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MONITORING OF BALLBEARINGS VIA VIBRATION ANALYSIS FOR PREDICTIVE MAINTENANCE PURPOSES

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Abstract. *Ball bearings are critical components of machinery and equipment in numerous industries, and their failure can result in significant damage and production downtime. To monitor ball bearing failures, a range of vibration monitoring techniques are employed, encompassing envelope analysis, kurtosis, bi-spectrum, and wavelet analysis. For example, the bi-spectrum is a higher-order spectrum that describes the non-linear interactions between frequency components in the vibration signal, and provides information about the correlation between frequency components. These techniques can identify the specific fault type by detecting and analyzing the vibration signals generated by ball bearing failures. However, detecting and analyzing these signals can be challenging due to weak signals and noise masking vibration patterns. Although current techniques are effective, they have limitations, such as requiring expert analysis, difficulty in detecting early-stage faults, and the inability to differentiate between different fault types. To overcome these limitations, new technologies and methods are being explored, such as machine learning and acoustic emission (AE) monitoring. Machine learning involves training algorithms to automatically detect and classify faults based on vibration signals, while AE monitoring detects the acoustic signals generated by ball bearing failures. Both approaches have shown promising results in early detection and differentiation between different fault types. Therefore, ball bearing failure can cause significant damage and production downtime in various industries, and effective detection and identification of these failures are crucial. Current techniques, such as envelope and wavelet analysis, are effective but have limitations. New technologies and methods, such as machine learning and AE monitoring, are being explored to improve fault detection and classification, providing early detection of faults and differentiation between different fault types, ultimately reducing the impact of ball bearing failures on machines and industries. This paper proposes to present a study of the ball bearing failure through vibration analysis from early-stage to advanced-stage of damage for predictive maintenance purposes, applying the envelope and FFT together with programming to enable the identification of defects in the bearing, especially in the inner race, through a signal acquisition system that can explain the presence of the defect through frequency graphs. Thus obtaining results that show the presence of defects in three different bearings, with gradual defect magnitudes, differentiating these data from an ideal bearing. The next step is to explore the new technologies like machine learning and artificial intelligence.*

Keywords: *Rail failure, signal analysis, envelope, kurtosis, bi-spectrum .*

1. INTRODUCTION

Bearings are one of the most important machine elements in the construction of machinery and transportation vehicles, present in various industries and crucial for many actions and mechanisms. They are components that replace slipping friction movement to rolling movement between two surfaces, and thus serve to reduce friction contact, avoiding loss of movement energy (Jiang *et al.*, 2023). The rolling bearing can be produced in different setup, but the most commonly used is the ball bearing, which is capable of supporting either axial and radial loads. Due to its practical assembly, this was the selected rolling bearing selected as a specimen for this study.

These mechanical components are widely employed in the industry and constitute one of the most crucial elements, particularly in rotating machinery. As evidence of the significance of rolling bearings, numerous research efforts and studies have been conducted over the years, and they continue to be undertaken with the aim of enhancing bearing performance. While the manufacturing of rolling bearings has now achieved high levels of quality, leading to increased durability and lifespan, they are still susceptible to wear and potential failure.

Failures can occur in various ways, through electrical discharge, impact, overload, or material oxidation (DIAS, 2021). Regardless of the mechanism of failure, it is necessary to monitor the condition of the bearing in a manner that allows for replacement before it reaches a critical operational state. This procedure is a well-known method of predictive maintenance. Thus, the tool employed for this purpose is vibration analysis.

Among the variables of defects that may be present, defects present in the inner race of the bearings will be specifically addressed. Which can have significant effects on its reliability and performance, so this targeted approach increases the efficiency of the maintenance system. Therefore, it is necessary to develop methods for processing vibration signals to detect and characteristic components of failure in that element in question. Such processing methods are not trivial procedures and require specialized treatment to obtain reliable and accurate results. So, to identify defects in the inner race of a bearing, a new signal acquisition and processing system was developed, using programming and specific vibration concepts. This mechanism is capable of managing input signals and presenting, if present, the characteristic frequencies of this defect.

The objectives of this work are to set up an experimental test rig for data acquisition and subsequently process the data using a LabView program. The program will be designed to read signals emitted by the bearings, both with and without defects, and apply various vibration analysis techniques such as signal filtering, Hilbert Transform, FFT (Fast Fourier Transform), and envelope analysis. The processed data will then be plotted on specific graphs for further analysis. The main focus of the program and methodology is to accurately identify the frequencies associated with defects in the inner race of bearings.

In this study, vibration analysis has been employed with the assistance of a data acquisition system. The initial step involved acquiring the bearing signature, which serves as a reference signal for subsequent comparisons between bearings without defects and those exhibiting various faults. This signature provides a baseline for identifying and diagnosing bearing defects. The current focus of this project is to identify the defect in the inner race of the bearing and graphically display its frequencies. Through the experimental setup, four types of bearings will be studied: one without any defects (bearing signature) and three with progressively increasing defects, varying in the degree of defect magnitude.

All stages were carried out at the Laboratory of Vibrations and Acoustics (LVA) - UFV.

2. THEORETICAL FOUNDATION

2.1 ROLLING ELEMENT BEARING TYPE

The ball bearings are characterized by having different components from other machine elements, each with its own specific function and subjected to its own stress and wear. Thus, defects can occur during their use or even during the manufacturing process, affecting any of the components and impacting their main parts, such as the outer race, cage, rolling elements, and inner race (Santos *et al.*, 2017). This work will be based on studies of a specific type of bearing, self-aligning bearings, as shown in Figure 1.

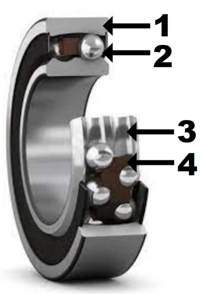

Figure 1. This is a self-aligning ball bearing and its components, 1- Outer racer, 2- Rolling elements, 3- Inner race, 4- Cage.

Source: (SKF, 2023)

2.2 FREQUENCIES

Vibration analysis can be performed in the time and frequency domains, correlated to amplitude, where each domain provides a different perspective (Kramti *et al.*, 2021). However, in certain contexts, the time domain may not provide much relevant information, and so the transforming the signal to the frequency domain becomes interesting and more useful, allowing for observation from a different standpoint.

Also known as the vibration spectrum, it can be used to provide a clearer monitoring of changes occurring in the equipment, specifically referring to modifications in amplitude and appearance of different frequencies generated by the material and neighboring sources.

Therefore, the bearing generates certain frequencies related to the passage of each of its components over defects or through friction, which generates vibrations due to imperfections between the components, as shown in Figure 1. As a defect begins to appear, the frequencies associated with its passage stand out from the others in the spectrum.

It is also important to consider an essential point of comparison, which is the bearing signature. This refers to the initial signal emitted by the bearing, establishing a vibration pattern that will be used to identify any signal alterations.

In this approach, it becomes feasible to identify and trace faults in the spectrum. This is achievable because the frequencies that usually manifest themselves are already known and can be calculated through geometric relationships. In cases where not all dimensions of the bearing are available, approximations can be adopted to establish, for example, a relationship between the number of rolling elements and the frequency of defects. The following expressions can be utilized for this purpose (Büchner, 2001):

$$BPFO = RPM \cdot (\frac{N_e}{2} - 1.2), \tag{1}$$

$$BSFI = RPM \cdot (\frac{N_e}{2} + 1.2), \tag{2}$$

$$BSF = \frac{RPM}{2} \cdot (\frac{N_e}{2} - \frac{1.2}{N_e}) \text{ and} \tag{3}$$

$$FTF = RPM \cdot 0.45 - 0.35. \tag{4}$$

Where N_e - Number of rolling elements, RPM - rotation per minute, $BPFO$ - Ball Pass Frequency Outer Race, $BSFI$ - Ball Pass Frequency Inner Race, BSF - Ball Spin Frequency, and FTF - Fundamental Train Frequency .

Thus, bearings can exhibit multiple defect frequencies owing to their composition of various components, each with its own unique defect passage frequency. For example, defects in the outer race correspond to BPFO, while those in the inner race are associated with BPFI. The rolling element pass frequency is denoted by BSF, and the cage pass frequency is represented by FTF (Jiang *et al.*, 2023). By examining these characteristic frequencies more closely, it is possible to observe distinct aspects among them. The peaks, with their specific amplitudes and possible sidebands, can reveal the type of defect present in the bearing through this signal analysis. These spectra are one of the main points of comparison with the bearing signature, as they can highlight existing faults. These spectra can be directly obtained or can also be related to rpm counts (Büchner, 2001), which are also included in the Eq. (1), (2), (3) and (4).

2.2.1 FREQUENCIES FILTERS

Usually, when measurements are taken on real equipment, several of its components or even nearby sources can generate noise simultaneously. This noise mixes with the desired signal, which typically has low frequencies and a high energy content. This leads to signal masking and makes it challenging to distinguish the signal of interest. To solve this problem, specific filters can be applied in each case to obtain frequency intervals that exclude the noise from the main signal, making it easier to diagnose the defect. Three specific filters can be used:

- Low-pass filter: Allows signals below a maximum cutoff frequency to pass through, while frequencies above the cutoff will be excluded from the visualization.
- High-pass filter: Allows signals above a minimum cutoff frequency to pass through, while frequencies below the cutoff will be excluded from the visualization.
- Band-pass filter: Specifies a range of frequencies, where frequencies within the range will be displayed and those outside the range will be excluded.

2.2.2 FREQUENCY DOMAIN

When vibration data is obtained from a machine or mechanical structure through a sensor, this continuous signal is in the time domain, which is not very useful and requires more time for conclusions. To make the signal more valuable and applicable, it can be transformed into the frequency domain using the Fast Fourier Transform (FFT), a mathematical approach to mapping a time-domain function into a frequency-domain function, that computationally applies the Fourier Transform. This transformation offers advantages such as low operational costs and shorter processing time (Kramti *et al.*, 2021). The time domain signal and its correspondent frequency domain are shown in Figure 2.

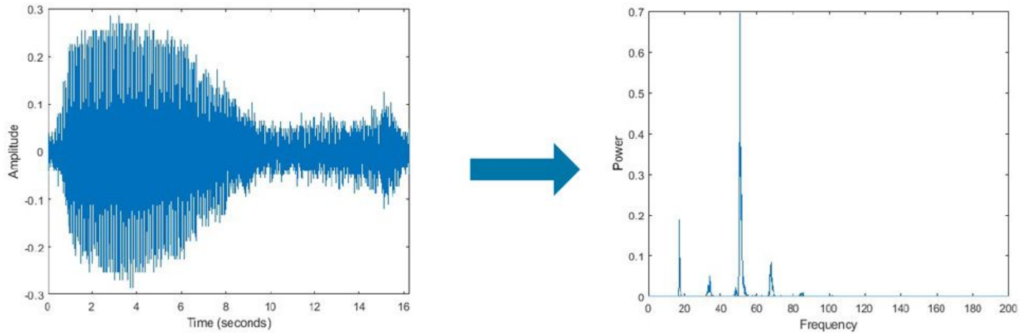

Figure 2. Here there are two examples, in the left is the time domain signal and in the right is the correspondent spectrum (FFT).

Source: (MathWorks, 2023)

2.3 HILBERT TRANSFORM

The Hilbert Transform is a widely used process for signal demodulation, especially when dealing with mechanical faults such as bearing defects, which often result in modulated signals. This technique enables the generation of complex signals from real signals, which are then used to obtain the signal envelope (Al-Obaidi and Towsyfyan, 2019). It is particularly useful in detecting and quantifying faults in bearing components. The Hilbert Transform is an essential tool in vibration analysis and diagnosis. It can be mathematically expressed by the Eq. (5) (Büchner, 2001):

$$y(t) = H\{x(t)\} = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{x(y)}{t-y}dy, \tag{5}$$

where:
$x(t)$ - Original data in time domain.

2.4 ENVELOPE TECHNIQUE

It is important to note that when analyzing signals, the received signal is not clean and contains various noises and frequencies that are not of interest, and they should be discarded. To overcome this unwanted condition, the technique of the envelope is used (DIAS, 2021).

This technique consists of correlating a high-frequency signal, called the carrier, which carries the signal from one point to another, with another signal called the modulator, which modulates the carrier, so that a high-frequency signal is modulated by another low-frequency signal (Büchner, 2001).

In vibration analysis, this is known as demodulation, which is nothing more than separating the two signals in order to decode the received signal and find the modulator, which is ultimately the signal of the defect. Thus, graphically, a line that continuously traverses the maximum peaks of the signal is known as the envelope.

The application of the envelope should follow the following steps:

1. The signal should be obtained in the time domain.
2. This signal should be transformed into the frequency domain by applying the Fast Fourier Transform (FFT), and based on this spectrum, the resonances where changes occurred are analyzed.
3. The signal is then filtered by applying a low-pass, high-pass, or band-pass filter around the chosen resonance.
4. The signal is acquired again in the time domain.

5. The Hilbert Transform is applied to the signal, as it is a digital signal.
6. Acquiring the envelope of the signal, the Fast Fourier Transform (FFT) is applied to transform the signal into the frequency domain and obtain its spectrum (Büchner, 2001).

These steps can be illustrated by Figure 3:

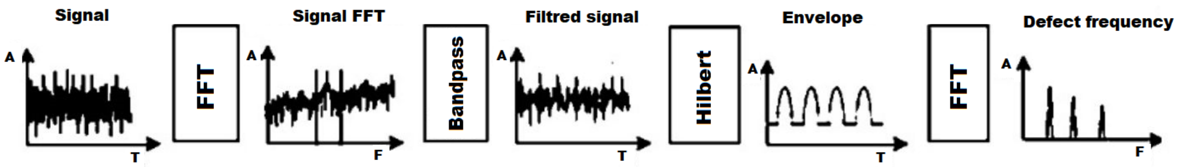

Figure 3. Basic scheme for obtaining the envelope spectrum.
Source: (Bezerra, 2004)

3. SIGNAL ACQUISITION

To perform signal acquisition, the entire experiment was conducted in a controlled laboratory equipped with specific materials for signal measurement. A custom experimental setup was built using concrete as a foundation, which provided a stable platform for assembling the motor system, bearing housings, and shaft.

The system consists of a motor that applies torque to a shaft, two bearing housings with bearings are mounted on the shaft, and the rotation of the shaft generates the movements and vibrations that will be captured. The assembly was designed to ensure optimal material compatibility, facilitate bearing insertion, and enable easy replacement without the risk of introducing additional forces that could cause unintended defects. It's important to note, that the shaft hasn't an extra load, only its own weight, that is about 1.7 kg, what demand of the acquisition system a better sensibility to get results. The materials used in the experimental setup are shown in Figure 4 .

(a) Experimental bench used (b) Equipment used

Figure 4. Figure 4a. 1- accelerometers, 2- self-aligning bearings, 3- shaft, 4- support, 5- acoustic sensor and Figure 4b. 6- phase inverter, 7- motor, 8- computer and monitor.

The bearing housings serve as the basis for the signals to be analyzed. Acoustic sensors and accelerometers (PCB Piezotronics, sensitivity of 99,0 mV/g), were installed around the bearing housings to capture the noise and signals generated by the bearings. These sensors transmit the data to a dedicated National Instruments computer, the NI PXIe-1071, capable of reading and processing the acquired signals. The signals are then analyzed and processed using the vibration analysis concepts mentioned earlier, utilizing the LabView engineering software.

3.1 LABVIEW SOFTWARE - OPERATION

With all the theoretical knowledge and practical means at hand, LabView was the main computational tool used for signal analysis, being fundamental to the research, it made it possible to store and work with the experimental data, thus leading to results by integrating concepts and steps with the software.

The software has an initial interface that interacts with the user, that it was designed to provide inputs such as the type and frequency range of the applied filter, selection of specific channels for data recording (accelerometer signal channels, acoustic sensors, or excitation hammer), as well as outputs such as step-by-step graphs, these display the initial signal, the signal after the application of the filter, the graphical representation of the envelope after Hilbert transform, and the final frequency spectrum plot, which presents the type and magnitude of apparent defects in the bearing. Statistical data analysis is also performed, including measures such as median, mode, mean, variance, standard deviation, rms, and kurtosis. These are conceptually applied to the signal, and by obtaining these values from the bearing signature and subsequently from defective bearings, they serve as another basis for comparison to determine which variable is the most sensitive.

The layout of the initial page was designed to be user-friendly, ensuring ease of understanding and interaction. Additionally, it aimed to have a good visual appearance that enhanced the value of the program. The developed program consists of blocks and wire connections, where the entire programming logic revolves around finding solutions through signal analysis using built-in structures and developing around them. This results in a useful program that enables the project by working with the signal from its acquisition to envelope generation and obtaining the frequency spectrum. An example of the interface layout is shown in Figure 5.

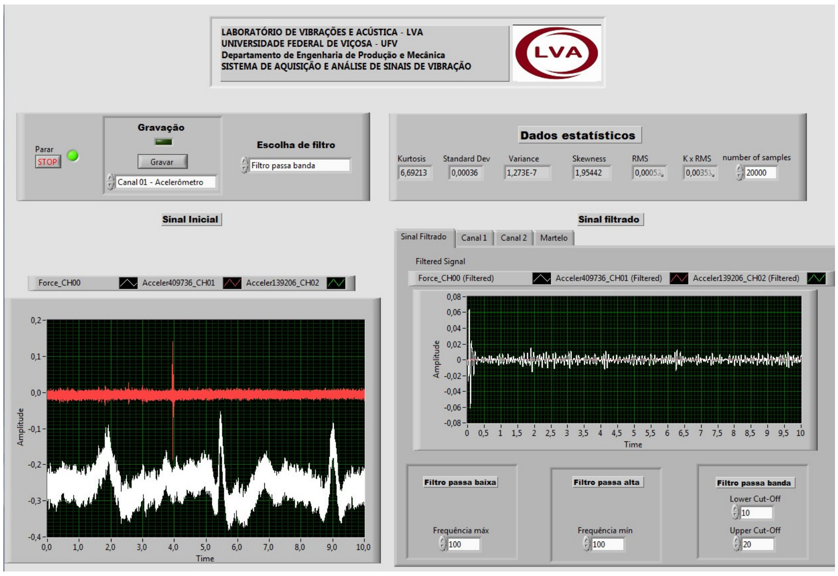

Figure 5. Initial page layout with signal graphics, recording options, statistical data and choice of filters.

3.2 DEFECTS

The bearings will also undergo the process of defect insertion. This analysis will involve a metallographic examination of the bearings and the introduction of localized defects in their components (Figure 1). Experimental tests will be conducted to obtain vibration signals from these defective bearings. The damage on the inner race specimen has been observed through Optical Profilometer (Figure 6). When the penetrator is pressed against the surface, it creates a mark. In the center of this mark, a hole is formed, accompanied by some strain hardening region around it.

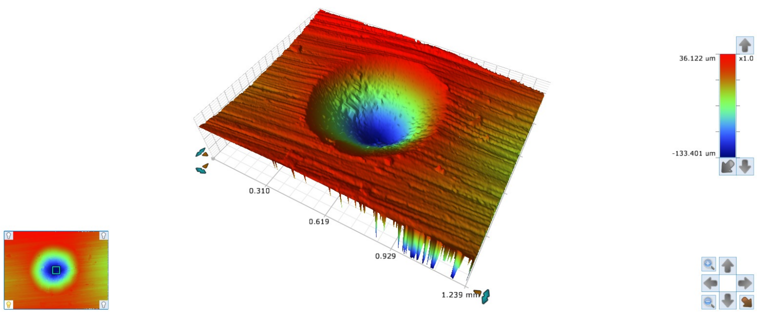

Figure 6. Defect image taken through Optical Profilometer 3D - Contour GTK.

Thus, the procedure of introducing the defect in the three bearings was carried out, where performing the disassembly of the mechanism and having the inner race in hand to be only worked on in this step, it was supported on a support in V and demarcated its surface, to fix a load application point, the damages were done in the laboratory by a penetrator from a hardness tester, which were named as G1, G2, and G3, corresponding to the forces applied to create the damage, as shown in Table 1.

Table 1. Defect forces

	G1	G2	G3
Kgf	60.0	150.0	250.0

3.2.1 FREQUENCIES OF DEFECTS

To perform the spectral analysis of the envelope, it is necessary to know the characteristic frequencies that are related to bearing defects. These frequencies can be calculated using the formulas 1,2,3 and 4, which involve the number of rolling elements. To simplify the calculation and visualization, the values are expressed in Hz and the rpm factor can be converted to Hz by dividing its value by 60. Thus, the experimental setup was used with the motor generating a fixed rotation of 597 rpm (approximately 9.95 Hz) on the shaft. By using this value and considering the 12 rolling elements of the bearing, were obtained the expected values for the defect pass frequencies, which can vary by up to 24 %, as shown in Table 2.

Table 2. Defect passing frequencies

Hz	BPFO	BPFI	BSF	FTF
9.95	47.76	71.64	29.35	4.13

Based on this and having conducted experiments for a specific type of defect, the frequency band to be analyzed is that of the inner race defect (BPFI). Using Equation (2), was determined that the defect frequencies should be present in the range of 54.4 Hz to 88.8 Hz, which will also be the minimum and maximum cutoff values for the filter applied to the signal.

4. RESULTS AND DISCUSSION

4.1 ANALYSIS OF THE ENVELOPE SPECTRUM

Having already calculated the frequency range in which the defect in the inner race should be present, this was analyzed for the bearings without defects and with defects G1, G2, and G3. Following the established frequency pattern, filters were applied to obtain data within this 24% range of component defect. The first measurement corresponds to the bearing signature without any defects, considering the inner racer, as depicted in Figure 7.

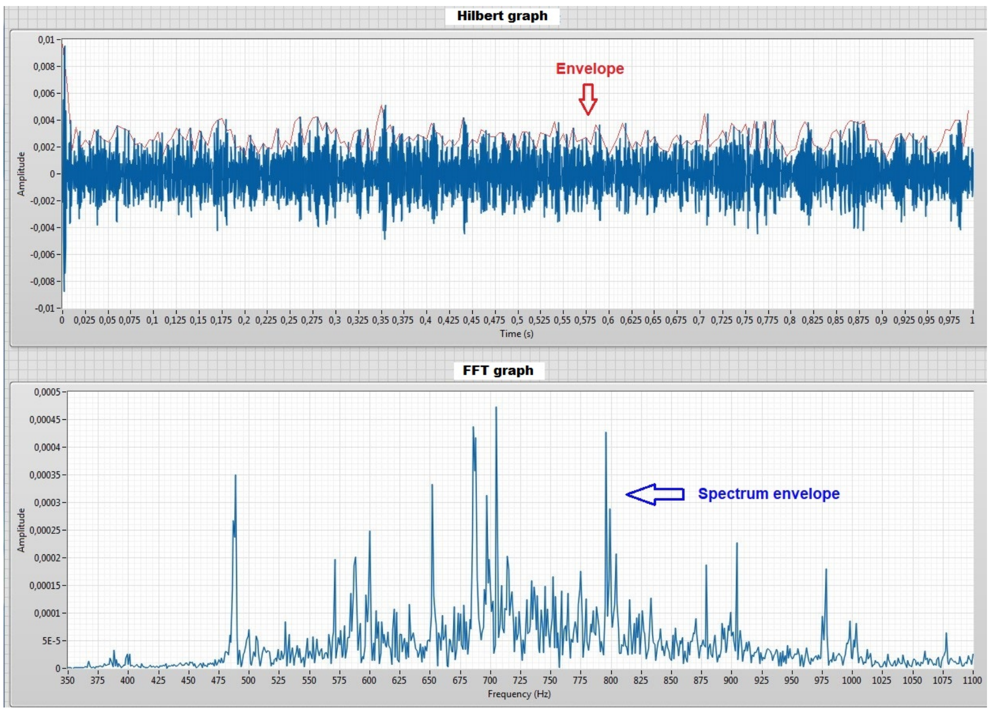

Figure 7. Bearing signature, in red on the Hilbert graph is the envelope and in blue on the FFT graph is the frequency spectrum.

In Figure 7, it shows graphical aspects of the envelope and the frequency spectrum. The frequency spectrum, or just spectrum, is formed by spectral lines. Each of them has a frequency, which may or may not be related to something of interest, such as the frequency of passage in bearings. The spectrum shows any small peaks with irrelevant amplitudes that probably indicate problems of imbalance and misalignment. Using the envelope and envelope spectrum graphs, it is possible to conclude whether the defects exist by delimiting the x-axis from 350 Hz to 1100 Hz, which is the range where the defect's passing frequencies are located. The peaks related to multiples of the BPFI frequency are accompanied by the identification of the defect and the corresponding multiple value. Then, with the G1 defect inserted in the bearing, the signals in Figure 8 were obtained.

In these results, it is more important and relevant to look at the FFT graph, where are present the frequency spectrum, that is extracted from the envelope by the FFT. Therefore, this is our main focus for the results.

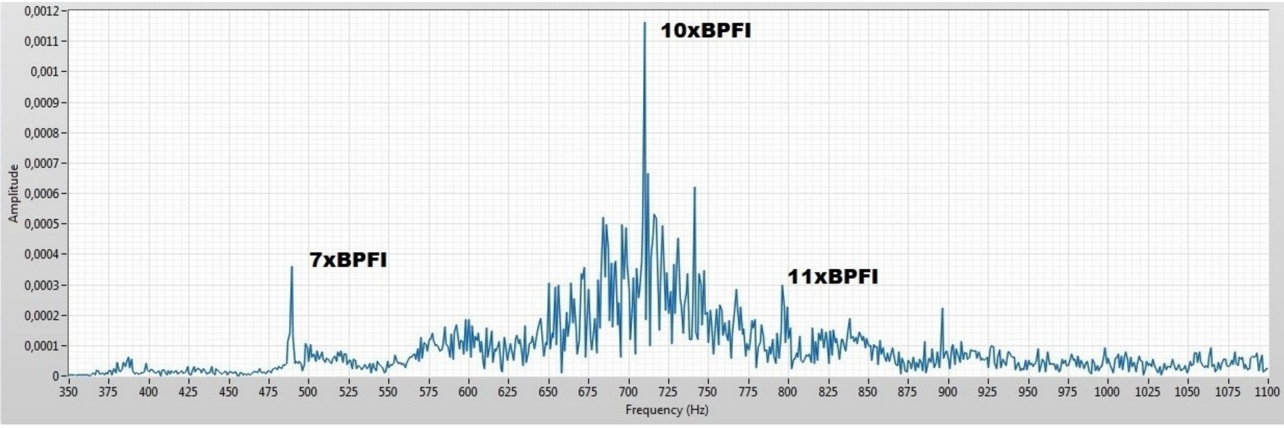

Figure 8. Envelope spectrum, with BPFI identified in the G1 defect. In focus, 489 hz - 7xBPFI, 710 hz - 10xBPFI, 796 hz - 11xBPFI, approximated values.

There is a noticeable increase in the amplitude values, indicating a higher magnitude and intensity of the signal. Three multiple frequencies of BPFI were found, considering the approximations and the range where the defect is located, it is also possible to observe regions where there is a higher intensity of frequencies with greater amplitude, indicating greater resonance. In this way, it is possible to conclude that the defect is indeed present in the bearing. Then, the previous was replaced, and the bearing with defect G2 was introduced. It is expected to see normal graphical changes, but with noticeable BPFI frequencies still present, as in Figure 9.

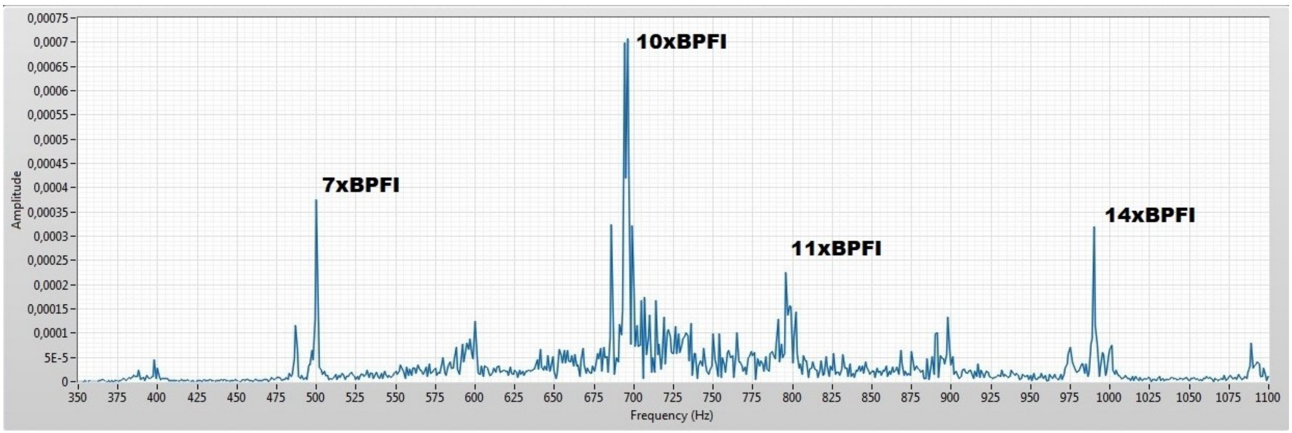

Figure 9. Envelope spectrum, with BPFI identified in the G2 defect. In focus, 500 hz - 7xBPFI, 696 hz - 10xBPFI, 796 hz - 11xBPFI, 990 hz - 14xBPFI, approximated values.

Thereby, the signals from the defect in Figure 9 have changed, but the pattern remains with multiples of 7 and 10 times BPFI and a narrow band of intensified frequencies, similar to G1. In addition to these defect frequencies, peaks at 11xBPFI and 14xBPFI were also obtained with distinctive amplitudes, providing sufficient evidence to conclude once again that the defect (BPFI) is present in the bearing. Finally, after introducing the bearing with the G3 defect, new envelope and spectrum graphs were obtained, which provided conclusive results for the project, as noted in Figure 10.

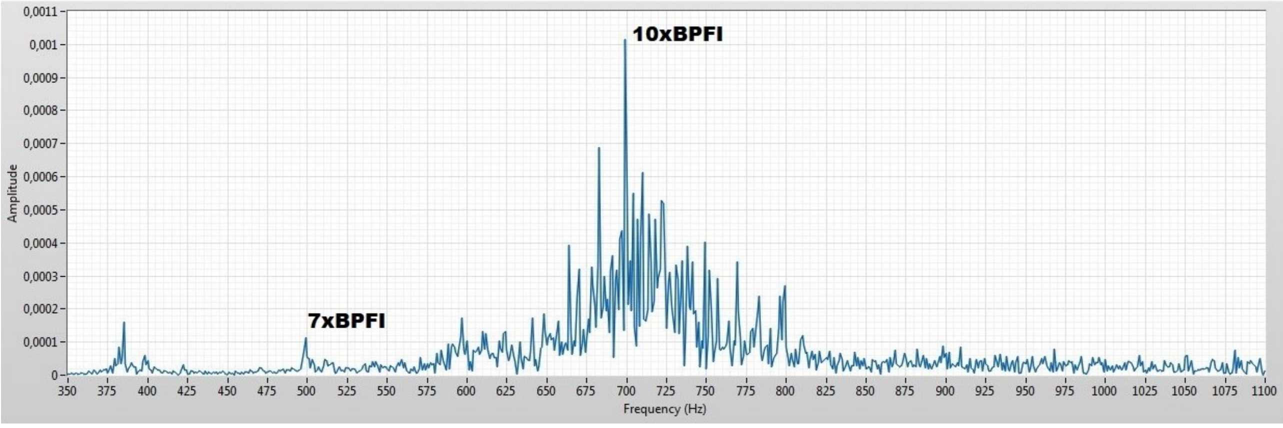

Figure 10. Envelope spectrum, with BPFI identified in the G3 defect. In focus, 499 hz - 7xBPFI, 699 hz - 10xBPFI, approximated values.

Thus, it can be observed that the spectrum of the envelope behaved as expected with the new defect, which maintained patterns such as multiples of 7 and 10 times BPFI, similar to G1 and G2. This indicates that the defect being studied is the same and exhibits greater variations in its magnitude. It is also noteworthy that there was another narrow band of intensified frequencies, that showed a higher elevation compared to the previous cases. Therefore, it is possible to once again conclude that the BPFI defect is present in the bearing.

Thereby, having used the spectrum graph with defect frequencies, the values in focus are able to conclude about the presence of the defect in the inner race, and the narrow band of intensified frequencies show that defects have a higher resonance in this region, which also explains the type of defect in the bearing.

5. CONCLUSIONS

With the application of the proposed method, the LabView program was able to process the data, whether a bearing with defect or not, the signal of each bearing was evaluated in the experimental setup through the computational system. Applying the vibration analysis techniques presented, the defects in the bearing's inner race were found, and their signs could be shown and differentiated from those of a non-defective bearing. Thus, the processed data can be shown in frequency graphs, which show the presence or absence of the defect in the inner race, it is also possible to see the main frequencies of the defects, if presented.

At the conclusion of the study, it becomes evident how the implemented method can get results. From signal acquisition to the final spectrum analysis of the envelope, signals were processed with expected accuracy, permitting a better comprehension of the correlation between signals acquired and the defects in the bearings. And, even without an extra load, with only the weight of the shaft, it's noted that the program could be sensitive enough to show the presence of the defects in the bearing's inner race.

As it has been observed, adept utilization of these techniques allowed the extraction of data that evidenced the presence of defects within the inner race of the bearing. Across three specimens of bearings, each one featuring a defined degree of defect, a consistent relationship was observed between vibration amplitude and severity of damage. Thus, they exhibit similar or identical defect frequencies with varying magnitudes.

In conclusion, the developed program is still being in improvement, but it is already able to monitor defect pass frequencies systematically in bearings. Therefore, it becomes clear how the significant problem of bearing failures in industries and vehicles requires attention. However, with this proposed method, monitoring bearings with defects in the inner race becomes possible and can be further developed for implementation, thus identifying these defects and preventing losses in industrial areas. Additionally, it highlights the importance of this topic in the academic community, making it possible to study the method further and disseminate it for more effective applications.

To future projects, it will be added the capabilities with new technologies, such as Wi-Fi and other techniques and methods, and encompassing the identification of other types of bearing defects and their combinations, and thus, creating an autonomous system capable of managing and monitoring the performance of ball bearings and, when detecting the first signs of defects, the system, using Wi-Fi, will ensure that bearings are replaced in a safe timeframe, preventing failures.

6. ACKNOWLEDGEMENTS

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viable.

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