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DEVELOPMENT OF A LOW-COST PROTOTYPE FOR PREDICTIVE MAINTENANCE APPLICATIONS BY VIBRATION ANALYSIS

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Abstract. Rotary machines typically have vibrations which, due to deterioration and lack of proper maintenance, cause equipment failure. Predictive maintenance by vibration analysis has the task of evaluating the operating conditions from global root mean square (RMS) velocity measurements, comparing them with standards established by technical norms. It is possible to define the causes of vibrations from the frequencies. Characteristics observed in the frequency spectrum. Nowadays the conventional equipment used for these analyzes has a high cost and often have a very complex user interface. In this context, this work proposes the development of a low-cost instrument for vibration analysis, as this is the main barrier to the application of this technique. The prototype should be able to acquire system acceleration from this data, calculate instantaneous speeds and RMS speed within a fixed time frame, the latter being sent to an online server allowing the evolution of vibration severity to be monitored remotely. By the user. The data obtained will be recorded on a micro SD card so that you can perform more detailed analyzes with a computer, such as frequency domain spectrum analyzes. To assist in the analysis, a software with an interactive interface capable of importing the data from the generated text files, performing the fast Fourier transform (FFT) and plotting the graph for analysis was developed. For validation of vibration analysis, an Agilent® benchtop analyzer was used. In the calibration tests with the commercial model, the low-cost prototype was able to identify the defects, unbalances and misalignments, provided in a rotary system, compared to the Agilent® analyzer. RMS acceleration and 25% for speed. Even with the errors obtained in the measurements, the developed prototype proved to be effective for the application of low-cost predictive maintenance, since besides being able to identify the defects in the rotating systems, it can remotely follow the evolution of the vibration severity.

Keywords: Predictive maintenance; Mechanical vibrations; Vibration analyzers; Cost; Rotary machines.

1 Introduction

Industry 4.0 has been dominating the world scenario and is gaining ground in the Brazilian industry, even at an early stage, through the implementation of digital technologies. According to data from the National Confederation of Industry (CNI) [1], between early 2016 and 2018, the percentage of large companies using at least one of the digital technologies went from 63% to 73%, and the number of large companies that would like to invest in digital technologies in 2018 is 48%.

However, the industry still faces many barriers to the adoption of digital technologies, among them, the most recurring is the high cost of deployment, Fig. 1, which mainly affects small and medium companies.

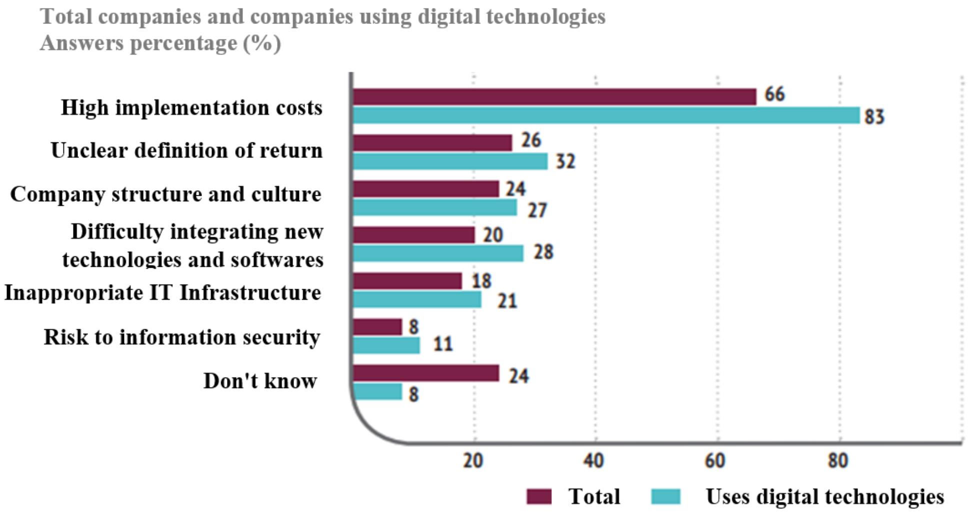


Figure 1. Internal barriers that hinder the adoption of digital technologies.

The inclusion of these technologies is aimed at improving the production process of industries, keeping machines and equipment with minimal downtime or unexpected maintenance. To avoid such unusual stops, the maintenance industry must always have continuous control and monitoring of machine operating conditions. As any equipment in intermittent work situations typically suffers vibrations, which depending on the level of it leads to early deterioration, in this way the vibration analysis becomes important for high performance. With vibration analysis it is possible to obtain RMS (Root Mean Square) signals as to frequency spectrum, thus allowing to identify if the machine is operating within pre-established standards and also the types of defects that can lead to more serious failure.

Nowadays there are some types of works applying microcontrollers for some analysis as is possible to see in González [2], González [3] and Sousa [4]. All of them used the vibration analysis in continuous monitoring to predict possible failures on the system, which permits better application of maintenance. Although some limitations like instabilities of the equipment, high-cost, the data limits, and better analysis were not considered. In this context, the current work proposes to develop low-cost equipment for continuous monitoring of rotating machines using the concepts of predictive maintenance by vibration analysis and internet of things (IoT) looking for to facilitate the analysis and the way of the access of the warnings when the equipment be with some instabilities.

2 Materials and methods

The prototype development process proposed in this paper was divided into seven steps as shown in Fig. 2.

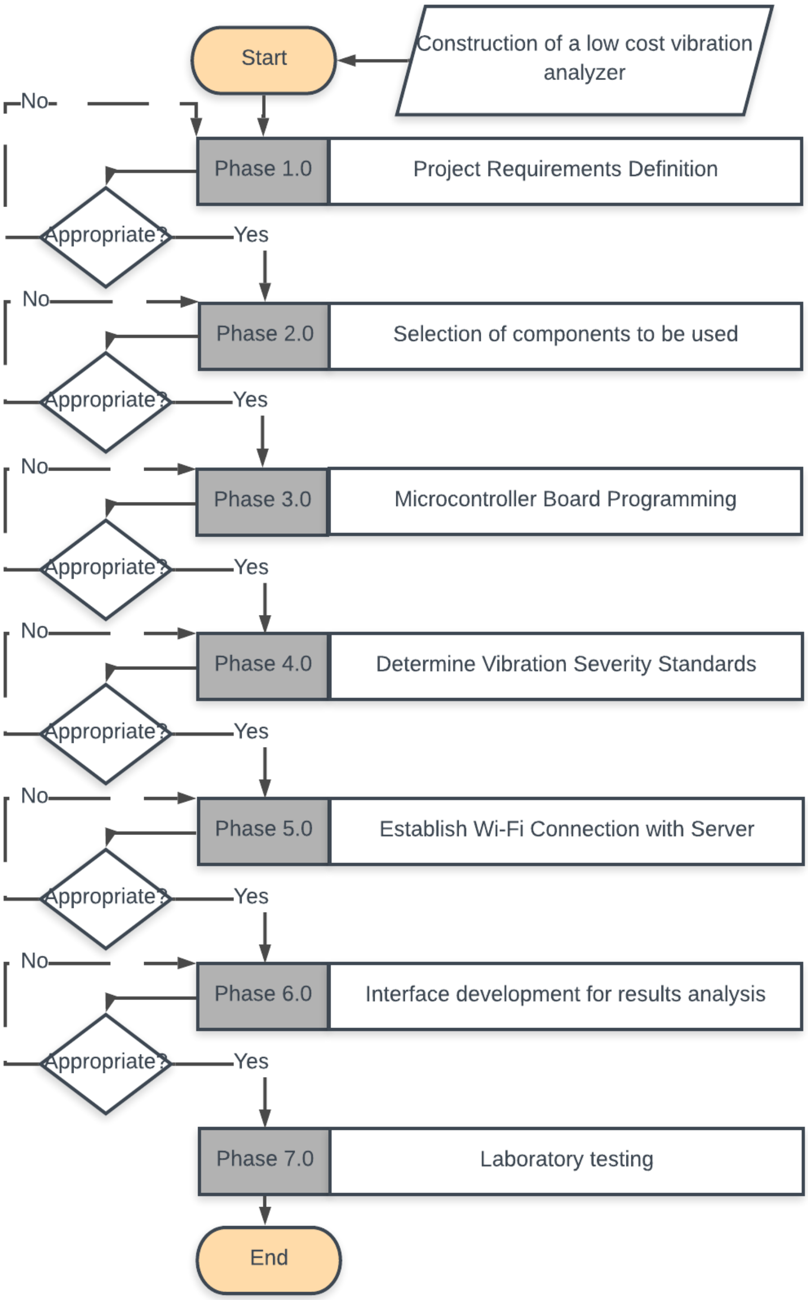


Figure 2. Prototype development flowchart.

In first phase, the requirements that were used for project development were defined. In phase 2, were selected the components that are part of the system, in which the best microcontroller and the components that fit the proposed requirements were sought.

For phase 3, the programming (in c ++) of the microcontroller board was chosen, aiming at a simple way of the codes to perform the demands of the task. During phase 4, the vibration severity standards to be used as analysis parameters were determined using the standards used by the country.

In phase 5, the WEB server was chosen and the connection to the prototype was made, the server should receive the RMS velocity data and when the alarm levels are reached should send some alarms. During phase 6 an interface was developed that allows the data import and is able to generate graphs for analysis (in time and frequency domain). Finally, in phase 7, tests were performed to validate the results obtained by the prototype in comparison to other vibration analyzers.

2.1 Project requirements

To, achieve the objectives described in this paper, it was necessary to know the design requirements. That will be used as a reference for comparison and selection of materials and components that will be necessary for prototype development. These requirements are listed below:

- Prototype components should be low cost;
- Be able to connect to the internet;
- Present the vibration level via internet;
- Send an alert if the levels exceed the allowed;
- Save data from instant acceleration;
- Allow local visualization of vibration levels;
- High data acquisition speed;
- Components are available in local suppliers.

2.2 Components

The choice of components for the prototype was made based on the requirements shown. Were prioritized user-friendly items that are easily found on the local market. It is also important to note that components must be able to communicate with each other and share information with the user. Figure 3 shows the assembly of the prototype with the selected components.

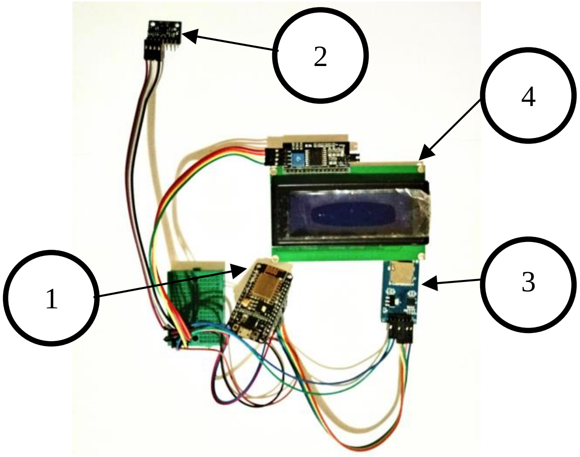


Figure 3. Prototype assembly.

1. **Microcontroller Board** - It is a programmable integrated circuit capable of executing and giving orders stored in memory, it will be responsible for giving, receiving and processing the data coming from the other components. The microcontroller chosen was the NodeMCU board. This board was chosen because it already has a built-in Wi-Fi connection and is compatible with the modules and sensors that will be used.

2. **Accelerometer** - The accelerometer will be the sensor responsible for measuring the signal of the mechanical vibration and sending it to the microcontroller. The MPU6050 was chosen for the application because it is capable of measuring acceleration on all three axes with a 16bit

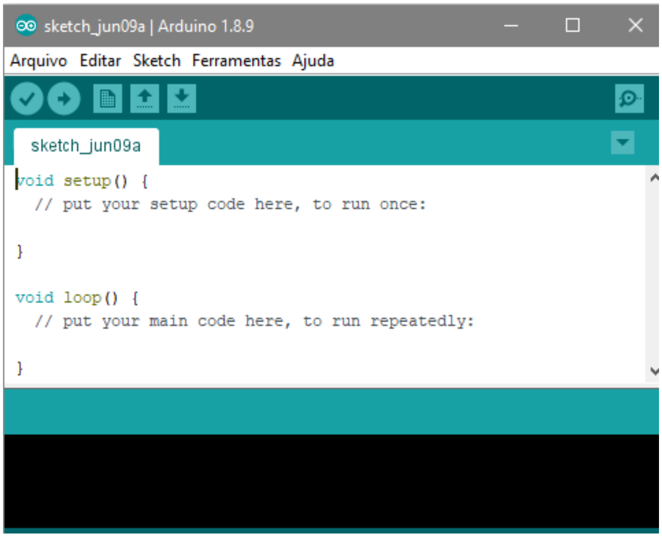
digital to analog converter. The reading range is programmable and can be set to ± 2G, ± 4G, ± 8G and ± 16G. For this application, a 2G range has been set, so the sensor sensitivity will be 16384 LSB/G.

3. **SD Card Module -** This shield allows the microcontroller to access an SD card, allowing it to access files for reading or even create files. The purpose of storing data is to allow the user to perform a detailed analysis of the data, such as frequency spectrum analysis, even if it is from a previous day or month.

4. **LCD Monitor -** An LCD monitor will be used to allow the user a local inspection of the vibration levels. The LCD monitor will display the 3-axis vibration velocity RMS value from the last reading taken by the sensor. The monitor chosen for this task is a low power 20x4 LCD.

2.3 NodeMCU board programming

One of the advantages of the NodeMCU module is because it is easy to programming, once connected to the computer it can receive Lua language scripts through the serial port. The Arduino development interface, Fig. 4, can also be used for this purpose. In this case, the programming should be done in the C ++ language, the same used by Arduino, and be sent the script to the microcontroller. The interface itself will make the conversion of language (C++ to Lua).



```
void setup() {
  // put your setup code here, to run once:

}

void loop() {
  // put your main code here, to run repeatedly:

}
```

Figure 4. Arduino development interface.

The algorithm was made following the flowchart presented in Fig. 5. As we can see in the flowchart, the microcontroller will loop until the expected number of readings is completed, this number will be set during the variable definition step. This data will be saved in the SD card and that data can be used to obtain the Fourier transform, is important to have enough points to not lose the quality of the curve, so a total of ten reading points was defined.

Besides, the time interval between the above-mentioned loop executions is defined, to not overload neither the memory card nor the online server. Therefore, it has been defined that data acquisitions will be performed for 1 minute with an interval of 1-hour to next acquisition, allowing machine condition to always be monitored without overloading the prototype or server with data.

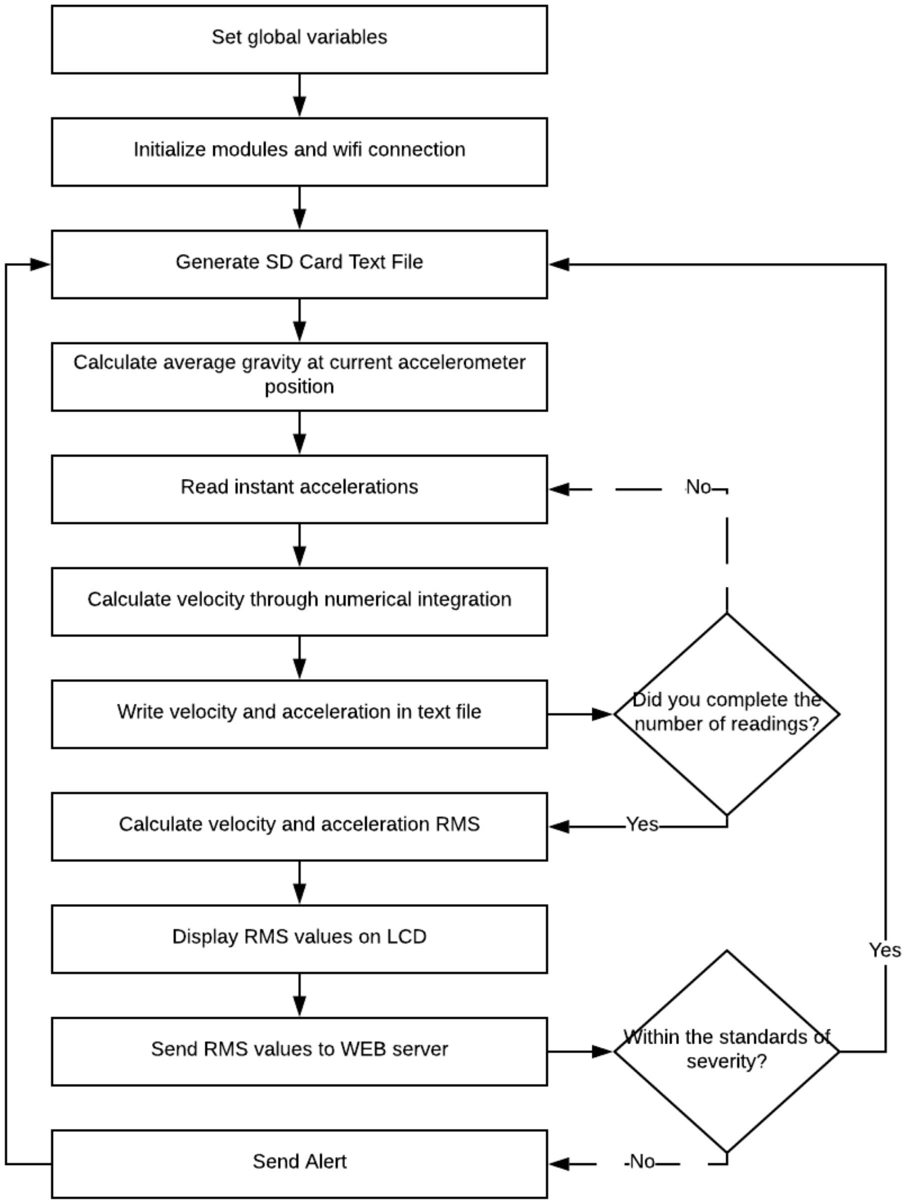


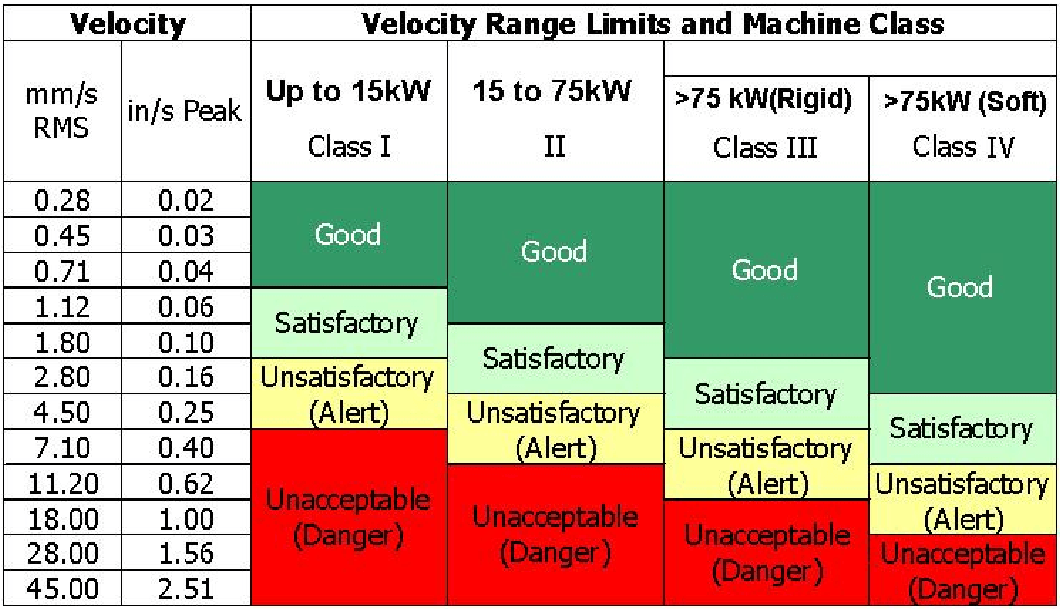
Figure 5. Algorithm prototype operation.

2.4 Vibration severity standards

The basic task of vibration analysis is not to measure but to evaluate the condition of the machine: whether it is in acceptable, critical condition or needs urgent maintenance. To assist in this task were created standards of vibration using parameters of velocity or peak amplitude RMS. The RMS values represent the signal energy obtained from the system and is defined by eq. (1):

$$V_{RMS} = \sqrt{\frac{\sum_i^n V_i^2}{n}} \tag{1}$$

The velocity RMS measured are compared with the standards of vibration for rotary machines to define whether the observed vibration levels are under normal conditions or it needs maintenance immediately. In Brazil is used the standard of ABNT NBR 10082/2011 [5], in Fig. 6 is shown the vibration severity standards.



Velocity		Velocity Range Limits and Machine Class			
mm/s RMS	in/s Peak	Up to 15kW Class I	15 to 75kW II	>75 kW(Rigid) Class III	>75kW (Soft) Class IV
0.28	0.02	Good	Good	Good	Good
0.45	0.03				
0.71	0.04				
1.12	0.06	Satisfactory			
1.80	0.10		Satisfactory		
2.80	0.16	Unsatisfactory (Alert)		Satisfactory	
4.50	0.25		Unsatisfactory (Alert)		Satisfactory
7.10	0.40	Unacceptable (Danger)		Unsatisfactory (Alert)	
11.20	0.62		Unacceptable (Danger)		Unsatisfactory (Alert)
18.00	1.00			Unacceptable (Danger)	
28.00	1.56				Unacceptable (Danger)
45.00	2.51				

Figure 6. Vibration severity standard according to ISO 10816 [6].

According to NBR 10082 and ISO10816 the machine classes can be defined according to the criteria:

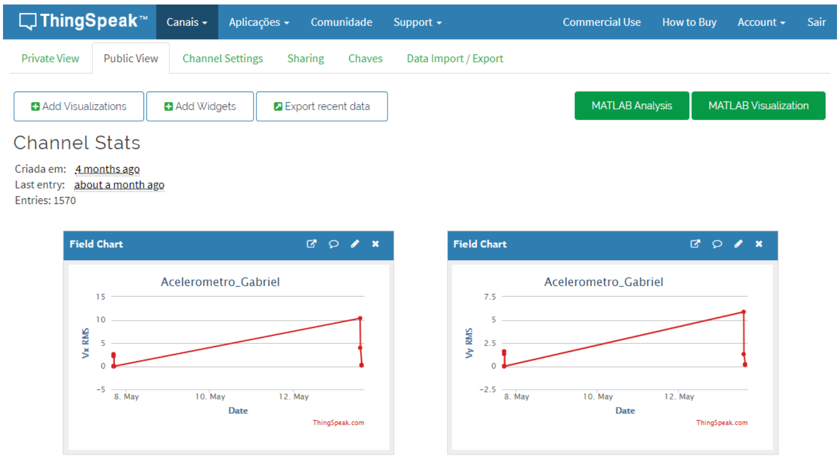
- Class I: Individual parts of machines and motors, integrally connected to the complete machine in its normal operating condition (electric motors up to 15KW of power).
- Class II: Medium-sized machines (15KW to 75KW electric motors).
- Class III: Large driving machines and other large rotary mass machines mounted on rigid and heavy foundation.
- Class IV: Large driving machines and other large rotary mass machines mounted on relatively flexible foundations.

2.5 Online communication

To access the data remotely via the internet, the microcontroller must communicate and send data from the HTTP protocol. This works in the client-server model, where there is communication through messages: the client sends a request message from a resource and the server sends a response message to the client with the request. For this paper, the client will be the programming performed on the NodeMCU board.

The server chosen was thingspeak, as it allows a connection to NodeMCU for free. There is a data usage limitation, allowing you to send one measurement every 15 seconds and a limit of 8200 data per day, however, for this purpose will not concern.

Data visualization can be done through graphs available in the channel, Fig. 7, and can be defined as public or private, depending on the application to be made.

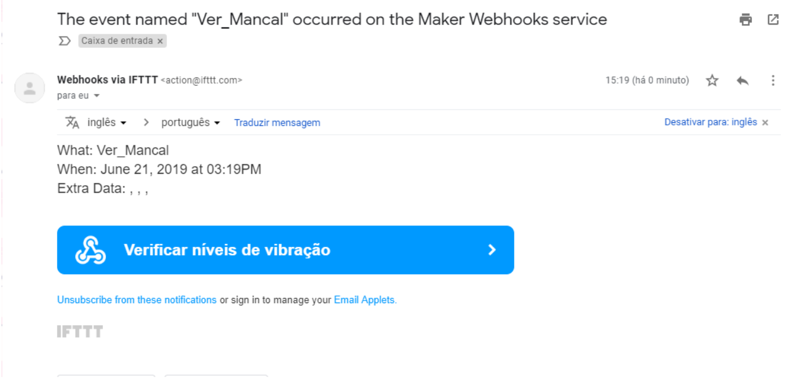


Channel Stats

Criada em: 4 months ago
Last entry: about a month ago
Entries: 1570

Figure 7. Thingspeak graphs.

Also, the server allows defining actions that are activated if the data passes over pre-established conditions. For this work, it was defined when the RMS velocities reach vibration severity according to the standards level C (alert), it will send an email to the responsible for the machine, Fig. 8.



The event named "Ver_Mancal" occurred on the Maker Webhooks service

Webhooks via IFTTT <action@ifttt.com>
para eu
15:19 (há 0 minuto)

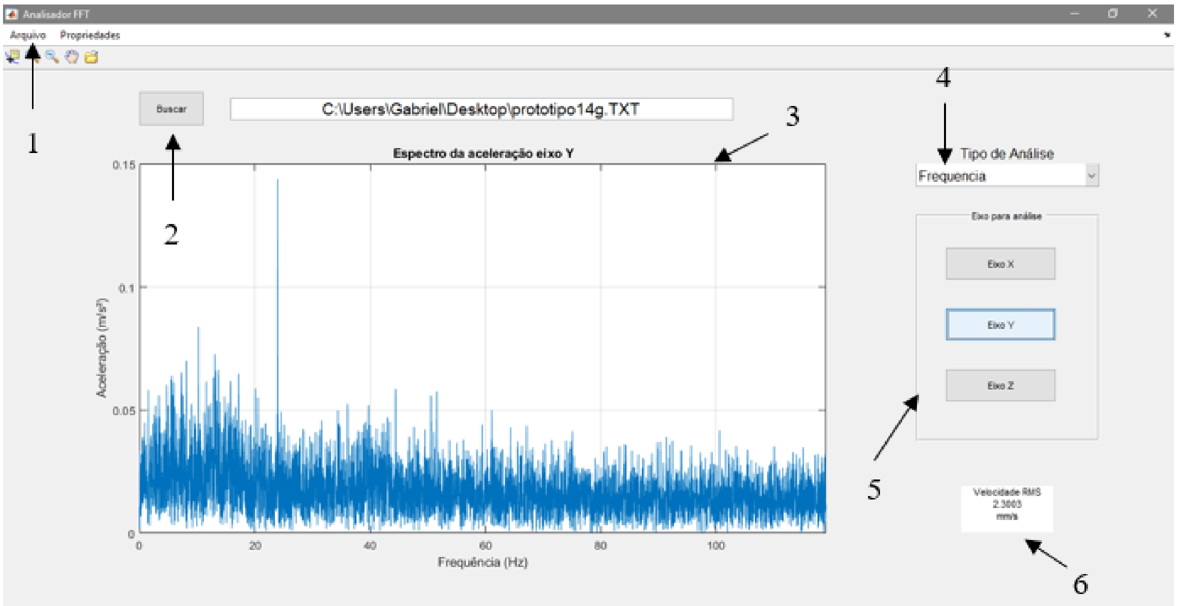
What: Ver_Mancal
When: June 21, 2019 at 03:19PM
Extra Data: , , ,

Unsubscribe from these notifications or sign in to manage your Email Applets.

Figure 8. Email sent by prototype.

2.6 Interface for data analysis

For data analysis, were proposed to develop an application with a user-friendly interface; that allows us to import the text files generated by the prototype and with this data, generate graphics (frequency spectrum, time-domain spectrum and spectrogram) for better analysis of the system. In Figure 9, were shown the interface with the main functions followed by the descriptions.



C:\Users\Gabriel\Desktop\prototipo14g.TXT

Tipo de Análise: Frequencia

Velocidade RMS
2.3003
mm/s

Figure 9. Interface for data analysis.

1. Menu Bar - The interface has two menus, “File”, to open the files to generate the graphics and save the points used and generate the active chart in a PDF file, and the “Properties”, to relate to the graph, such as: enable or disable grid, set axis limits and overlay graphs.

2. Browser Tool - Opens a window that allows the user to select the file with the data to analyze.

3. Graph Area - This area will display the graphs to analyze. It is also possible by activating the “Overlap” function in the “Properties” menu to overlap graphs for comparisons.

4. Analysis Type - In this section it is listed the types of graphs to be plotted.

5. Axis buttons – As the prototype saves the data in all three axes of the accelerometer, this button will select which one axis be used to plot the graph.

6. Speed Display - Shows the RMS velocity of the chosen data.

2.7 Test bench

To validate the prototype was adopted an existing test bench, Fig. 10, in LVI / UFCG to simulate the operation of a rotating machine. In this workbench were possible to induce system defects, such as unbalance, to verify the prototype sensitivity in detecting such instabilities.

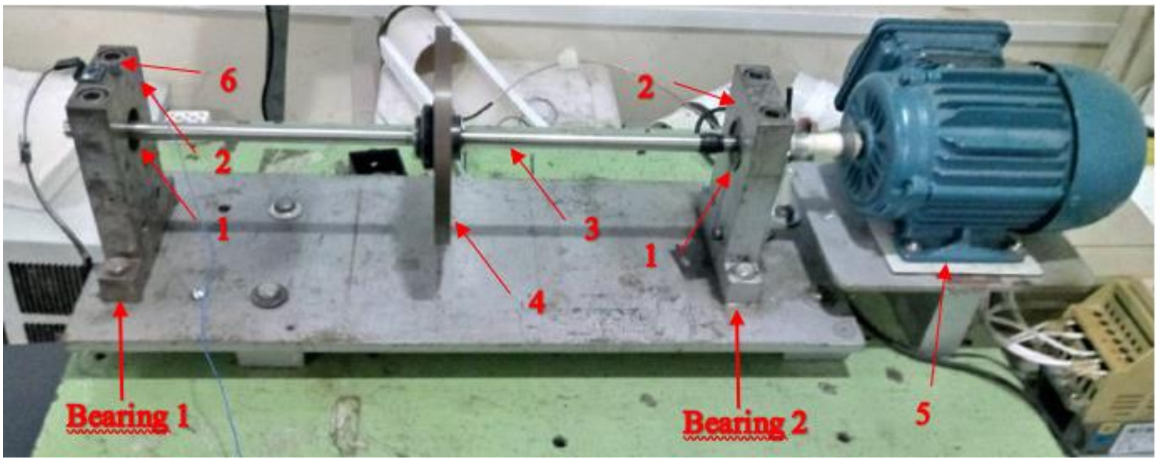


Figure 10. Test bench.

The components of the test bench are 1. Bearings - SKF 6001 bearings; 2. Bearing housing; 3. Shaft – with 12mm in diameter and 500mm in length; 4. Disc – with 200mm in diameter and 12mm in thickness; 5. 0.5CV Electric motor; 6. Accelerometer PCB model 352B10 with a sensitivity of 10.58 mV/g. Since the engine power is 0.5CV, our system will fit the Class I rotary machines, Figure 6.

Also were used the Agilent® model 35670A dynamic signal analyzer was used, Figure 11. The obtained data from this analyzer will be used as a basis for calculating the prototype error, allowing to make comparisons of velocity and acceleration RMS, as well as of the frequency response spectra. Finally, the errors obtained in these analyses will serve as a basis for prototype calibration, making their measurements more reliable.

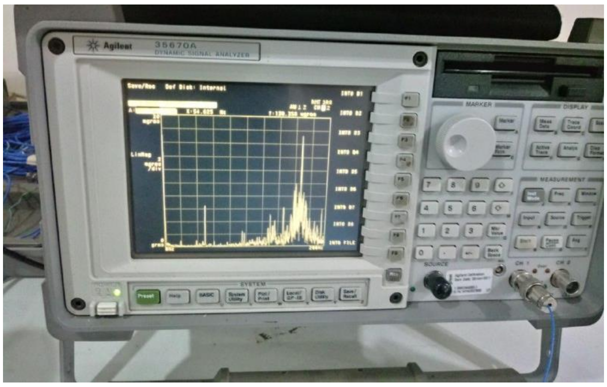


Figure 11. Dynamic Signal Analyzer.

To obtain reliable data were made before the tests the calibration with both analyzers, for the Agilent system was used a calibration device and for the Prototype was done by a code that must be executed on the board while the accelerometer is stopped in the horizontal position.

3 Results and discussions

Were made tests with the test bench mentioned above, for different unbalance conditions (14g and 22g). The constant motor speed of 25Hz was used, which frequency is near to the natural frequency of the system, and all data were obtained on Bearing 1 in the vertical direction.

3.1 RMS acceleration and velocity tests

To validate the RMS values, 9 experiments were made for each unbalanced condition (14g and 22g), thus calculating the averages and the respective standard deviations. With this information, the inherent error of the prototype reading can be obtained and it is also possible to compare the dispersion of the data with the reference system (Agilent Analyzer).

For the first condition, with unbalance mass of 14 grams applied to the rotor, were obtained the RMS accelerations and velocities, Table 1.

Table 1. Acceleration and Speed RMS for 14g unbalance.

	Analyzer	1	2	3	4	5	6	7	8	9
Acceleration RMS (m/s^2)	Prototype	1,17	1,06	1,17	1,16	1,07	0,91	0,87	0,78	0,87
	Agilent	0,89	0,97	0,68	0,80	0,80	0,96	0,94	0,98	1,24
Velocity RMS (mm/s)	Prototype	0,42	0,46	0,51	0,39	0,36	0,40	0,43	0,38	0,40
	Agilent	0,48	0,56	0,51	0,51	0,61	0,62	0,58	0,50	0,61

For the second condition, with a 22-gram unbalanced mass on the rotor, the obtained RMS acceleration and velocity results can be seen in Tab. 2.

Table 2. Acceleration and Speed RMS for 22g unbalance.

	Analyzer	1	2	3	4	5	6	7	8	9
Acceleration RMS (m/s^2)	Prototype	1,56	1,50	1,00	0,95	0,98	0,93	0,90	1,32	1,28
	Agilent	1,29	1,97	1,21	1,21	1,30	1,25	1,06	1,05	1,10
Velocity RMS (mm/s)	Prototype	0,6	0,55	0,62	0,68	0,45	0,45	0,54	0,38	0,41
	Agilent	0,61	0,64	0,59	0,6	0,64	0,63	0,61	0,6	0,61

For this work, we will consider the all data obtained by the Agilent® vibration analyzer as reference, to make the comparison with the data of the developed prototype. The values of the relative error, standard deviations and relative standard deviations are shown in Tab. 3 and Tab. 4 for the 14- and 22-gram unbalanced tests conditions respectively.

Table 3. The relative error for 14g unbalance.

	Analyzer	Mean	Relative error	Standard deviations	relative standard deviations
Acceleration (m/s^2)	Prototype	1,01	10%	±0,15	15%
	Agilent	0,92	-	±0,16	17%
Velocity (mm/s)	Prototype	0,42	25%	±0,029	11%
	Agilent	0,55	-	±0,039	10%

Table 4. The relative error for 22g unbalance.

	Analyzer	Mean	Relative error	Standard deviations	relative standard deviations
Acceleration (m/s^2)	Prototype	1,16	9%	±0,26	22%
	Agilent	1,27	-	±0,28	22%
Velocity (mm/s)	Prototype	0,52	15%	±0,10	20%
	Agilent	0,61	-	±0,02	3%

From these results, it is possible to observe a relative error of readings of the acceleration close to 10% for both conditions. For velocity, a relative error of the order of 25% with an unbalanced mass of the 14 grams and 15% in the test with higher mass (22 grams). The standard deviation of acceleration and velocity observed in Tab. 3 and Tab. 4 are quite high, especially in the case of velocity for the 22g test, there was a large prototype deviation from the reference. These deviations observed in the readings were already expected due to the nature of MEMS accelerometers, which present noises that arise due to the capacitors used by them.

3.2 Acceleration spectrum

Also were made analyses of the frequency spectrum, which was obtained applying the Fourier transform. The results for the unbalanced conditions with a mass of 14 grams were shown in Fig. 12a, 12b and 13.

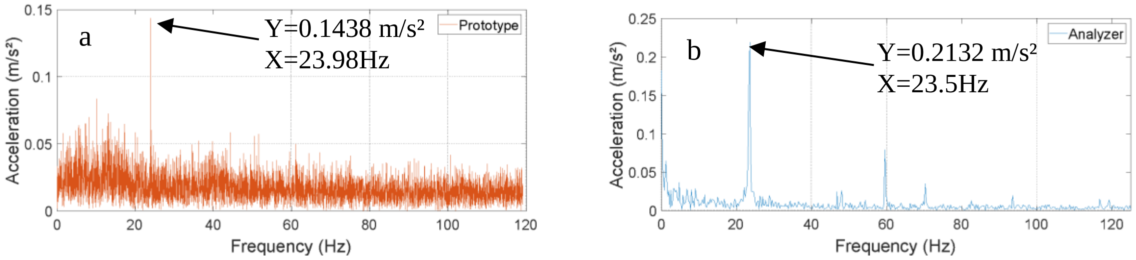


Figure 12. 14-gram unbalance Fourier transform: (a) prototype, (b) Agilent.

In this spectrum, it is possible to notice the presence of the first harmonic at 23.98Hz (1xRPM) with an amplitude of 0.1438m/s²; this being the only harmonic present, according to Bilosova [7], characterizing the unbalance of the system. The harmonic frequency is below the rotational speed showed in the inverter of the test bench system due to coupling losses to the rotor shaft, so the rotation speed was measured with the tachometer, thus obtaining a speed of 23.9 Hz. Besides, the noise in all frequencies of the signal is due to the nature of accelerometers (MEMS type), as capacitive accelerometers which make them very susceptible to external influences, such as eddy currents. Graphic noise can be improved by using filters or by improving system grounding and cabling shielding, avoiding interference by eddy current.

In Figure 12b were shown the Fourier transform provided by the Agilent® analyzer for the same unbalance conditions and is possible to note a peak in the first harmonic at 23.5Hz (1xRPM) with an amplitude of 0.2132m/s², thus with a greater amplitude than that observed in the previous spectrum, This is due to the lower noise level compared to the prototype data. Due to the excessive noise of the first graph, it is also not possible to observe the peaks present at 59.5Hz and 70.25Hz

The comparison between both analyzers was made, as shown the Figure 13.

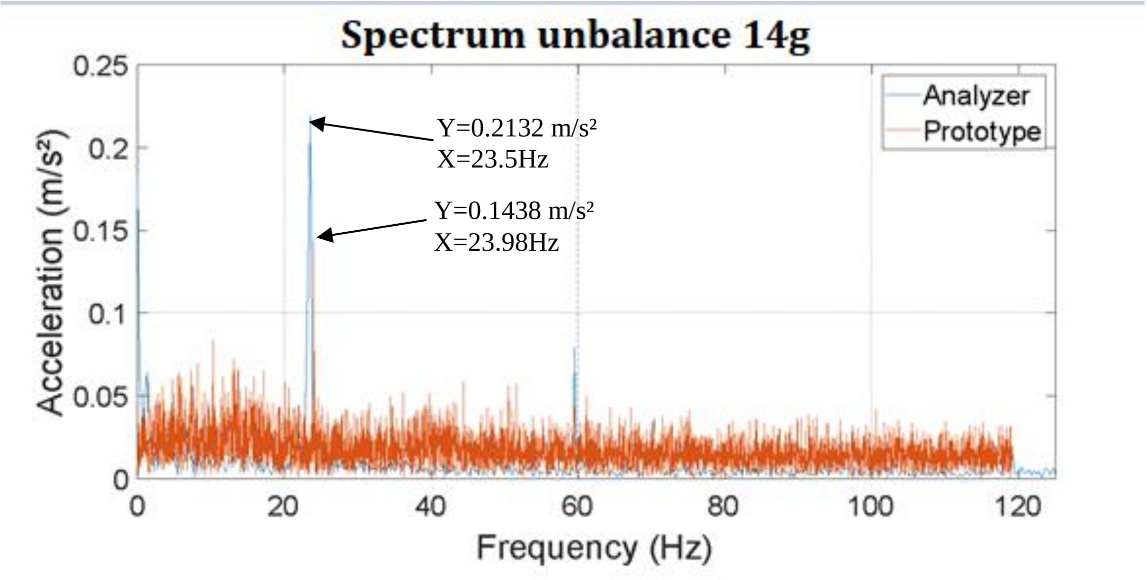


Figure 13. Comparison between prototype and analyzer to unbalance 14g.

For the unbalanced conditions with a mass of 22 grams for both analyzers were obtained the Figures 14a e 14b.

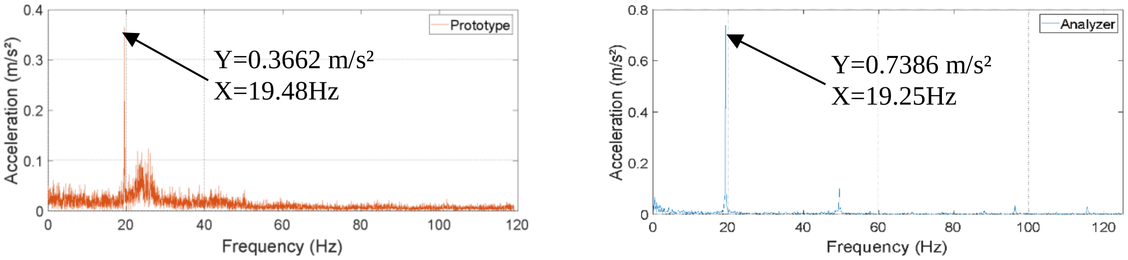


Figure 14. 22-gram unbalance Fourier transform: (a) prototype, (b) Agilent.

In this spectrum it is possible to notice the presence of the first harmonic at 19.48Hz (1xRPM) with an amplitude of 0.3662m/s², which is the only harmonic present in the spectrum, characterizing the unbalance. The harmonic frequency below the programmed speed due to the higher mass present in the rotor, so the actual shaft rotation speed, measured by the tachometer, is 19.5Hz. Also, the signal has noise in all frequencies, especially in 30Hz, as in the previous case, this signal can be improved by using filters.

The signal obtained by the Agilent® signal analyzer under the same conditions shown a peak in the first harmonic at 19.25Hz (1xRPM) with an amplitude of 0.7386m/s², thus with greater amplitude in comparison with the Prototype signal. This is due to the lower noise level compared to the prototype data. It is also possible to observe the peak present at 50.0Hz, in Figure 14a, which peak it is not possible to see for in Figure 14b because of the noise.

For a better comparison of these results, Fig. 15 presents an overlap of the acceleration spectra for the unbalance condition discussed.

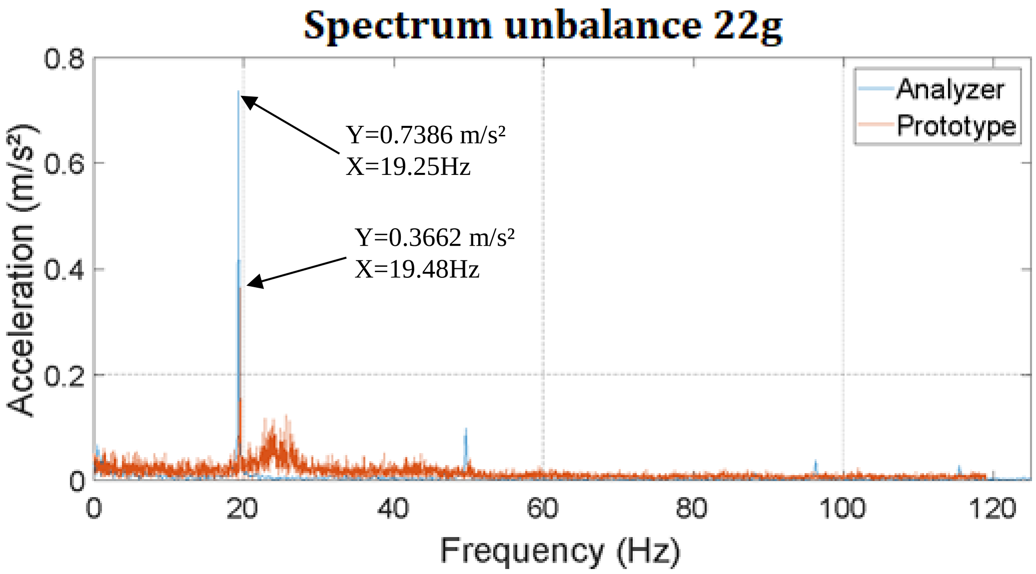


Figure 15. Comparison between prototype and analyzer to unbalance 22g.

4 Conclusions

In this work, was developed a prototype of a vibration analyzer of low-cost for application on predictive maintenance. Which allows continuous monitoring of vibration severity of rotating machinery, using the concepts of IoT (Internet of Things) that are applied through online charts showing the evolution of the RMS values of the system, and also through alerts sent via email.

The principal requirement was the low cost of the prototype that had a cost equivalent to R$ 235.10 (62 US$), which means affordable for every type of company or maintenance team.

The prototype was compared with a laboratory analyzer, Agilent® model 35670A, which shown some limitations as 10% deviation of acceleration and 25% of speed when compared to Agilent® dynamic signal analyzer; 240 Hz sampling frequency, limiting the frequencies seen in the Fourier transform to a maximum of 120Hz; High noise, causing a loss in quality of frequency domain graphics, which may lead to the concealment of smaller peaks.

Despite these limitations, the prototype shows to be effective for low budget applications on detecting unbalancing, presenting the harmonic frequency peak on exactly the rotation frequency and sending alerts to the responsible person as soon the prototype notices the high level of vibration.

Acknowledgments

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