, that are used for vibrations higher than 100 Hz, to be exact, the frequency range is 1-1000 Hz. Compared to displacement sensors, velocity detectors are only mounted onto the machines. Although, those detect higher frequencies, they have lower sensitivity and are more fragile against amplifier overloads. The velocity measurement is done using an electromagnetic coil and a magnet system that generate the velocity signal.

Figure 4. Example of velocity sensor. [35]

Accelerometers, an example is presented in figure 5, are the most preffered motion sensors due to their ability to measure low to very high frequencies.

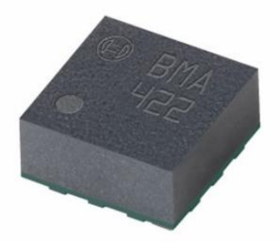

Figure 5. An example of an accelerometer.[36]

These are used in aerospace, automotive and manufacturing systems. In addition, these sensors are often available for application-specific systems. There are numerous types of accelerometers, such as micro-electro-mechanic accelerometer, piezoresistive, piezoelectric, charge mode piezoelectric and voltage-mode internal electronic piezoelectric accelerometers. [7.; 8.; 9.]

2.7 Subtypes of Common Vibration Sensors

Due to the popularity of sensors and to provide a more thorough overview abour vibration sensors, it is prudent to point out the most common subtype ones too and describe them in more detail for the future readers of this study to assist them in their sensor projects.

Micro-electro-mechanical accelerometers are commonly used in smartphones due to their small size and low cost. In addition, they can be mounted directly to circuit boards. However, as frequency and amplitude increase the data quality is degraged more. Despite this, the power consumption is low.

Piezoresistive accelerometers have a strain gauge design that produces resistance changes when the sensor experiences motion. Their benefit is that they measure down to 0 Hz, enabling to calculate velocity and displacement effectively, and have a very wide bandwidth giving them the option to transmit a lot of data quickly. They are excellent for detecting shock-events which happen at high frequencies. However, they are sensitive to temperature increases and decreases, thus requiring special attention to the environment where this sensor is used. Furthermore, due to their expensiveness compared to micro-electro-mechanical accelerometers, they are rarely used for lower frequency measurements.

Piezoelectric accelerometers are the most popular sensors for industrial devices. As a machine accelerates the sensor produces an electric charge which is to be measured. Compared to micro-electro-mechanical and piezoresistive accelerometers, piezoelectric detectors have very low noise and superior performance characteristics. These sensors detect vibrations in one or three dimensions and have a bandwidth from 0 to several thousands of Hertz.

Charge mode piezoelectric accelerometers are used in harsh environments where the temperatures vary a lot between -200C to +400C. Those require charge amplifiers to provide sufficient output data and require shielding for cables.

Voltage mode internal electronic piezoelectric accelerometers share similarities with piezoelectric accelerometers with an exception of having a built-in amplifier, which negates the need for special cables thus decreasing cost. The operating temperature range is from -40C to +125C. [7.]

3 BeGo Bundle and Used Sensors

The sensors used in the practical parts of this work are contact microphone CM01B, dual axis inclinometer LCH-A-D and piezoelectric sensor LDT0-028K. The sensors are integrated into a BeGo Solutions’ ready-made bundle that transmits the data to a file. A more thorough overview about the components follows.

The contact microphone CM-01B has a black sensitive rubber pad - PVDF piezoelectric film on its top which is a chemical called ployvinylidene fluoride with very good performance qualities. Inside it is connected to a low-noise amplifier that outputs a strong enough signal for measurements. The vibration motion hits the central rubber, the oscillation is detected, signal amplified and output via shielded cables to a measurement device. [10.; 11.]

The inclinometer LCH-A-D is a tilt-sensor that measures angles when the device is tilted. The inclinometer is capable of measuring angles in two directions X and Y up to 60°. Inclinometers have similar operating principles as accelerometers, as both use gravitational field and a mass inside the sensor to detect change in the environment and output the data. The LCH-A-D outputs voltages in accordance with the movement of the mass inside the device. There are two sensing elements inside it, thus enabling to measure angles in two directions as mentioned. In addition to sensing elements, there is a processor that converts the received data into angles which is then converted to voltage. [13.]

Contact microphone used in this study, the piezoelectric LDT0-028K vibrating sensor also has a PVDF film which is very thin – 28um. The thin layer is attached to two silver electrodes. However, this sensor is attached to a device so that the leaf vibrates in free space generating high voltages accordingly. The voltages are generated because the leaf changes position from its neutral axis and thus the sensor bends and the bending results in high voltages. This sensor can act as an accelerometer and a vibration sensor, which resonance frequency can be altered by changing the length or adding mass onto the film layer. [12.]

In the later stages of this project the company decided to exchange the inclinometer LCH-A-D with a gyroscope-accelerometer hybrid sensor MPU-6000 because there was no need to have an inclinometer that measures in two axis. Furthermore, the MPU-6000 was fully compatible with the ready-made bundle. The sensor is programmable low-noise gyroscope and accelerometer. It requires 3-5V supply voltage and can be directly connected with an Arduino processor. [31.] The company plans to use this sensor in later stages.

The bundle, shown in figure 6, uses 5V as a supply voltage using an USB cable.

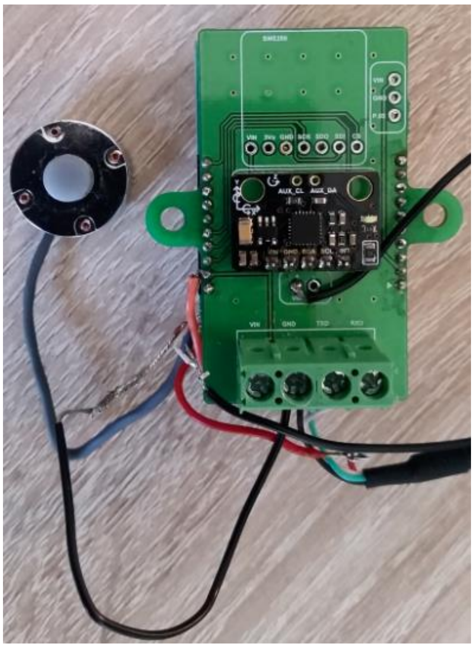

Figure 6. BeGo Solution custom-built bundle.

It has two nests for batteries and a voltage regulator that steps down the input voltage to meet the needs of the devices on the boards. Because this is the BeGo Solutions self-made platform, the details are not discussed.

4 Market Survey

According to BeGo Solutions, by 2022 the market for the product tested in this study will grow significantly. Therefore, a market survey was prudent. The selection criteria was formed on the basis of the pre-selected sensors being contact microphone CM-01B, inclinometer LCH-A-D and piezoelectric sensor LDT0-028K and the guidelines provided by BeGo Solutions. The goal was to select two-three sensors per scope and to use online stores mouser.fi, arrow.com and digikey.fi. Following the results the author provides a market survey summary and suggest a sensor from each scope what could be used first in future developments.

4.1 Criteria for Market Survey

Based on the sensors' characteristics and the guidelines provided by BeGo Solution, universal requirements were formed. The goal was to find similar and better components as used in practical parts. The first criteria is for the contact microphone, given in table 2.

Table 2. Component requirements for a contact microphone. Data gathered from CM-01B [11].

Scope	Requirement
Sensitivity	40dB, +/-10dB
Frequency range	10 Hz -10 kHz
Electronic noise	1 mV pk-pk, +/- 1mV pk-pk
Supply voltage	4-30 V, +/- 1 – 3V
Supply current/Operating current	0.1 mA, max 15mA(LCH-A-D)
Operating temperature	+5 to +60 °C
Installation complexity	Wireless data transfer
Certification	EU - CE, USA - FCC, Apex(hazardous)

Availability/lead time	1 month/2weeks
Size(x, y, z)without wires	18.17,18.17,11.3(mm), +/- 10% mm
Cost per item	45.52€

The next item on the list is a piezoelectric sensor that vibrates in free space. Criteria is given in table 3.

Table 3. Component requirements for a piezoelectric sensor vibrating in free space. Data gathered LDT with Crimps Vibration Sensor/Switch [12].

Scope	Requirement
Sensitivity (average)	425mV/g, +/-10% mV/g
Resonance frequency (average)	110 Hz, +/- 10% Hz
Sensitivity at resonance (average)	8.8V/g, +/- 10%
Operating temperature	0 to +85 °C
Installation complexity	2 pins, must be able to vibrate in free space
Certification	EU - CE, USA - FCC, Apex(hazardous)
Availability/lead time	1 month/2 weeks
Size(x, y, z) with pins	30.1,13.0,<0.125(mm), +/- 10% mm
Cost	5.40€ +10%

Finally, for the inclinometer and an accelerometer the LCH-A-D characteristics, as well as the sensitivity of the piezoelectric sensor were used to form the criteria is in table 4.

Table 4. Component requirements for an inclinometer and/or accelerometer. Data gathered from LCH-A-D-60-05-Inclinometer sensor. [13]

Scope	Requirement
Sensitivity/error rate, inclinometer(degrees) or accelerometer(mV/g)	+/-1°, +/- 10% or 425mV/g(average from LDT0145), +/- 10%
Supply voltage	7-30V, - 10% V
Supply current/Operating current	15mA, <15mA
Operating temperature	-40 to +85 °C
Installation complexity	2 screws, wireless data transfer
Certification	EU - CE, USA - FFC, Apex(hazardous)

Availability/lead time	1 month/2weeks
Size(x, y, z)	39.0,46.0,10.5 (mm), +/- 10% mm
Measuring range	+/-10° to +/-60°, +/- 10°
Cost	75.30£ max

Not all the previously acquired sensor characteristics were used to form the requirements. The scope and criteria were selected based on their universality, meaning these provide a thorough overview yet do not go into the details too much, which would have made the market survey significantly more difficult due to the lack of these kinds of sensors. In addition, the scopes availability and lead time were decided considering the fact that if a component is to be ordered the waiting time would not be long. The requirement ”wireless data transfer” was added because in the later stages BeGo Solutions wants to use their bundles with sensors so that the data is transferred wirelessly to a cloud.

4.2 Market Survey Result

The survey was held from 25.02.2019 to 27.02.2019, thus the components and their data originate from this time period. The found components share the most similarities between the criteria and the sensors' characteristics, despite the fact that few characteristics differ significantly from the formed criteria and the sensors' characteristics. The characteristics of the sensors found from market survey are shown in the same manner as their criteria to later simplify comparison. In addition, each sensor has a general description based on their datasheets.

This CMM-3312AT-44308-TR microelectromechanical – MEMS sensor detects sounds in all directions. It senses audiovibrations via direct contact. Its sensitivity is between -41 to -47 dB with a frequency range from 100 Hz to 10 kHz. A closer look into the characteristics of this sensor is provided in table 5. [14.]

Table 5. Characteristics of CMM-3312AT-44308-TR MEMS Microphone. Data gathered from CMM-3312AT-44308-TR. [14]

Scope	Characteristics
Sensitivity	-47 to -41 dB
Frequency range	100 Hz – 10 kHz

Electronic noise	0.2 %
Supply voltage	1.6 - 3.6 V
Supply current/Operating current	80 μA
Operating temperature	-40 to +100 °C
Installation complexity	Must be soldered
Certification	RoHS
Availability/lead time	Immediately/9 weeks
Size(x, y, z)without wires	3.3, 3.3, 1.2 (mm)
Cost per item	1.35€

Figure 7. CMM-3312AT-44308-TR MEMS Microphone. [14]

Although, its size is quite small, visible in figure 7 where the diameter is 3.3 mm, it does requires soldering and/or wires depending on the design. The frequency response begins from 12 dB at 100Hz and increases to 0 dB at 500 Hz. The sensitivity begins to increase at 5 kHz until 100 kHz. Internally, this sensor includes a capacitor for output and a resistor for voltage source. [14.]

This MEMS CM03OS-0342-A1 sensor is another microelectromechanical microphone sensor with a radio frequency filter. In addition, the datasheet points out three certifications: RoHS indicating the component is lead free, ISO9001:2000 signifiying the international standard and REACH pointing out that the sensor does not include any chemicals that fall under the European Union regulation which lists high-concern substances. The standards as well as other important numerical values are shown in table 6. [15.]

Table 6. Characteristics of MEMS CM03OS-0342-A1. Data gathered from CM03OS-0342-A1 [15].

Scope	Characteristics

Sensitivity	-45 to -39 dB
Frequency range	50 Hz – 35 kHz
Electronic noise	Total harmonic distortion 1 - 10 %
Supply voltage	2.0 V
Supply current/Operating current	70 – 100 uA
Operating temperature	-40 to +100 °C
Installation complexity	Must be soldered
Certification	ISO9001:2000, REACH(EU), RoHS
Availability/lead time	Must be quoted
Size(x, y, z)without wires	3.76, 2.95, 1.1 (mm)
Cost per item	Must be quoted

An illustrative picture of the contact microphone is given in figure 8.

Figure 8. MEMS CM03OS-0342-A1 series.[15]

The sensitivity is highest between 5 kHz and 10 kHz and is about 2.5 dB, at other frequencies it ranges between -45 dB to -39 dB. The microphone is omnidirectional meaning it receives data around itself. The sensor includes an amplifier and a radio frequency filter to further increase the quality of the output signal. It must be pointed out that this device can easily be damaged permanently by static electricity. [15.]

The MiniSense 100NM vibration sensor is the first of the two piezoelectric vibration sensors that vibrate in free space. The cost of this component offers sensitivity up to 65mV/g over a frequency band of 200 Hz. Detection is increased at a resonance frequency at about 360 Hz being 6mV/g. The component has a PVDF sensing layer which has two solderable pins for installation. What makes this sensor durable is its shielded sensor area that increases the rejection from electromagnetic interference. A closer look to the numerical values are shown in table 7. [16.]

Table 7. Characteristics of MiniSense 100NM. Data gathered from 1007158-1 datasheet.

Scope	Characteristics
Sensitivity	65mV/g
Resonance frequency	360 Hz
Sensitivity at resonance	6 mV/g
Operating temperature	-20 °C to +60 °C
Installation complexity	2 pins, vibrates in free space
Certification	RoHS
Availability/lead time	Yes/not specified
Size(x, y, z)	17.8, 7.0, 1.0(mm)
Cost	3.32$

The sensor that vibrates in free space is illustrated in figure 9.

Figure 9. MiniSense 100NM Vibrations Sensor. [16]

This sensor can be installed on machines that output continuous or non-continuous vibrations or even when impacts are measured, such as car crashes or in medical appliances and security devices. Measuring low frequencies can be improved by adding an external circuit accordingly. It is interesting to point out that, although, in the datasheet under description it is written as moderate sensitivity, on the main page the sensor is described as high sensitivity. [16.]

SEN0209 sensor is a combination of a leaf that vibrates in free space and a printed circuit board. The sensor is the LDT0-O28K which is the initially-acquired sensor, but has improved operation. As the leaf vibrates the voltage outputs are from -90V to +90V. With the assistance of the integrated circuit the sensor is able to detect frequencies from 0.001

Hz to 10000 MHz enabling it to use it in a large variety of applications. More specifications in table 8. [17.]

Table 8. Characteristics of Piezoelectric vibration sensor SEN0209. Data gathered from Sen0209[17].

Scope	Characteristics
Sensitivity	Not specified
Resonance frequency	0.001 Hz – 1000 MHz
Sensitivity at resonance	Not specified
Operating temperature	0 to 85 °C
Installation complexity	Requires screws, pins, wires,
Certification	RoHs(leav only)
Availability/lead time	Immediately/not specified
Size(x, y, z)	27, 22, xx (mm)
Cost	5.09€

A representation of the SEN0209 device is given in figure 10.

Figure 10. Vibration sensor SEN0209.[17]

The SEN0209 requires operating voltage of 5V, is Arduino compatible and it can be used as a switch with states on and off. The device comes with one digital cable. Although, the availability and lead times were not shown, it was prudent to add this device to the list as it matched the search criteria closely. [17.]

The accelerometer MXR7305VF is capable of sensing in two dimensions. In addition, this sensor measures dynamic acceleration, that is vibration, and static acceleration meaning gravity. This accelerometer uses heat instead of a center mass to detect acceleration, which is possible because inside the casing the temperature is equal in all four sides in respect to the center. As acceleration happens the temperature profile is disturbed and thus a voltage output is generated. Additional information provided in table 9. [18.]

Table 9. Characteristics of accelerometer MXR7305VF. Data gathered from Memsic Accelerometer Components[18].

Scope	Characteristics
Sensitivity/error rate	250 mV/g
Supply voltage	4.50 – 5.25V
Supply current(operating current)	3.2 to 5.0 mA
Operating temperature	-40 to +95 °C
Installation complexity	Requires wires
Certification	RoHS
Availability/lead time	Immediately/3 weeks
Size(x, y, z)	5.0, 5.0, 2.0 (mm)
Measuring range	+/- 5g
Cost	9.26€

The accelerometer's physical appearance is as in figure 11.

Figure 11. The accelerometer MXR7305VF.[18]

This chip has a sensitivity compensator for temperature differences to increase sensitivity. This component measures in one axis with a very low bandwith about 27 Hz and with the sensitivity of 250mV/g. The sensor requires soldering and does not come with wires, thus the installation is more problematic. Furthermore, another negative side of this component is that as temperature increases the sensitivity decreases in a near-linear motion. Finally, when deployed, it requires an external capacitor between the clock, ground and voltage source connections. [19.]

This programmable ADIS16201CCCZ sensor works as an accelerometer and inclinometer and provides dual axis measurements. The accelerometer method is possible because inside the sensor there are capacitive characteristics that change as acceleration occurs, whereas, the inclinometer calculates the angles using the horizontal plane as a reference value. Most important numerical values are concluded in table 10. [19.]

Table 10. Characteristics of ADIS16201CCCZ. Data gathered from ADIS16201CCCZ [19].

Scope	Characteristics
Sensitivity/error rate	+/- 5 mV
Supply voltage	3.0 – 3.6V
Supply current(operating current)	11 – 14 mA
Operating temperature	-40 to +125 °C
Installation complexity	Requires wires
Certification	RoHS
Availability/lead time	Not specified/12 weeks
Size(x, y, z)	9.2, 9.2, 3.9 (mm)
Measuring range	+/- 90 °
Cost	40.91€

The hybrid sensor appearance is as illustrated in figure 12.

Figure 12. The Accelerometer and Inclinometer ADIS16201CCCZ.[19]

What makes the installation problematic in this case is the necessity of soldering and additional wires. In addition, because it is programmable setting up this sensor would take more time. Regardless, the item was put onto this list due to its similarities with the criteria as well as its diverse functions. [19.]

The G-NSDOG2-001 dual axis sensor measures angles with an integrated filter which increases efficiency enabling to use this sensor in noisy environments. The sensor is also used in building control, vehicle applications and stationary cranes. The inclinometer measures ranges up to +/- 90° with an accuracy of 0.5° in 2 dimensions X and Y. A closer look into the numerical values of this sensor is given in table 11. [20.]

Table 11. Characteristics of the inclinometer G-NSDOG2-001. Data gathered from G-NSDOG2-001 [20].

Scope	Characteristics
Sensitivity/error rate	0.15° to 0.5°
Supply voltage	8-30 VDC
Supply current(operating current)	15 mA
Operating temperature	-40 to +85 ℃
Installation complexity	Requires wires, connectors
Certification	EU – CE, RoHS
Availability/lead time	Immediately/15 weeks
Size(x, y, z)	70.5 ,45, 15 (mm)
Measuring range	+/- 90 °
Cost	109.52€

The sensor is inside a protective case as illustrated in figure 13.

Figure 13. The Inclinometer G-NSDOG2-001.[20]

The installation is simple because it requires only two screws to attach it onto a device. The sensor comes with a cable that can be connected to a connector and to a gateway device. In addition, the voltage transfer characteristic is linear in respect to the increase of the tilt angle. The negative aspects of this device are the significantly large size and the high cost. [20.]

4.3 Problems During Market Survey

During the course of conducting the market survey, many problems were encountered. The most problematic issue was that there were significantly less components available that would fulfill the requirements than expected. In addition, the differences between the used sensors' datasheets and the ones provided in online shops made the selection more challenging. For instance, none of the found components's datasheets included information about the certificates of CE - EU, FFC - USA or any other country or Apex which is for hazardous environments. Furthermore, the installation complexity was another problematic criteria as many sensors similar to the criteria were signifcantly more difficult to integrate with BeGo Solutions existing system meaning many required extra cables, custom circuit board layouts resistors, amplifiers, diodes but also protective casings. It was decided to loosen the criteria on installation complexity, lead time, availability and cost per item. Furthermore, many components shown in online shops were discontinued or had insufficient datasheets, some products were given on the named websites, although, were only purchasable on other sites. On few occasions the price of the component was only accessible via quotation.

4.4 Comparison of Market Survey and Criteria

This chapter compares the sensors' characteristics with the formed criteria that was used to find components for future development purposes. The frst column specifies the theme of the criteria, the second column specifies the criteria formed before market survey and the third column provides the characteristics of the sensor.

The first category is contact microphone and the first sensor is CMM-3312AT-44308-TR MEMS, compared in table 12.

Table 12. Requirements versus CMM-3312AT-44308-TR MEMS. Data gathered from table 2 and table 5.

Scope	Requirement	MiniSense 100NM
Sensitivity (average)	40dB, +/-10dB	-47 to -41 dB
Frequency range	10 Hz – 10 kHz	100Hz – 10 kHz
Electronic noise	1 mV pk-pk, +/- 1mV pk-pk	0.2%
Supply voltage	4-30 V, +/- 1 – 3V	1.6 - 3.6 V
Supply current/Operating current	0.1 mA, max 15mA(LCH-A-D)	80 μA
Operating temperature	+5 to +60 °C	-40 to +100 °C
Installation complexity	Wireless data transfer	Must be soldered
Certification	EU - CE, USA - FCC, Apex(hazardous)	RoHS
Availability/lead time	1month/2 weeks	Immediately/9 weeks
Size(x, y, z) with pins	18.17,18.17,11.3(mm), +/-10% mm	3.3, 3.3, 1.2 (mm)
Cost	45.52€	1.35€

The electronic noise is defined differently in the datasheet as the requirement specifies. However, in terms of numerical values 0.2% of signal distortion is insignificant. The sensitivity, supply voltage and operating temperature meet the criteria. However, the installation complexity differs a lot – the data transfer is possible only via wires. The component only holds RoHS certification. The size is well below the maximum size of the requirement and well below the maximum value is the cost per item as well.

The next component found while conducting the market survey is the contact microphone MEMS CM03OS-0342-A1 given in table 13.

Table 13. Requirements versus MEMS CM03OS-0342-A1. Data gathered from tables 2 and 6.

Scope	Requirement	CM03OS-0342-A1

Sensitivity	40dB, +/-10dB	-45 to -39 dB
Frequency range	10 - 10 kHz	50 Hz– 35 kHz
Electronic noise	1 mV pk-pk, +/- 1mV pk-pk	Total harmonic distortion 1 - 10 %
Supply voltage	4-30 V, +/- 1 – 3V	2.0 V
Supply current/opera-ting current	0.1 mA, max 15mA(LCH-A-D)	70 – 100 uA
Operating temperature	+5 to +60 C	-40 to +100 °C
Installation complexity	Wireless data transfer	Must be soldered
Certification	EU - CE, USA - FCC, Apex(hazardous)	ISO9001:2000, REACH(EU), RoHS
Availability/lead time	1 month/2weeks	Must be quoted
Size(x, y, z)without wi-res	18.17,18.17,11.3(mm), +/-10% mm	3.76, 2.95, 1.1 (mm)
Cost per item	45.52€ max	Must be quoted

In this case the frequency range exceeds the limit by 3.5 times. The electronic noise in terms of numerical values is relatively insignificant being maximum of 10%. The supply voltage as well as the supply/operating current are well below the criteria. In addition, the operting temperature meets the requirements. However, the certifications do not, although, three other certifications are provided that increase the credibility of the component. The availability and the lead time can be obtained by making a quote for the company. The size is well in the limits. The cost is unknown but can be clarified if quoted.

The piezoelectric vibration sensor MiniSense 100NM is compared in table 14.

Table 14. Requirements versus MiniSense 100NM. Data gathered from table 3 and table 7.

Scope	Requirement	MiniSense 100NM
Sensitivity (average)	425mV/g, +/-10% mV/g	65mV/g
Resonance frequency (average)	110 Hz, +/- 10% Hz	360 Hz
Sensitivity at resonance (average)	8.8V/g, +/- 10% Hz	6 mV/g
Operating temperature	0 to +85 °C	-20 to +60 °C

Installation complexity	2 pins, must be able to vibrate in free space	2 pins, must vibrate in free space
Certification	EU - CE, USA - FCC, Apex(hazardous)	RoHS
Availability/lead time	1month/2 weeks	Yes/not specified
Size(x, y, z) with pins	30.1,13.0,<0.125(mm), +/- 10% mm	17.8, 7.0, 1.0
Cost	5.40€ +10%	3.32$

To start with, the sensitivity mV per g is more than 10% bigger for MiniSense 100NM than the criteria specified. Although, at 3g the criteria was 800mV/g, the sensor would give 195mV/g making the sensitivity at 3g significantly better than the criteria specified. When comparing the resonance frequency, the MiniSense datasheet does not specify at what g is the 360 Hz and thus it is not sufficient to compare it with the criteria. The next requirement was the operating temperature where the MiniSense is approximately 20°C lower than specified. The installation complexity is in accordance with the criteria that it must be able to vibrate in free space and has to have two pins. Whereas, with certifications, the MiniSense only has RoHS. With availability, the sensor can be ordered instantly; if the stock is empty, it is not clear how long would it take to manufacture new components. The size of the MiniSense is roughly twice as smaller as the criteria thus fulfilling the requirement. Finally, the cost also falls under the criteria making it about 2.5€ less expensive.

The next component to be compared is the vibration sensor SEN0209. It must be clarified that the SEN 0209 is a combination of a printed circuit board, a microcontroller and the sensor with slots for wires - this and other informaton is given and compared in table 15.

Table 15. Requirements versus SEN0209. Data gathered from tables 3 and 8.

Scope	Requirement	SEN0209
Sensitivity (average)	425mV/g, +/-10% mV/g	Not specified
Resonance frequency (average)	110 Hz, +/- 10% Hz	0.001 – 1000 MHz
Sensitivity at resonance (average)	8.8V/g, +/- 10% mV/g	Not specified

Operating temperature	0 to +85 °C	0 to 85 °C
Installation complexity	2 pins, must be able to vibrate in free space	Requires screws, pins, wires,
Certification	EU - CE, USA - FCC, Apex(hazardous)	RoHs(lead only)
Availability/lead time	1month/2 weeks	Immediately/not specified
Size(x, y, z) with pins	30.1,13.0,<0.125(mm), +/-10% mm	27, 22, xx (mm)
Cost	5.40€ +/-10%	5.09€

The sensitivity of the SEN0209 is not given failing to meet the criteria. In addition, the resonance frequency is not specified, although, the operating frequency range is. On the basis of the operating frequency range it can be said the component nearly falls under the criteria. Following that, the sensitivity at the resonance frequency is not determined. However, the operating temperature is equal to the one provided in the criteria. The installation complexity is similar in terms of connecting the sensor with another device with wires. RoHS is the only certification provided for the component, any other certifications or standards are not given on the online shop and on the datasheet. Although, SEN0209 can be shipped immediately, the lead time is unknown. At the time of registering the component there were few in the stock and shipping to the customer could take place immediately, whereas, no lead time was mentioned. It could be said the size of the SEN0209 fills the requirement except the hight of the component is unknown. And finally, the cost meets the excpectation.

Moving on to the accelerometer/inclinometer comparisons, the first in line is the MXR7305VF as shown in table 16.

Table 16. Requirements versus MXR7305VF. Data gathered from table 4 and table 9.

Scope	Requirement	MXR7305VF
Sensitivity(accuracy i.e error rate)	+/-1°, +/- 10% or 425 mV/g	250 mV/g, +/-1 g to +/- 70g
Supply voltage	7-30V, - 10% V	4.50 – 5.25V
Supply current/Operating current	15mA	3.2 to 5.0 mA

Operating temperature	-40 to +85 °C	-40 to +95 °C
Installation complexity	2 screws, wireless data transfer	Requires wires
Certification	EU - CE, USA - FFC, Apex(hazardous)	RoHS
Availability/lead time	1 month/2weeks	Immediately/3 weeks
Size(x, y, z)	39.0,46.0,10.5 (mm), +/- 10%	5.0, 5.0, 2.0 (mm)
Measuring range	+/-10° to +/-60°, +/- 10°	+/- 5g
Cost	75.30£ max	9.26€

Beginning with the sensitivity, it is clear that those do not match because the criteria was set in angles and degrees, whereas, the MXR7305VF provided a mV/g numerical values. Although, it is logical because the angles and degree requirement is for an inclinometer. The accelerometer and inclinometer share similarities and accceleration can be measured with inclinometer work methods. Continuing with supply voltage and current the requirements are met where the supply voltage for the sensor is lower than the criteria. Operating temperature falls under the limits, whereas the installation complexity does not due to the sensor requring wires, yet the criteria was wireless data transfer and attaching the component with two screws. The accelerometer only has RoHS certification. The size fits and cost are within limits. However the measuring range is defined differently.

The next component ADIS16201CCCZ operates as an accelerometer and an inclinometer. The comparison between criteria and the ADIS16201CCCZ is shown in table 17.

Table 17. Requirements versus ADIS16201CCCZ. Data gathered from tables 4 and 10.

Scope	Requirement	ADIS16201CCCZ
Sensitivity(accuracy i.e error rate), inclinometer or accelerometer	+/-1°, +/- 10% or 425mV/g	+/- 5 mV
Supply voltage	7-30V, - 10% V	3.0 – 3.6V
Supply current/Operating current	15mA	11 – 14 mA

Operating temperature	-40 to +85 °C	-40 to +125 °
Installation complexity	2 screws, wireless data transfer	Requires wires
Certification	EU - CE, USA - FFC, Apex(hazardous)	RoHS
Availability/lead time	1 month/2weeks	Not specified/12 weeks
Size(x, y, z)	39.0,46.0,10.5 (mm), +/- 10%	9.2, 9.2, 3.9 (mm)
Measuring range	+/-10° to +/-60°, +/- 10°	+/- 90 °
Cost	75.30£ max	40.91€

Although, the sensor acts both as an inclinometer and an accelerometer, the sensitivity was shown only in mV. The supply voltage and the supply current/operating current meet the requirement and operating temperature. Installation complexity, however, does not as it requires wires for transferring the output. The component only has the RoHS certification and the availability is not defined, although, the sensor is manufactured within 12 weeks. The size and 30° larger measuring range fill the excpectations. Finally, the cost is about two times lower than the maximum limit.

The final component under the category of accelerometers/inclinometers is an inclinometer G-NSDOG2-001 compared in table 18.

Table 18. Requirements versus G-NSDOG2-001. Data gathered from table 4 and table 11.

Scope	Requirement	G-NSDOG2-001
Sensitivity(accuracy i.e error rate), inclinometer or accelerometer	+/-1°, +/- 10% or 425mV/g	0.15° to 0.5°
Supply voltage	7-30V, - 10% V	8-30 VDC
Supply current/Operating current	15mA	15 mA
Operating temperature	-40 to +85 °C	-40 to +85 °C
Installation complexity	2 screws, wireless data transfer	Requires wires, connectors

Certification	EU - CE, USA - FFC, Apex(hazardous)	EU – CE, RoHS
Availability/lead time	1 month/2weeks	Immediately/15 weeks
Size(x, y, z)	39.0,46.0,10.5 (mm), +/-10%	70.5 ,45, 15(mm)
Measuring range	+/-10° to +/-60°, +/- 10°	+/- 90 °
Cost	75.30£ max	109.52€

This inclinometer meets very well the sensitivity criteria as well as the supply voltage and operating current requirements. In addition, the operating temperature is met as well. However, the installation complexity is not as for data transfer the sensor must have wired connections. The sensor has CE and RoHS certifications which simplfies documentation requirements in EU. Although, the availability is met, the lead time is exceeded over seven times. Furthermore, the size is about twice larger and the cost is slightly higher.

4.5 Market Survey Conclusion

The survey resulted in seven options: two devices for piezoelectric vibration sensor, three for the accelerometers and/or inclinometers and two for contact microphone. However, in each scope the components differ. To provide a simpler starting point for future development one sensor from each scope is suggested.

The first option comes from piezoelectric sensors being the MiniSense 100NM sensor. The differences between this and the SEN0209 are significant, for instance, the sensitivity and the sensitivity at resonance were not specified in SEN0209 datasheet. Furthermore, to integrate the SEN0209 to an existing system requires additional resources such as wires but also time to program and make the device compatible with an existing system making it the second option and the MiniSense 100NM the priority.

The second sensor option for an accelerometer and/or inclinometer has two options that depend on the goal of the future development. If the aim is to build an inclinometer vibration sensing device then the selection is G-NSDOG2-001 because it meets with the sensitivity, supply voltage and supply current but also with operating temperature and some of the certifications requirements. For the accelerometer the option is MXR7305VF which has a significantly better sensitivity than the criteria, supply voltage, as well as the supply current fall well below the criteria and the price is drastically lower than the maximum limit.

Finally, for the contact microphone the suggestion is the MEMS CM03OS-0342-A1. Although, the sensitivity and total harmonic distortion but also the supply voltage and supply current are higher than the CMM-3312AT-44308-TR MEMS characteristics. What speaks for the former one is the larger frequency range and the certification data.

Despite the bundle does not consist the LCH-A-D and LDT0-028K, considering the growing market, the market survey provides options for future development purposes that are compatible with the BeGo Solution custom-made bundle.

5 LabView Applications and Its Main Functions

The goal of this study is to find out is it possible to build an entry-level application that analyzes vibrations using Fast Fourier Transform method. The application was built in NI LabView. In the later stages of this research BeGo Solutions decided to focus on basic FFT analysis and data accuracy and after this study to continue with advanced analysis in LabView. For this reason, this chapter includes the functions that were added in the early stages to the application, although, will only be used after this study.

5.1 Main Functions in Initial and Used LabView Applications

The application used for testings is given in appendix 1, where the first part is the functional block diagram and the second is the front panel used for presenting the graphs and giving commands for the application. Appendix 2 was the initial application designs that will be used after this study. However, these were built before it was decided to use only contact microphone and basid FFT analysis.

The averaged FFT, symbolised in figure 14 and shown in appendix 2, analyzes the vibrations by using Fast Fourier Transform method.

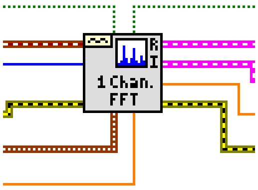

Figure 14. Averaged FFT symbol in the application.

The FFT function holds many parameters that enable better data filtering but also determine the amount of data transferred to this function.This function calculates the average FFT spectrum of a time signal. In addition, it can output both real and imaginary parts. Because the incoming data and output data is in frequency domain, window functions play a crucial role.

FFT uses a finite set of data over an integer number of periods, four periods. However, often measured oscillations are not in an integer number of periods, for example, 4.25 periods. This affects the analysis and results in a spectrum that has different characteristics than that of the original motion signal. The outcome is that on the spectrum diagram, those anomalies have significantly higher values than the Nyquist frequency which is the highest possible frequency that the measured signal can represent. The Nyquist frequency is half of the sampling frequency which itself determines how many samples are to be taken over a specified time duration. [21.; 22.]

The FFT function captures a signal fragment from a signal within a specified time interval and is re-created to match the original signal as shown in figure 15.

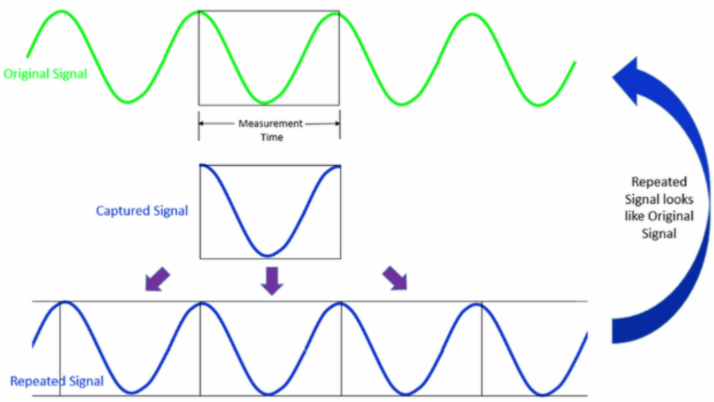

Figure 15. FFT functioning in LabView.

As seen in figure 15, the original motion is marked with green, the captured motion in a short blue waveform and the final result is a reconstructed oscillation named "Repeated Signal". However, the start and end timing can likely be non-integer values which when analyzed the re-created wave has sharp transients pointed out in red circles in figure 16.

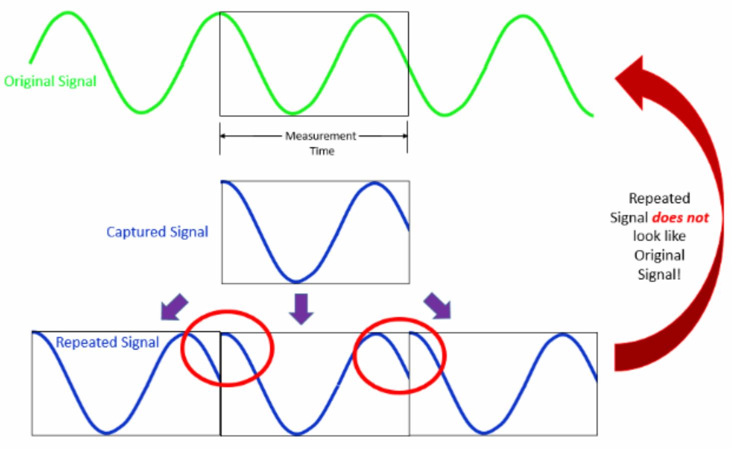

Figure 16. FFT functioning in LabView.

Analyzing those transients and outputing them to a diagram, the signal results span around the point of the frequency, known as leakage, instead of a single result. Windowing reduces the sharp transients by smoothing the re-created waveform, however, the transients do not entirely dissapear. [24.;25.; 32.]

The window function in the application is illustrated in figure 17 used in LabView application shown in appendix 2.

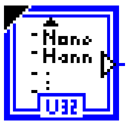

Figure 17. Window symbol in LabView.

For the user a different symbol is shown illustrated in figure 18.

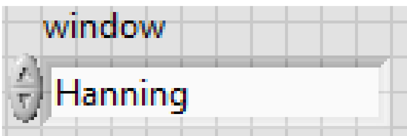

Figure 18. Window selection symbol.

There are many window types each having their own specific drawbacks and merits. Common window functions for vibration analysis are Hamming, Hanning, Rectangular and Flat top. NI has provided explanations about all window functions given in table 19.

Table 19. Different Window functions. Copied from Software filtering: Windowing – General Analog Concepts. [23.]

Type of Signal	Window
Transients whose duration is shorter than the length of the window	Rectangular
Transients whose duration is longer than the length of the window	Exponential, Hanning
General-purpose applications	Hanning
Spectral analysis (frequency-response measurements)	Hanning (for random excitation), Rectangular (for pseudorandom excitation)
Separation of two tones with frequencies very close to each other but with widely differing amplitudes	Kaiser-Bessel
Separation of two tones with frequencies very close to each other but with almost equal amplitudes	Rectangular
Accurate single-tone amplitude measurements	Flat top
Sine wave or combination of sine waves	Hanning
Sine wave and amplitude accuracy is important	Flat top
Narrowband random signal (vibration data)	Hanning
Broadband random (white noise)	Uniform
Closely spaced sine waves	Uniform, Hamming
Excitation signals (hammer blow)	Force
Response signals	Exponential
Unknown content	Hanning

Despite the many options and their functions, what kind of a window function to choose is a difficult task, yet there are some recommendations provided by NI what to bear in mind when choosing a window.

The bulleted list below is retaken from Software filtering: Windowing – General Analog Consepts. [23.]

1. If the signal contains strong interfering frequency components distant from the frequency of interest, choose a smoothing window with a high side lobe roll-off rate.
2. If the signal contains strong interfering signals near the frequency of interest, choose a window function with a low maximum side lobe level.

3. If the frequency of interest contains two or more signals very near to each other, spectral resolution is important. In this case, it is best to choose a smoothing window with a very narrow main lobe.
4. If the amplitude accuracy of a single frequency component is more important than the exact location of the component in a given frequency bin, choose a window with a wide main lobe.
5. If the signal spectrum is rather flat or broadband in frequency content, use the uniform window, or no window.

Those are the main things to consider when applying a window. Fortunately, the Hanning window works with most of the transients, thus, if it is not clear what window to choose, Hanning is an effective function to use. It is good practise to first conduct the analysis without a window function and after that, if necessary, with a window. [23.]

Beside the averaged FFT function, a function illustrated in figure 19, is added to the application that calculates normal FFT of input sequnce. Function also used in applications shown in appendices 1 and 2.

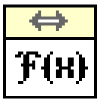

Figure 19. FFT function that computes the input data.

Using the function given in figure 19 the phase is seen by using a series of functions such as Rectangular To Polar that Unwrap Phase to show the phase values. Although, the FFT function shown in figure 14 provides an output for a magnitude graph, for the function shown in figure 19 it is necessary to take the logarithm with a base of twenty to convert the values into the correct form. [33.]

The vibration data is gathered from a CSV file which is an Excel program dataformat. The data is opened using File Path Control function, shown in figure 20, where the file must be placed from a computer to start the analysis. Following the file opening, the data is transferred to a Read From Datasheet that gathers the data from the specified file in File Path. This function is shown in appendices 1 and 2.

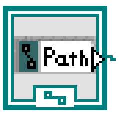

Figure 20. File Path Control.

The function requires the user to specify a file path by browsing the computer for the data file. The function opens the file for reading. For the user, only the symbol in figure 21 is visible.

Figure 21. File path function visible for the user.

The function that reads the data is Read From Delimited Spreadsheet function, visible in figure 22, that scans, reads and outputs the data inside the CSV file. This function is shown in appendices 1 and 2.

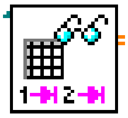

Figure 22. Read From Delimited Spreadsheet function in LabView.

The above named functions make it possible to analyze sensor data. The averaged FFT and the Window function will be used after this study. The next chapter explains the custom-built application working method.

5.2 The Working Principles of the Initial and Used LabView Applications

The initial LabView application to be used is given in appendix 2. However, in the later stages it was decided to focus on basic FFT analysis given in appendix 1. Although, much work was done prior to the decision, functions that would be used for inclinometer and vibrating leaf sensor in future development are also explained.

The initial application shown in appendix 2 which is divided into two parts: functions for the inclinometer and function block for the contact microphone and vibrating leaf. The inclinometer program begins with a specify-file-path-function after which the user-specified CSV file is read by Read from Spreadsheet function. The latter function has an addition: depending on how the data is separated in the CSV file, the delimiter must be specified accordingly. The word “Double” indicates the data read is in non-integer form. Following that because it is an array of data, it must be read element by element, thus an Index Array function is added which is followed by X and Y indicators representing the vibration data. In terms of the used inclinometer, X is the voltage data from X coordinate and Y is the voltage data from Y coordinate. This is followed by a Bundle which is necessary to visually represent the data on a graph. In addition to the named functions, the application includes two While Loops. As data comes in, the loops are activated. Both loops are identical. First loop is for X values, the other one for Y values. Both include a Power Spectrum Density analyzation and a window function selection as well as a numerical representation to further simplify reading exact numerical values from the graph. Both have a button to see the magnitude in dB and a stop button to stop the data reading in those loops.

The vibrating leaf sensor and contact microphone program also begins with a file path where the user must specify the datafile consisting of vibration data. Following that the program reads the CSV file after which the data is transferred to an Index Array function to transform the data which is in array form into individual elements to be analyzed element by element. The elements are analyzed in the same manner as data from inclinometer.

The largest While Loop begins with a function where the user can choose which sensor data to use. First analysis block analyzes FFT of both real or real and imaginary data. Whatever the format, the data is then transferred to the FFT, from there to a function block that transforms the complex data into rectangular components that are multiplied by the number of samples in the datafile. The user must specify the number of samples. Following that, the real and imaginary parts can be seen individually in numerical forms or by transferring the real and imaginary parts separately to Array Subset to show them on graphs.

The second function block, appendix 2 block diagram, determines what kind of a filter the vibration data looks like both in real or real and imaginary parts. This can be useful when analyzing vibration data. The graphs would be similar to filters to simplify understanding and perhaps ease the design of a new device that would not emit unwanted frequencies. This application shows the prototype design would emit high or low or band-pass filter type vibrations, for example. The data from CSV is transferred to Array Subset because it combines the samples number times 0.5 and increased by one to transfer the complex data to Rectangular To Polar function. From there to graphs where one shows magnitude and the other with the logarithm base of twenty decibels [33].

The third function block in the largest While Loop, appendix 2 block diagram view, is the averaged FFT values and Power Spectrum Density. Those give a thorough approximation about vibration analysis that can quickly be taken as a basis of general results. In both functions the user can choose a window function for better graphs.

For the contact microphone both applications - the used and the initial, given in appendices 1 and 2, built and used in this study begin with a file path function where the user locates and inputs the data file. In addition, the user must specify the number of samples in the data file. After that, user presses “Play” button marked as a white arrow and the data is read in Read From Delimited Spreadsheet function. Used application then continues to Index Array and from there to Array Subset to change the data into a format that can be multiplied with an amplitude of A equaling 0.25, per wish of the company, is added to the function y. Data is then multiplied with sinewave function and the number of times as there are samples. This multiplication is done in a For Loop that executes the multiplication as many times as there are samples. Finally, the data is output to FFT function that performs the vibration analysis and is transferred to a graph.

6 Tests With BeGo Solutions’ Bundle, Sensors and LabView

The remaining practical parts were testing the bundle with contact microphone CM-01B in different test cases and using received data in the custom-built LabView program for analysis. The tests were divided into two parts: testing CM-01B with heart pulses to check the functionality of the system and mounting and testing the sensor on an active pump with different inputs to mimic data available in industrial locations.

6.1 Testing CM-01B With BeGo Solutions’ Bundle and LabView Application

This chapter focuses on testing the contact microphone CM-01B with BeGo Solutions’ bundle in different test cases. In addition to the functionality of the contact microphone, the LabView application built during this study is also tested using the sensor data. In total there were four test cases. All tests included a water-filtering pump to mimic a motor with a rotating cylinder. The LabView application only provides FFT analysis because in later stages it was decided to focus on FFT analysis and in later stages after this study continue adding functions such as averaged FFT, PS and analysis for imaginary and real parts of vibration data gathered from vibrating leaf and indlinometer/accelerometer.

In the first test an active water-filtering pump was tested. The sensor was measured for approximately sixty seconds and the data was gathered to a CSV file using Realterm software and Excel, and analyzed in LabView. In Excel the data was filtered to have only ones and fives as values. Fives signified the highest values and the rest was converted to ones. After that in every case, the data was multiplied with sine function because as equations 1, 2, 3 and 4 show, mathematically vibrations are expressed with sine waves. Figure 23 illustrates the processed data of fives and ones before FFT analysis.

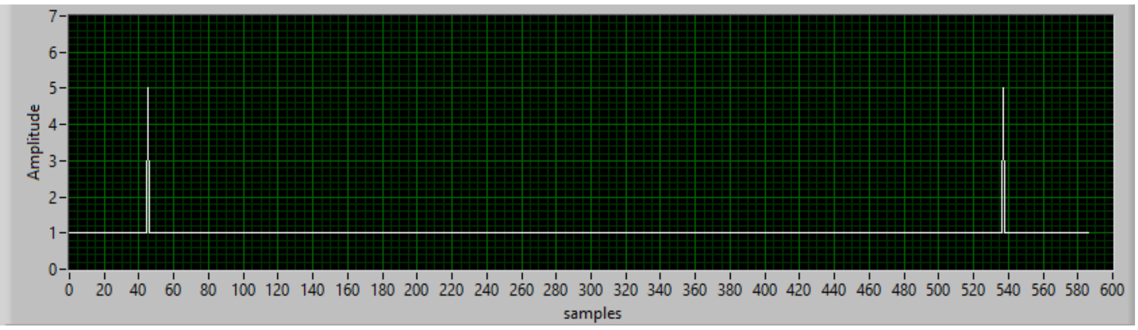

Figure 23. Water filtering vibration data after conversion.

Figure 23 shows the water filtering vibration data after converting highest values to fives and the remaining values to ones. Following that the data was multiplied with a sinewave function before performing FFT. The results are illustrated in figure 24.

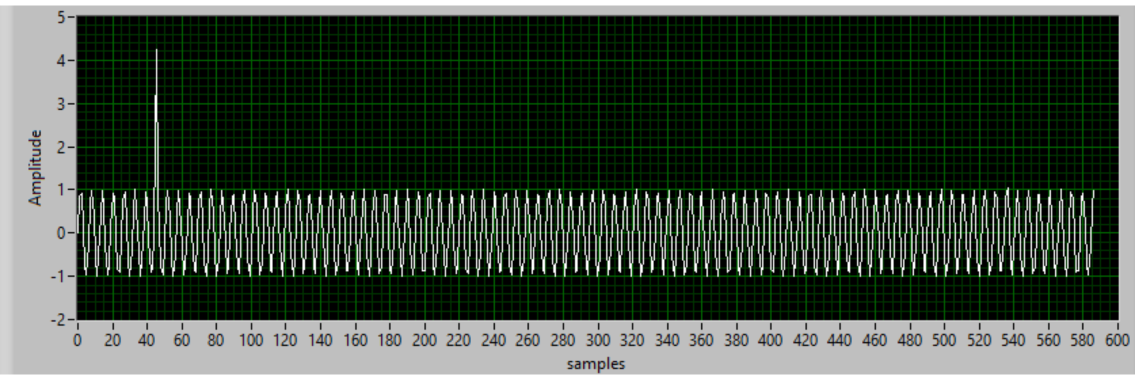

Figure 24. Water filtering vibration function.

In figure 24 there is visible one harmonic at 45th sample, however, the second harmonic, seen in figure 24, is not. There is a harmonic at 537th sample with a slightly higher amplitude indicating the second spike in the vibration data. Finally, the data in figure 24 was transferred to an FFT and the results are illustrated in figure 25.

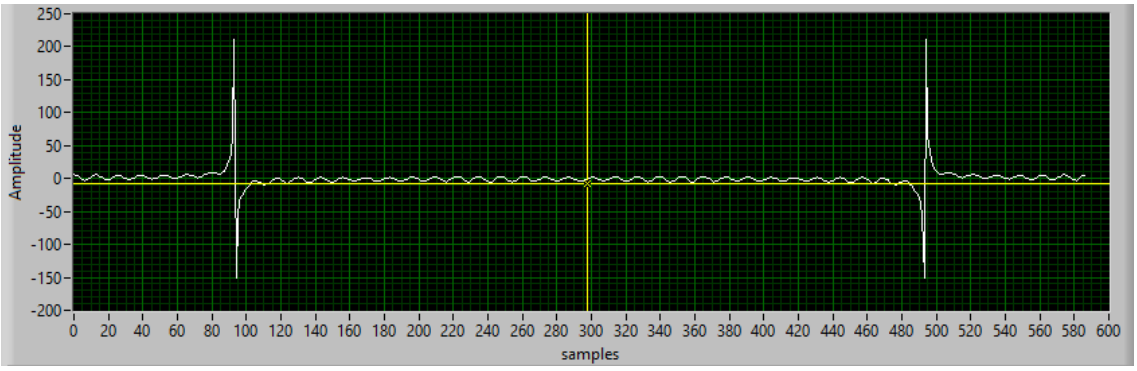

Figure 25. FFT analysis of water filtering data.

Graph on figure 25 suggests that there are some disturbances in the system shown by the vibrating waveform. If there would be no disturbances the graph would not oscillate. The amplitude of oscillations is 10 units from -5 to 5. The two spikes are mirror images and their sample value indicates the number of normal sinewaves on figure 24. The next test was done using heart pulse with the following results in figure 26.

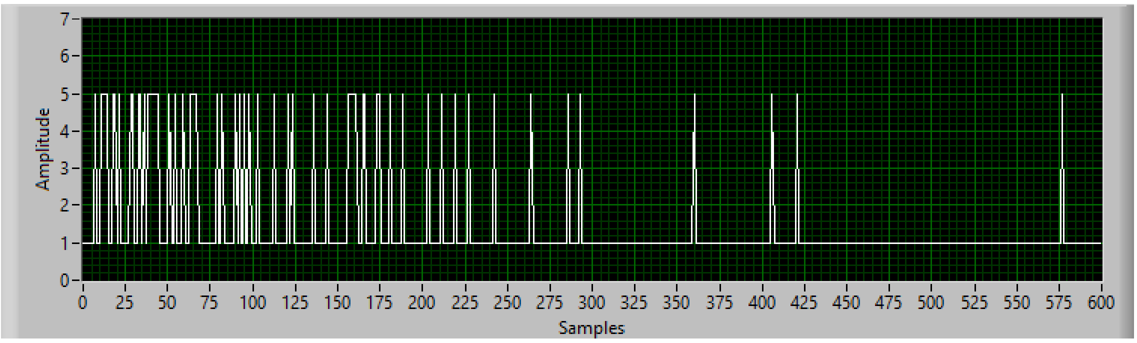

Figure 26. Heart pulse data converted to 1s and 5s.

The heart pulses have an amplitude of 5 and the rest have amplitude of 1 in figure 26. As seen, during the 600 sample and 60 second period, a portion of heart pulses are not visible. Possible reasons are that in the later stages of the measurement the sensor was slightly moved from place and/or the sensor was not pushed enough to pulsating area to detect the heart pulses. Following that, all the sample points were multiplied by a sine wave function before analyzing with FFT method. This is necessary to capture the abnormalities as a vibration function. The results are shown in figure 27.

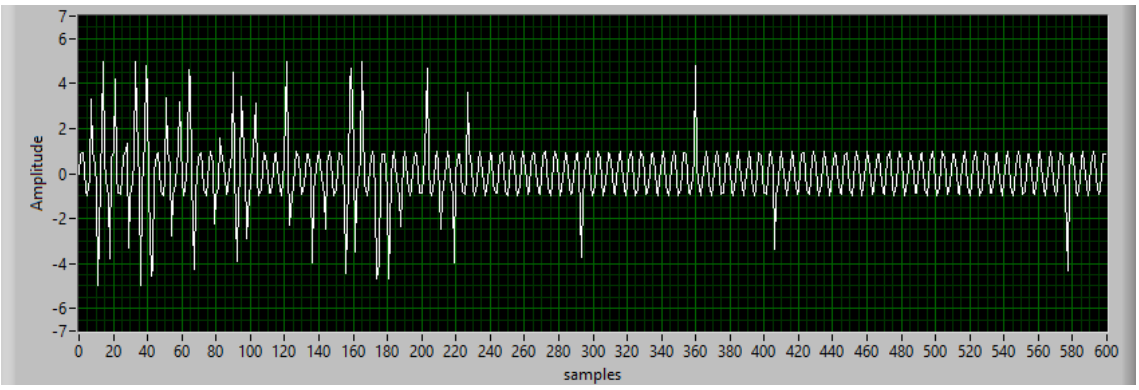

Figure 27. Heart pulse after sine wave function multiplication.

As seen from figure 27, the sinewave was multiplied by every point in the file forming an oscillation, the entire vibration function, where the majority of sinewave amplitude ranges between 1 and -1. The other spikes, or harmonics, have a larger amplitude ranging from -5 to 5 which are the heart pulses from figure 26. The last step was to use FFT on the data shown in figure 26 that generated the graph in figure 28.

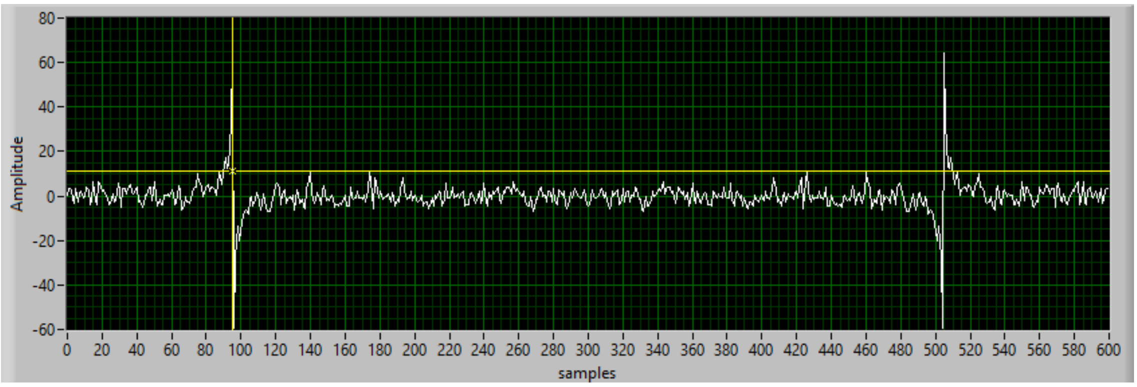

Figure 28. FFT from heart pulse data.

The first significant harmonic with value of 95 indicates the number of normal full sinewaves in figure 26 before FFT was performed. There were 65 harmonics that had a value larger than 1 or less than -1. If those 65 values would be added to 95 the result is

160 specifying the number of full sinewaves during a 60 second period. Each pulse was two samples long at amplitude 1 and after each pulse the pause was five samples, thus during a 60 second and 600 sample period, for a normally operating heart, there should be three pulses for every full sine wave in figure 27. The amplitude ranges from -31 to 44 without considering the high harmonics. Due to the oscillations in FFT result, the next step would be to use a power spectrum graph to show at what frequencies disturbances occur. This step could be one option to extend this study. Because this test was done using heart pulses, the actual disturbances would be pulses that occur after different periods.

The third test was done using dirt-water mixture in water-filtering pump. After the sensor data as filtered the results in figure 29 were obtained.

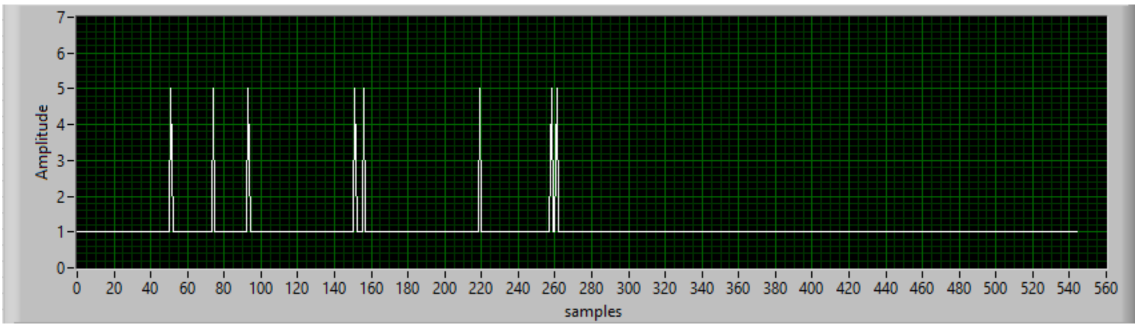

Figure 29. Water-filtering vibrations with water-dirt mixture.

From figure 29 it is clear there are eight amplitudes that had a higher value then other vibration data. The disturbances happened at irregular intervals. It could be explained that during the first half of the measurement the dirt was causing significantly more disturbances than during the second half-time. After the preliminary data filtering, it was multiplied with sinewave function outputting the graph in figure 30.

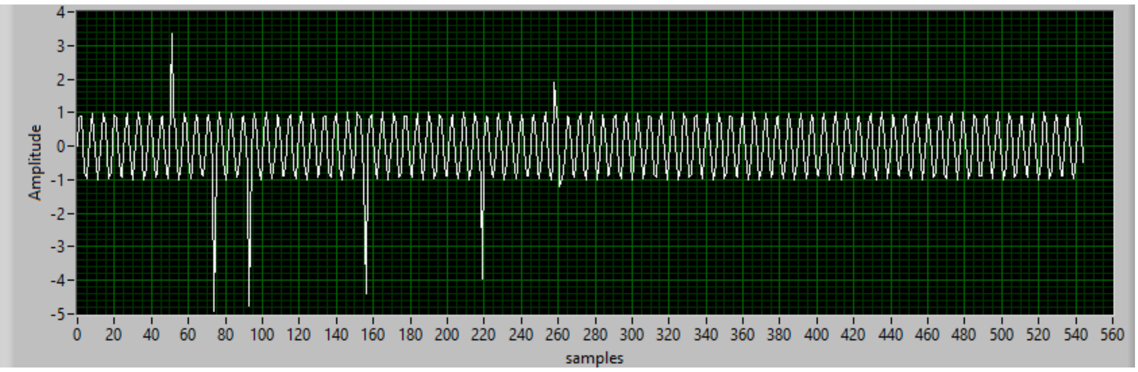

Figure 30. Water-dirt mixture filtering data after sinewave multiplication.

After multiplying the data in figure 29, the vibration function was obtained as in figure 30. After this step there are seven harmonics, whereas in figure 29 there are eight. It is likely that the sinewave function in LabView uses different calculations. This becomes apparent in the last test case where both Excel and LabView were used for analysis.

The last step of this test case was to apply the FFT to the data illustrated in figure 30. The results are provided in figure 31.

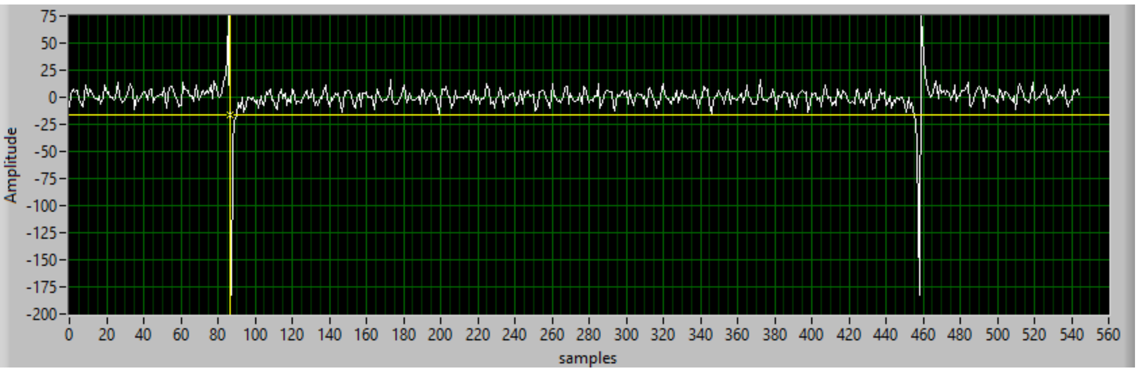

Figure 31. Water-dirt mixture filtering data after applying FFT.

In figure 31 the vibration function has an amplitude from -16 to 16. The largest harmonic has a sample value of 87 indicating the number of normal full sinewaves in figure 30. Compared to the FFT analysis on figure 28, the current FFT resulted in smaller amplitude indicating the disturbances in the system are smaller than with heart pulse data.

The final test was done by knocking the pump at every five seconds. Knocks occur in diesel engines from low-quality fuel or low engine compression which can generate excessive vibrations, thus damaging the motor and its environments [25]. Figure 32 shows the registered knockings.

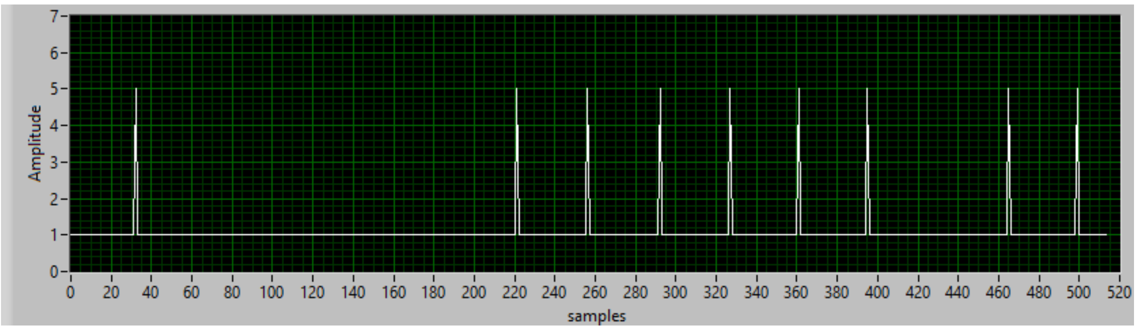

Figure 32. Vibrations from knocking the pump.

From figure 32 it can be said that most of the knockings were sensed. Some of the data was not measured possibly because each knocking was at a slightly different place. Next, the data was multiplied with a sinewave to form the vibration function shown in figure 33.

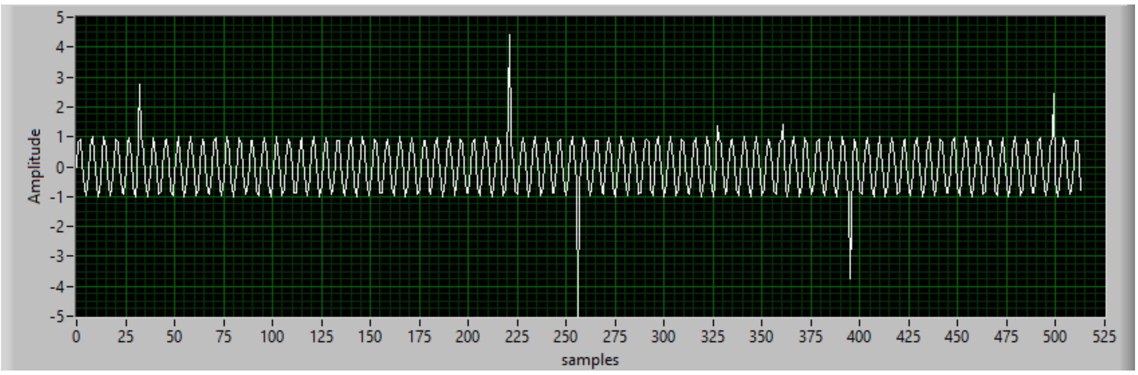

Figure 33. Knocking data after applying sine wave and amplitude multiplications.

It is clear from figure 33 that there are seven abnormalities that respond to knockings. The largest amplitude value is approximately 4.5 and the lowest -5. In this measurement the number of samples was 512. Following that the FFT seen in figure 34.

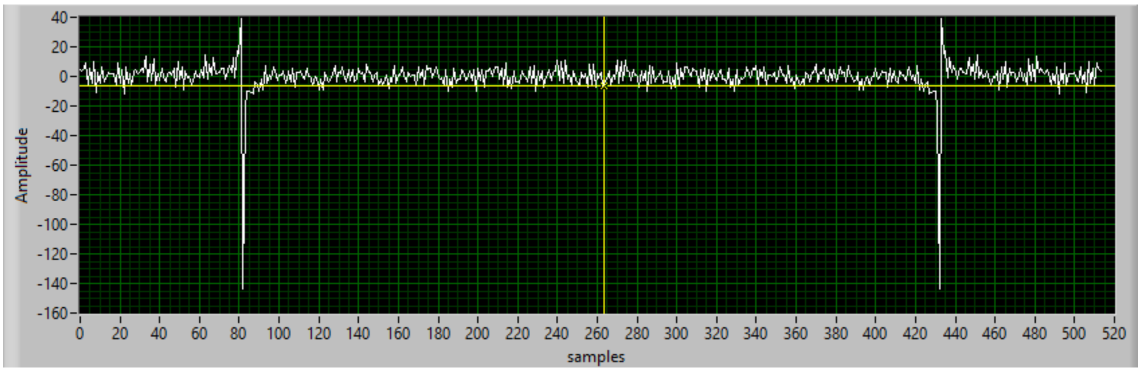

Figure 34. Results after applying FFT to knocking data.

In figure 34 the x coordinate or sample value is 82 which is equal to the number of full sinewaves without abnormalities. The average amplitude of the oscillations without the high harmonics in the vicinities of samples 82 and 433 varies between 10 and -13. In this test case it was decided to compare the data with information analyzed in Excel to see if the FFT performs differently. The following figure 35 is the knocking data after multiplying it with a sinewave to form the vibration function in Excel.

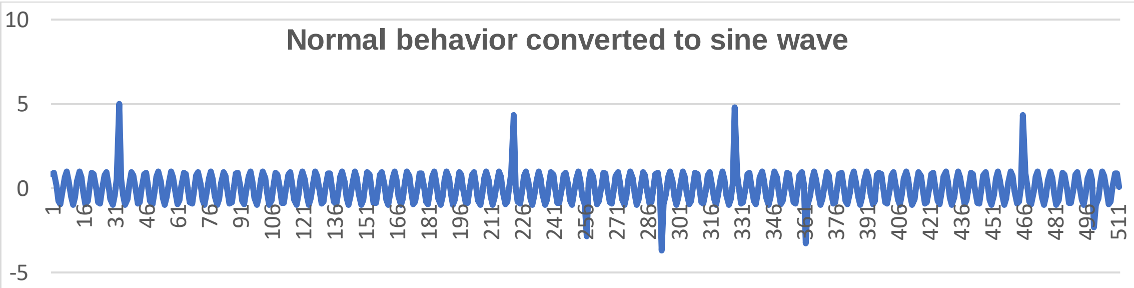

Figure 35. Knocking data after applying sine wave and amplitude multiplications in Excel.

As seen from figure 35 and comparing it to figure 33, there are significant differences, despite both graphs were formed in the same manner. In figure 35 there are eight amplitudes clearly visible corresponding to the knockings, whereas, in figure 33, only five are distinguishable and two are harder to spot at samples 326 and 360. However, both graphs have the same amplitude of one for normal sinewaves. Following that, the FFT was performed in Excel providing the result in figure 36.

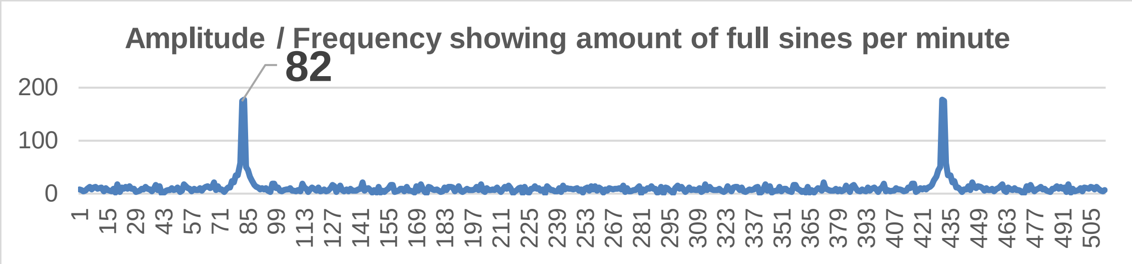

Figure 36. Results after applying FFT to knocking data in Excel.

In figure 36 the number 82 is the sample value indicating the number of normal full sinewaves in figure 35. Compared with figure 34, the graph in figure 36 does not have negative amplitude values, although, the same method was applied in both graphs. Despite this, both graphs have the harmonics at samples 82 and 435.

6.2 Measurement Conclusion

The sensor CM-01B was tested with the BeGo Solution low-cost bundle and custom-built LabView application in four cases. In each test case a water-filtering pump was used as the source of vibrations with different liquids. The tests and LabView graphs proved that using a low-cost BeGo Solution bundle with contact microphone and analyzing the vibrations in the custom-built LabView application provided sufficient vibration analysis information. The analyzed vibrations indicate that the contact microphone provides good approximation for vibrations with abnormalities from knocking, normal pump operation and when the liquid used in pump has dirt. Furthermore, the built LabView application analyzes the measured vibrations correctly by showing the disturbances or pulses in the system. The FFT graphs show that the more there are disturbances the more the graph oscillates and proved that the system works mathematically, although, the company seeks more investigation to this field. The system could be extended by using power spectrum to see at what frequencies motions occur and what are their power level. This can be further used to study how vibrations with certain power levels and frequencies affect the surrounding devices and people. Regarding the FFT numerical results, the smallest vibrations occurred during normal pump operation providing an amplitude after FFT of 10 and a fairly flat vibration function. However, the largest disturbances in a system occurred during water-dirt mixture filtering with an amplitude of 32 and a very oscillating function after FFT. Excel provided a different FFT graph than LabView. However, both gave the same FFT analysis results proving that LabView application works and can be developed without any confusions whether the application provides correct analysis.

7 Conclusion

This study was done in cooperation with a company called BeGo Solutions that focuses in sensors and data business. The idea originates from the company and was extended by the author of this work. This research studied the possibility to build a LabView application for vibration analysis using a pre-selected sensor and a ready-made bundle. In addition, for future development purposes, this study includes a market survey based on pre-selected sensors and BeGo Solutions' guidelines for the company. In the beginning of this study it was decided to use three different vibration sensors, however, in the later stages it was agreed to use one sensor to get the bundle, LabView application and sensor system working accurately.

This study found that it is possible to build an entry-level application in LabView that analyzes vibrations from a pre-selected contact microphone CM-01B using Fast Fourier Transform method. The vibration data was captured in four test cases using Realterm software, filtered in Excel and analyzed in CSV format in LabView application. All tests with liquid were done using a water-filtering pump to mimic motor vibrations where the system ought to be used. Tests showed that contact microphone registered most of the vibrations and the LabView application provided sufficient analysis data. The market survey resulted in seven options that can be integrated with BeGo Solutions bundle to expand the system capabilities. The options are accelerometer and inclinometer, contact microphone and a piezoelectric vibration sensor.

Significant problems occurred during testing the contact microphone with the bundle and analyzing the data in LabView application. During this it was concluded to continue only with contact microphone sensor and include accelerometer, inclinometer and piezoelectric vibration sensor in later stages after this study. In market survey it came apparent that there are very few sensor that fully meet the criteria indicating that the solutions BeGo Solutions is working on are not fully available on the market.

This work will be continued to include inclinometer, accelerometer and a piezoelectric vibration sensor. The LabView application can be improved so that the analysis occurs as vibration data is captured from three different sensors without using Excel and Realterm software. Furthermore, the system could be tested with motors and generators wirelessly where the data would be transferred to a cloud service.

This study proved that a low-cost vibration analysis system can be done, improved significantly and would have increasing market share.

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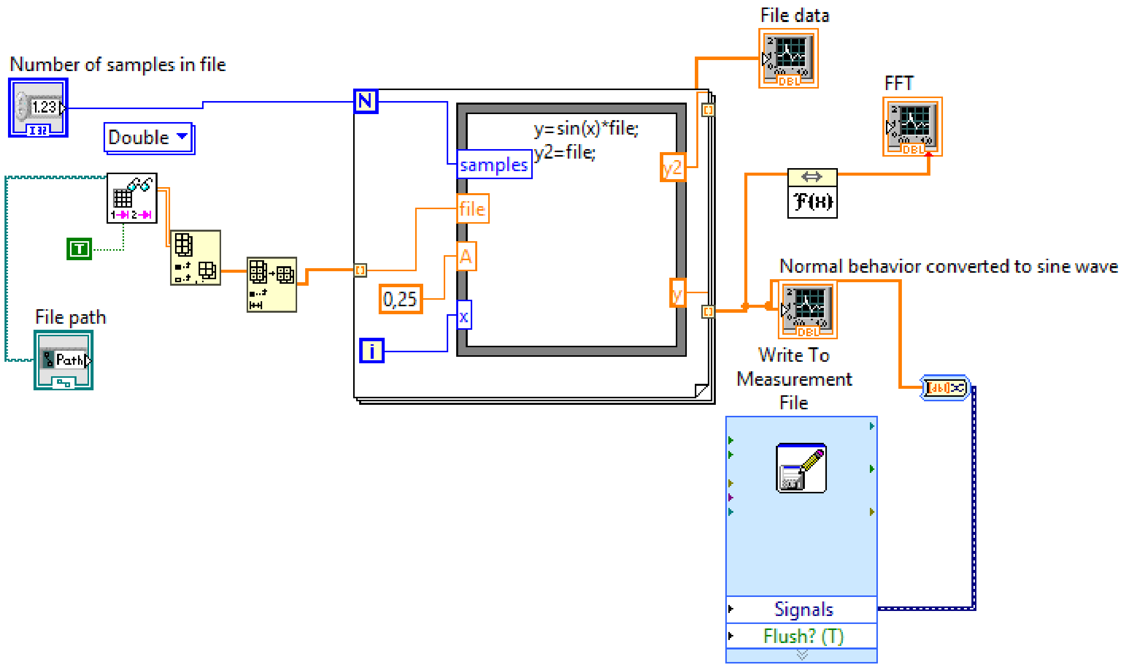
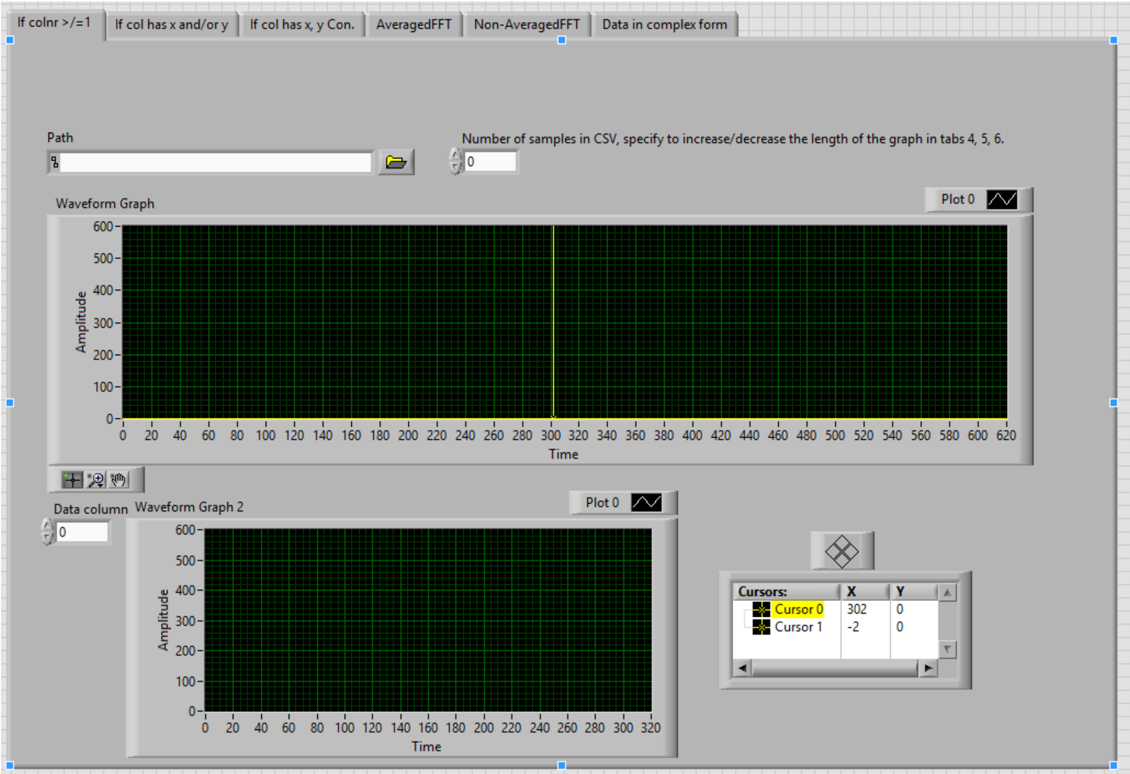
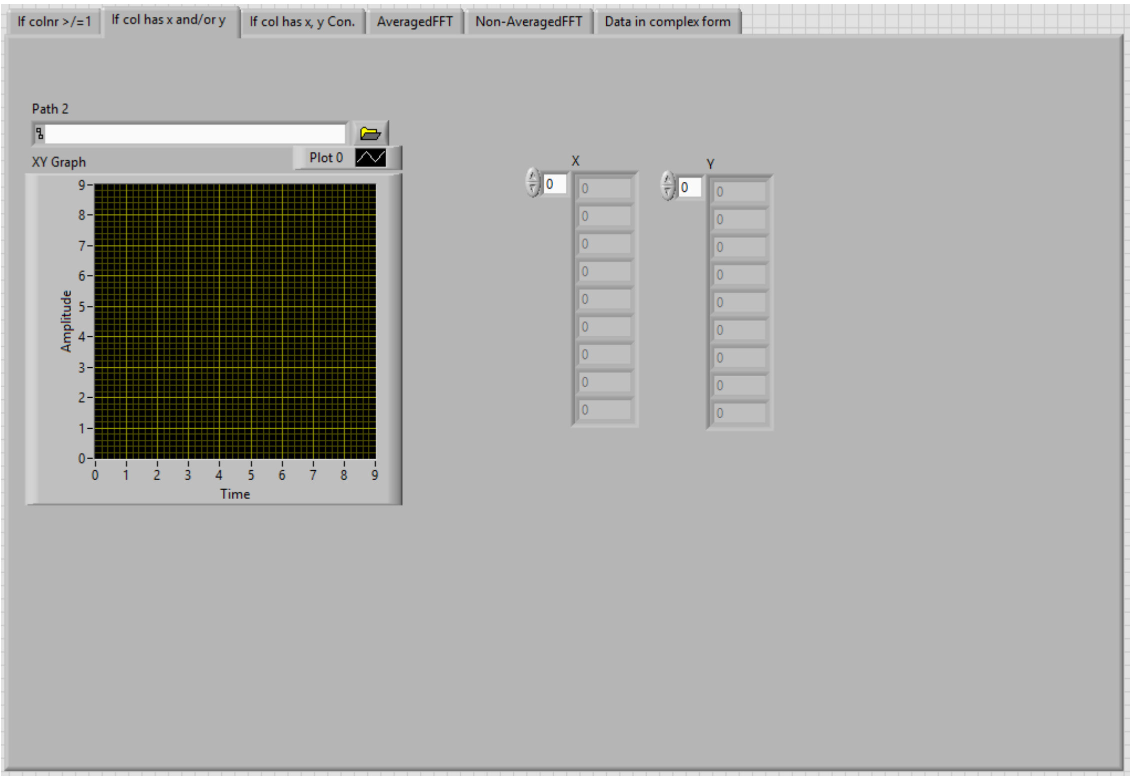
Appendix 1. Used Custom-built LabView Application Front Panel View

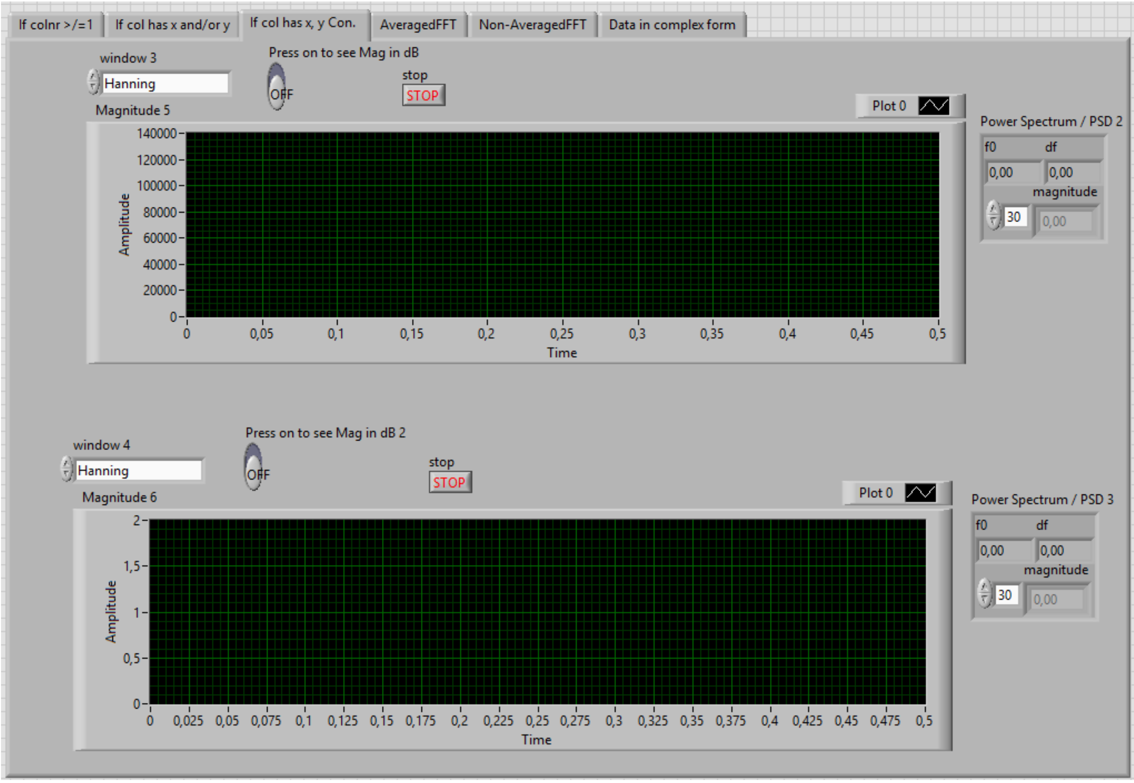
Used Custom-built LabView Application Block Diagram View

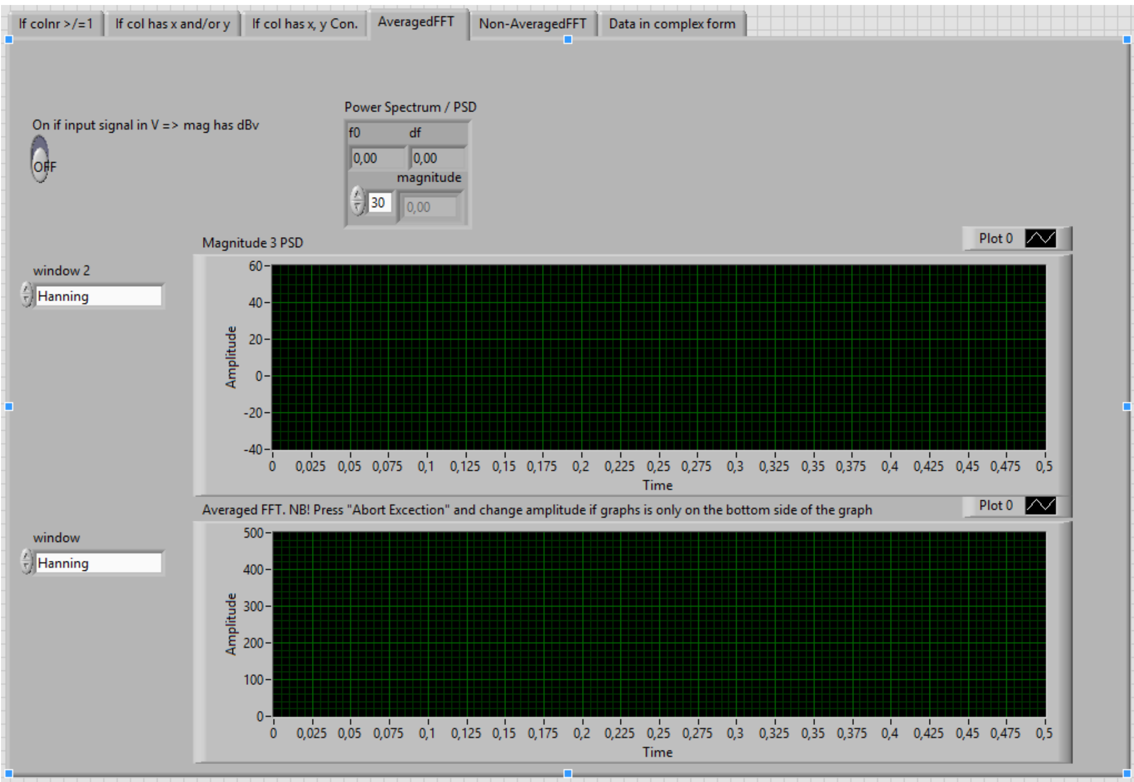


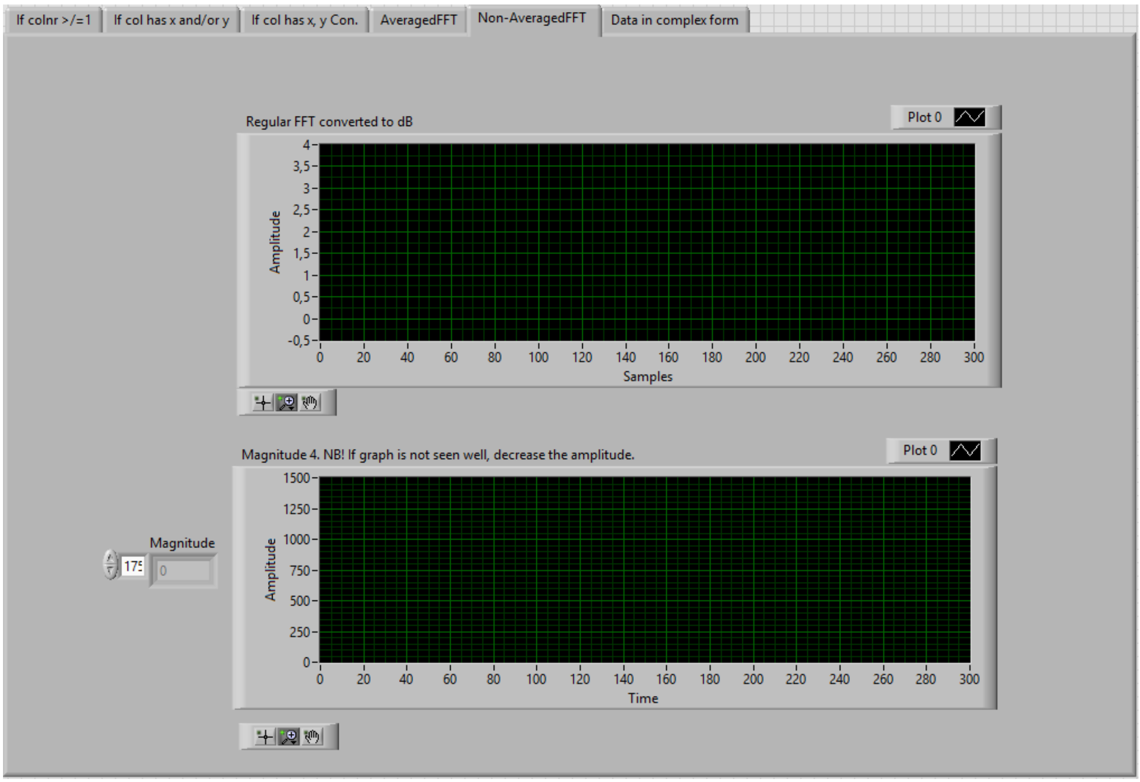
Appendix 2. Initial LabView Application Front Panel View

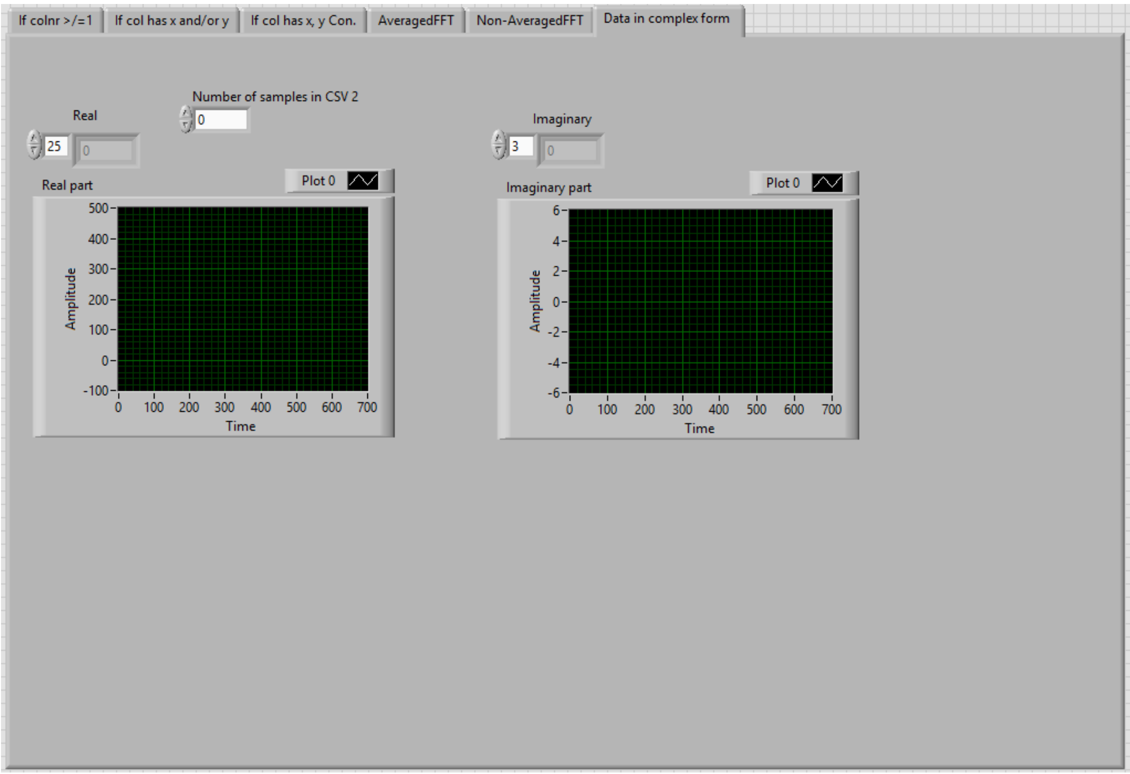





If colnr >/=1
If col has x and/or y
If col has x, y Con.
AveragedFFT
Non-AveragedFFT
Data in complex form
window 3
Hanning
Press on to see Mag in dB
OFF
stop
STOP
Magnitude 5
Plot 0
Power Spectrum / PSD 2
f0
df
magnitude
Amplitude
Time
window 4
Press on to see Mag in dB 2
Magnitude 6
Power Spectrum / PSD 3


If colnr >/=1
If col has x and/or y
If col has x, y Con.
AveragedFFT
Non-AveragedFFT
Data in complex form
On if input signal in V => mag has dBv
OFF
Power Spectrum / PSD
f0
df
magnitude
Magnitude 3 PSD
Plot 0
window 2
Hanning
Amplitude
Time
Averaged FFT. NB! Press "Abort Excection" and change amplitude if graphs is only on the bottom side of the graph
window


If colnr >/=1
If col has x and/or y
If col has x, y Con.
AveragedFFT
Non-AveragedFFT
Data in complex form
Regular FFT converted to dB
Plot 0
Amplitude
Samples
Magnitude 4. NB! If graph is not seen well, decrease the amplitude.
Plot 0
Magnitude
Amplitude
Time


If colnr >/=1
If col has x and/or y
If col has x, y Con.
AveragedFFT
Non-AveragedFFT
Data in complex form
Real
Number of samples in CSV 2
Imaginary
Real part
Plot 0
Amplitude
Time
Imaginary part
Plot 0
Amplitude
Time

Initial LabView Application Block Diagram View