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DEVELOPMENT OF A DIDACTIC MODULE FOR EVALUATING BEARINGS USING VIBRATION SIGNS ANALYSIS

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ABSTRACT

Motors are composed of several components, particularly bearings, which when defective, cause malfunctions that damage motors and cause downtime in the production process. To monitor the condition of the bearings, predictive maintenance is used, which may be through the analysis of the vibration signal of the bearings. Several techniques can be used for vibration analysis, highlighting the spectral analysis associated with the envelope technique. To elucidate existing information for didactic purposes, this work simulated the operating signals of a rotating system and faults in a bearing and then applied the envelope technique to identify these faults. In a second step, defects were induced in bearings, and experimental tests were conducted using a didactic bench developed for this purpose, with the acquisition of vibration signals and application of the envelope technique to identify and measure defects.

KEYWORDS: Vibration analysis; Bearing failures; Envelope technique; Didactic bench.

DESENVOLVIMENTO DE UM MÓDULO DIDÁTICO DE AVALIAÇÃO DE FALHAS EM MANCAIS ATRAVÉS DA ANÁLISE DE SINAIS DE VIBRAÇÃO

RESUMO

As máquinas são compostas por diversos componentes, destacando-se os rolamentos, os quais, quando apresentam defeito, causam desde mau funcionamento até danos às máquinas e paradas no processo produtivo. A fim de monitorar o estado dos rolamentos, utiliza-se a manutenção preditiva, podendo ser ela através da análise do sinal de vibração dos rolamentos. Diversas técnicas podem ser utilizadas para análise de vibrações, destacando-se a análise espectral associada à técnica do envelope. Buscando elucidar as informações já existentes para fins didáticos, neste trabalho foi realizada a simulação dos sinais de funcionamento de um sistema rotativo e de falhas em um rolamento e então aplicada a técnica do envelope para identificar estas falhas. Em um segundo momento, foram induzidos defeitos em rolamentos e realizados testes reais utilizando uma bancada didática desenvolvida para esse propósito, com a aquisição dos sinais de vibração e aplicação da técnica do envelope para identificação e mensuração dos defeitos.

PALAVRAS-CHAVE: Análise de vibrações; Falhas em rolamentos; Técnica do envelope; Bancada didática.

1 INTRODUCTION

Due to the robust growth of industries and the high market competition, the increase in production has become increasingly intense and necessary, which generates concern among companies regarding the performance of the equipment involved in the production processes. The high increase in production causes motors and equipment to operate increasingly closer to the design limit values, increasing the frequency of the need to exchange parts and materials; that is, there is a consequent increase in the need for the application of maintenance techniques, aiming to increase the useful life of these motors.

Aiming for industrial maintenance that demands a high production rate, the predictive maintenance technique stands out, which allows the user to identify failure modes before they occur. According to Nascif and Kardec (2009), predictive maintenance is updating performance criteria based on modifying operational conditions or performance parameters by using numerical approaches to predict the monitored conditions. When necessary, corrective action follows planned corrective maintenance procedures.

On the other hand, rolling bearings are motor elements present in various rotating equipment widely used in industrial applications. Due to its wide use, it has generated an elevated level of concern regarding monitoring these elements as if it were to fail, the motors would often become unusable, which could result in catastrophic losses for the company.

Therefore, it is necessary to propose techniques based on vibration analysis to efficiently identify defects in rolling bearings. Following this line of reasoning, this study initially generated vibration signals from rotating systems with bearing failures and implemented signal analysis techniques to identify the defects.

Accordingly, the study employed mathematical models of a rotating system with bearing defects and implemented vibration signal analysis techniques to identify faults. Based on the experience gained, the researchers designed a module for a teaching bench, enabling experimental tests that allowed the identification of induced bearing faults.

2 METHODOLOGY

This study developed a didactic module for analyzing vibration signals in bearings to demonstrate and identify diverse types of failures.

Initially, the study approached the problem theoretically, simulating rotation signals from a system with defects in bearing housing and applying the envelope technique to identify the characteristic frequencies of these faults. Subsequently, a didactic module was developed for the experimental validation of the simulated technique through the induction of defects in a bearing.

The researchers collected vibration signals using accelerometers and a data acquisition board and analyzed them using the envelope technique. This approach enabled the comparison of the results obtained, ensuring greater accuracy in fault analysis.

2.1 Signal Analysis

According to Budynas and Nisbett (2011), rolling bearings are the class of bearings in which the main load is applied through rolling elements. These loads are designed to support pure radial loads, axial loads, or a combination of the two types of loads.

Nepomuceno (1989), states that the main failures in rolling bearings arise from inadequate lubrication, incorrect assembly, inadequate seals, misalignment, passage of electric current, external vibrations, manufacturing defects, and fatigue.

Bezerra (2004) explains that contact between the defective surface and another non-defective surface of the bearing produces a shock, generating an impulse that excites resonances in the bearing and the motor. These impulses occur periodically and at a frequency determined solely by the location of the defect, which may be on the internal or external race or the rotating element.

Figure 1 shows the bearing dimensions used to calculate its elements' characteristic frequencies. The contact angle and main characteristic frequencies are also indicated. The diameter of the sphere (d), the pitch diameter (D), the inner race diameter (d_{pi}), the outer race diameter (d_{pe}), the contact angle (β) and the number of spheres (N_e).

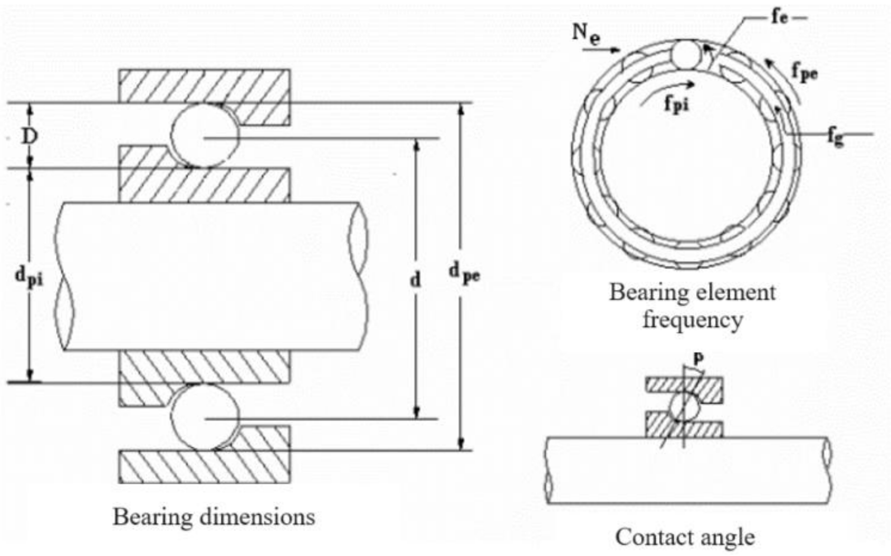

Figure 1: Frequencies, dimensions, contact angle of a bearing.

Source: Meola, 2006.

For the case in which the outer race remains stationary (f_{pe} = 0) and the rotation frequency is that of the inner race f_{pi}, the typical bearing frequencies are determined from Equations (01) a (04) (BARILLI, 2013).

Equation (01) represents the characteristic frequency of the bearing cage.

$$fg = \frac{f_{pi}}{2}\left(1 - \frac{d\cos\beta}{D}\right) \quad (01)$$

Equation (02) calculates the characteristic frequency of the inner race bearing.

$$fdpi = \frac{N_e f_{pi}}{2}\left(1 + \frac{d\cos\beta}{D}\right) \quad (02)$$

Equation (03) expresses the characteristic frequency of the outer race of the bearing.

$$fdpe = \frac{N_e f_{pi}}{2}\left(1 - \frac{d\cos\beta}{D}\right) \quad (03)$$

Equation (04) calculates the characteristic frequency of the bearing sphere.

$$fde = \frac{D f_{pi}}{2d}\left(1 - \frac{d^2\cos^2\beta}{D^2}\right) \quad (04)$$

According to Duarte (1998), most existing motors and equipment perform movements with a limited cycle, being alternative or rotary. As a result, the frequency spectrum of the vibratory quantities of these motors and equipment is characterized by a broadband noise added to discrete components of significant amplitudes, whose frequencies are closely related to the kinematics of the movement of each part of the mechanisms or the natural frequencies of the system.

Therefore, knowing the frequencies at which the main motor elements generate forced vibrations due to the alternation of movements, it is possible to identify, via frequency spectrum analysis, the part of the motor that is having problems.

2.2 Spectral Analysis

Fourier demonstrated that any periodic function admits a representation as a series of sines and cosines given by Equation (05), in which A_0 is the average signal level, A_i e B_i are the Fourier coefficients, T is the period and t is the time vector. Equations (06) and (07) calculate the Fourier coefficients A_i and B_i (Meola, 2006).

$$x(t) = \frac{A_0}{2} + \sum_{i=1}^{\infty} A_i \cos\left(\frac{2\pi i}{T} t\right) + \sum_{i=1}^{\infty} B_i sen\left(\frac{2\pi i}{T} t\right) \quad (05)$$

$$A_i = \frac{2}{T}\int_0^T x(t) cos\left(\frac{2\pi i}{T} t\right) dt \quad (06)$$

$$B_i = \frac{2}{T}\int_0^T x(t) sen\left(\frac{2\pi i}{T} t\right) dt \quad (07)$$

Using factorial notation, Equation (08) represents the terms of the Fourier series.

$$x(t) = \frac{A_0}{2} + \sum_{i=1}^{\infty} C_i e^{j\left(\frac{2\pi i}{T} t + \emptyset_i\right)} \quad (08)$$

where: $C_i = \sqrt{(A_i)^2 + (B_i)^2}$; $\emptyset_i = tg^{-1}\left(\frac{B_i}{A_i}\right)$; $j = \sqrt{-1}$

Figure 02 shows the representation of the components *Ci* of the signal. This type of graph, called a frequency spectrum, is analyzed through spectral analysis (Meola, 2006).

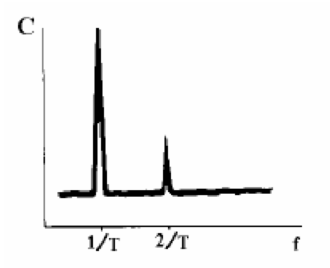

Figure 02: Representation of Components C_i of the acceleration signal.

Source: Meola, 2006.

In cases where the signal is not periodic, simply consider that it can be treated as a signal in which period T tends to infinity. In this case, the fundamental frequency $1/T$ tends to zero, and the frequency spectrum, which is discrete for periodic signals in a finite interval, becomes continuous, with the series replaced by the Fourier integral (MEOLA, 2006).

2.3 Envelope Method

Büchner (2001) states that, when measuring a motor, generally, several of its components or neighbors may be generating noise at the same time, with low frequencies, presents a significant energy content and ends up covering the failure signal of the bearing in the early stage, making it practically impossible to carry out a direct spectrum diagnosis. This phenomenon, known as masking, has a low ratio between signal and noise. This phenomenon, known as masking, occurs when the signal-to-noise ratio is low. Therefore, the envelope technique addresses such cases.

Excessive clearances and initial failures in motor components produce a series of impacts that are equivalent to an impulsive type of excitation, which acts on the structure, that is, the motor is excited at its natural frequencies. Mathematically, the natural frequencies of the motor modulate the excitation frequency. As these impacts last only briefly, they contain a remarkably high amount of energy that spreads across the entire frequency spectrum. Since the vibration spectrum of motors contains numerous spectral components at medium and low frequencies, the effects of these impacts appear most clearly in higher-frequency resonances, particularly in cases of rolling bearing failures, which exhibit remarkably high rigidity (Meola, 2006).

Envelope technique is a concept applied to data transmission and reception. A high-frequency signal (carrier) transports the signal from one point to another. The carrier signal modulates the signal of interest (modulator). Thus, the modulation process involves as a high-frequency signal modulating a low-frequency signal (RANDALL et. al., 2011).

According to Choudhury (1999), envelope analysis, or high frequency resonance technique (HFRT), identifies defects by extracting characteristics of signal defect frequencies. In signal processing, a band-pass filter removes unwanted signals, and afterward, and an envelope detector subsequently filters and demodulates the signal.

The Demodulation process is nothing more than separating the two signals. The objective, therefore, is to decode the received signal by finding the modulating signal, which, in fact, is the defect signal itself. Figure 03 shows an example of a signal envelope.

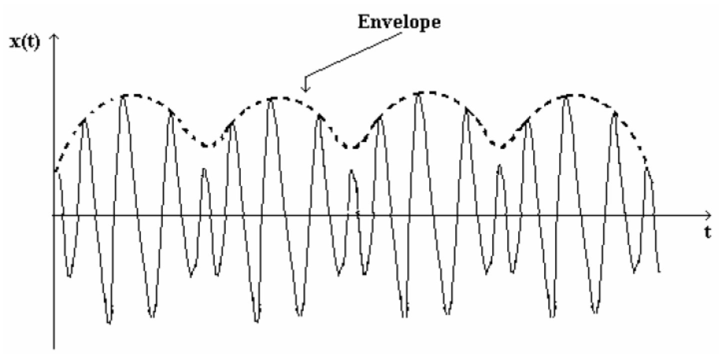

Figure 03: Example of Signal Envelope.

Source: Meola, 2006.

According to Brito (2012), Envelope analysis is a tool that highlights the repetitions of a pulse in each time interval. When studying bearing failures, the analysis identifies the frequency generated by the pulse resulting from the repetitive passage of the rolling element over the defect.

To apply the HFRT technique, the following order is necessary:

1. Acquire the signal in the time domain;
2. Apply the Fast Fourier Transform (FFT) to convert the signal into the frequency domain. Based on this spectrum, identify the frequencies where notable changes occur;
3. Filter the signal using a band-pass filter around the fault frequency. Use the signature spectrum to verify these changes;
4. Obtain the analytical signal (demodulation) via the Hilbert Transform;
5. Finally, apply FFT again to convert to a new domain and extract the characteristics bearing failure frequencies.

2.4 Rotating System Simulation

This study employed an MKP15-01 bearing with an external diameter of 32 mm, an internal diameter of 15 mm, nine rolling elements of 4.8 mm in diameter, and a contact angle of 0°. The rotational speed selected for the work was 1200 rpm (20 Hz).

Equations 01 to 04 allow estimation of the characteristic frequencies of the bearing components, as shown in Table 01.

The signal of a rotating component follows a sinusoidal pattern, as shown in Equation (09).

$$y = A.sin(2.\pi.f.t + \varphi) \quad (09)$$

where, A is the signal amplitude, f is the frequency in Hz, t is the time vector e φ is the phase signal.

Table 01: Characteristic Frequencies of the bearing components.

Bearing component	Frequency (Hz)
Shaft rotation (FR)	20,0
Inner race (FPI)	108,4
Outer race (FPE)	71,6
Rolling elements (FER)	47,0
Cage (FG)	8,0

Equation (09) models the signals from engine rotation (*f* = FR), system components (white noise), and all bearing components with their characteristic frequencies (FPI, FPE, FER, and FG).

The bearing components signals are modulated by the rotation signal to simulate bearing defects in the inner race, outer racer, rolling elements, and cage. In the first step, each fault is simulated individually to allow for reliable verification of the technique, before all of them were subsequently combined into a single simulation.

Amplitude values equal to 1.0 are assigned to the signals from the bearing and engine rotation components and 0.5 for the white noise representing to the system components. The phase was set to zero in all cases.

To illustrate the process, the simulation of an inner race fault signal is described. Initially, the signals for motor rotation (Equation 10), system components (Equation 11), and the inner race (Equation 12) are generated.

$$S_{mot} = A_{mot} \, . \, sin(2.\pi.FR.t + \varphi_{mot}) \quad (10)$$

$$S_{aleat} = A_{aleat} \, . \, White\_noise \quad (11)$$

$$S_{PI} = A_{PI}.sin(2.\pi.FPI.t + \varphi_{PI}) \quad (12)$$

where: A_{mot} e φ_{mot} are the amplitude and phase of motor signal, A_{aleat} is the amplitude of the system components signal, White_noise is a random signal that simulates the systems components, A_{PI} e φ_{PI} are the amplitude and phase of the inner race signal.

The motor rotation and system components signals are associated, creating the system signal by Equation (13), and the inner race signal is modulated at the rotation frequency by Equation (14).

$$S_{sist} = S_{mot} + S_{aleat} \tag{13}$$

$$S_{mod\_PI} = A_{PI}.sin(2.\pi.FPI.t + \varphi_{PI}) \ .A_{mod}.sin(2.\pi.FR.t + \varphi_{mod}) \tag{14}$$

where: A_{mod} e φ_{mod} are the amplitude and phase of inner race modulation by the rotation signal.

Finally, the system signal is associated whit the modulated inner race signal by Equation (15).

$$S_{sist\_PI} = S_{sist} + S_{mod\_PI} \tag{15}$$

2.5 Experimental Tests

After the mathematical analysis, real tests were performed. For this, the didactic bench of rotating machine elements located in the Laboratory of Vibrations, Acoustics, and Control at the ICTE 2 campus of the Federal University of Triângulo Mineiro (UFTM) was used, composed of:

- Electric motor model W22 IR3 with 0.5 HP, 4 poles, three-phase 220V/380V;
- Panel with frequency inverter for activation and speed control, model CFW300, 220V;
- Bearing housing model KP15;
- Carbon steel shaft 1020, diameter 9/16” (14.2875 mm);

For vibration signal acquisition, data reading, and modeling, the following equipment was utilized:

- ICP accelerometers PCB models 352C33 and 352C22;
- Accelerometer Calibrator PCB 394C06;
- Magnetic bases for accelerometer;
- BNC/UNF 10-32 cables;
- 4-channel data acquisition board NI 9234 and USB cDAQ 9171 module;
- Notebook;
- MATLAB® program.

Figure 04 illustrates the system used in the work.

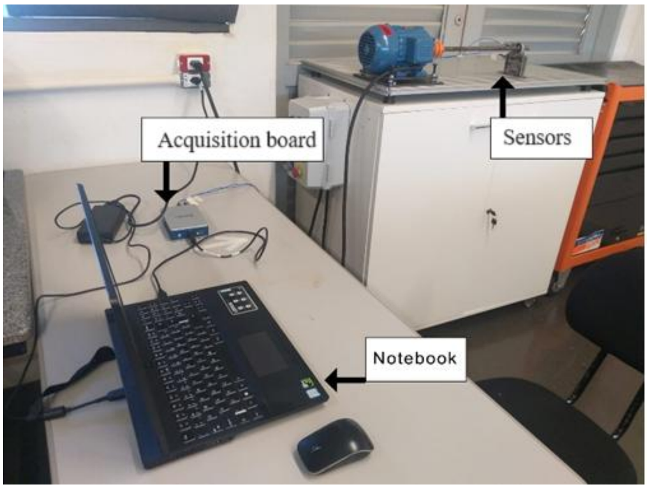

Figure 04: Testbed and Instrumentation.

Source: Author, 2022.

Figure 05 shows the positioning of the three accelerometers used in the test.

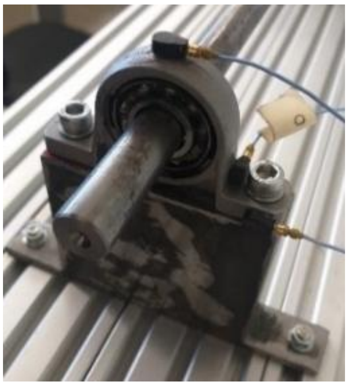

Figure 05: Posicionamento dos acelerômetros no mancal de rolamento.

Source: Author, 2022

2.6 Data Acquisition

The signals were acquired at a frequency of 2560 Hz, according to the Nyquist-Shannon Sampling Theorem, which establishes the criteria to prevent distortions and frequency overlaps (Shannon, 1949). The motor rotation was controlled at 1200 RPM (20 Hz), repeating the simulated pattern. The data acquisition time was 10 seconds per sampling, with a spectral resolution of 0.1 Hz. In total, there were 10 measurements per analysis.

The signals acquired by the accelerometers (analog) are then sent to the data acquisition board, which performs the analog-to-digital (A/D) conversion, thus discretizing the signal into discrete samples at equal time intervals. The samples were numbered from 1 to 10 and separated into a control folder, named according to the corresponding faults analyzed.

2.7 Signal Acquisition Logic Flowchart

In the modeling of theoretical and experimental fault signals, a systematic approach was implemented for signal acquisition and fault frequency identification. Therefore, a flowchart was structured to describe the steps, as shown in Figure 06.

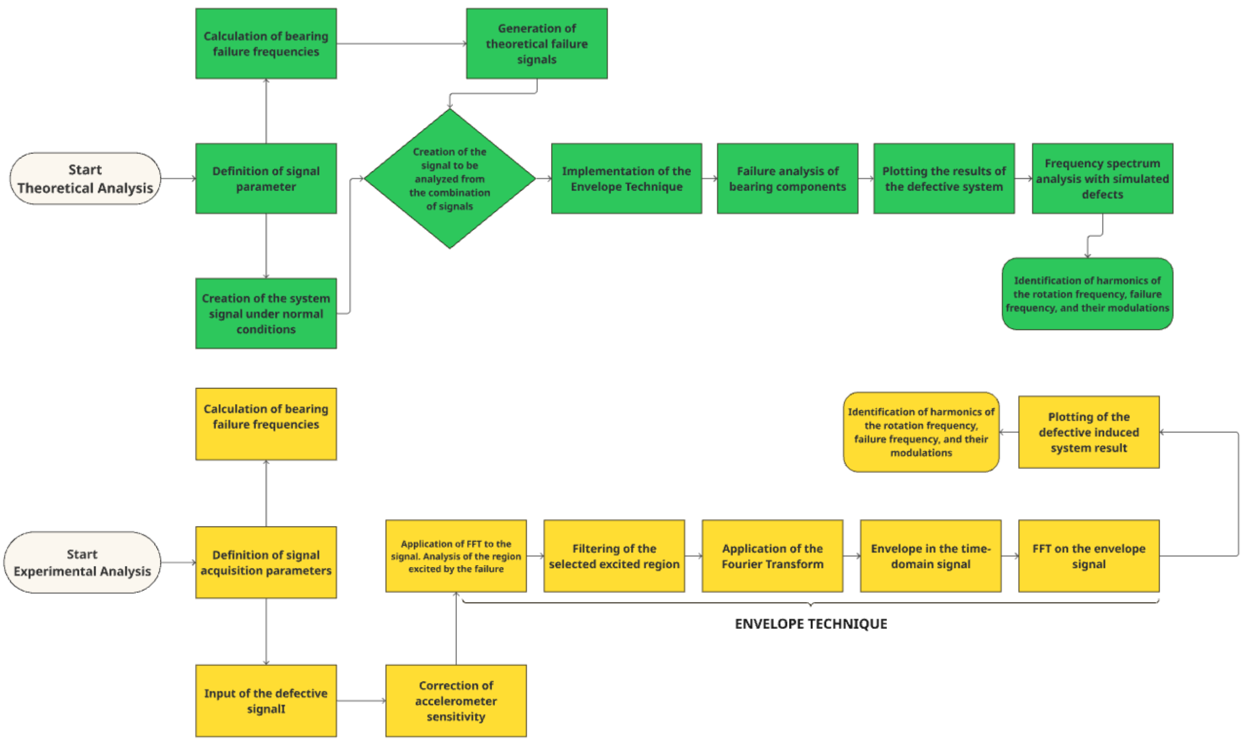

Figure 06: Signal acquisition logic flowchart.

Source: Author, 2022

2.8 Adition of Bearing Failures

Previously, probable causes of bearing defects were described. The predominant type of failure is the damage to the tracks through the generation of fatigue cracks. Due to the difficulty of finding a part with the defects necessary for the study and the high hardness of the material, the defects were induced in a new bearing by cutting the tracks using a grinder. This process aimed to experimentally reproduce failures in bearing components.

The cut was made from the outside of the bearing to a depth that reached the insider of the outer race, in contact with the balls. Then the depth of the cut was increased, reaching the cage and the rolling elements. In the last step, the cut was deepened once more, reaching the inner race. deepened once more, reaching the inner race.

3 RESULTS AND DISCUSSIONS

Initially, the mathematical model for simulating a rotating system with defects in bearing components was evaluated.

In Figure 07, one can observe the frequency spectrum of the envelope of a signal with a defect simulation in the inner race, modeled as explain in Equations (10) and (15). Note the presence of four peaks:

- First harmonic of the FR (Frequency Response): 40 Hz;
- FPI: 108.4 Hz;
- FPI modulation ± 2 x FR: 68.4 Hz and 148.4 Hz;

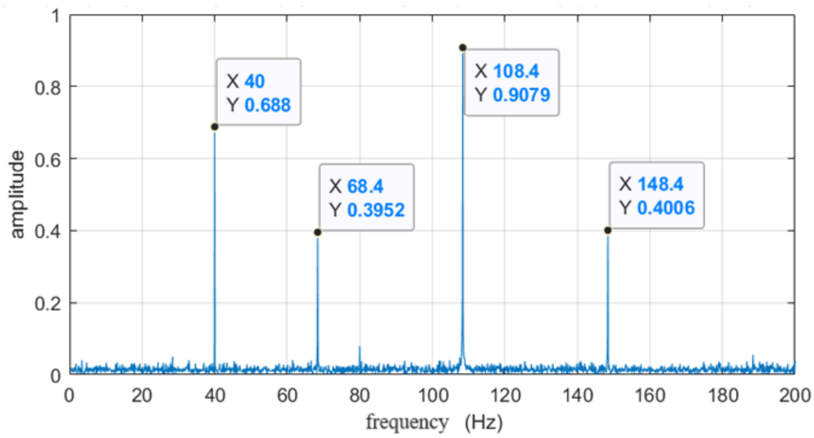

Figure 07: Simulation of the frequency spectrum of the envelope of an inner race defect signal.

In Figure 08, the frequency spectrum of the envelope of a signal with a defect simulation in the external track is observed. The four peaks visualized refer to:

- First harmonic of FR: 40 Hz;
- FPE: 71.6 Hz;
- FPE modulation ± 2 x FR: 31.64 Hz and 111.6 Hz.

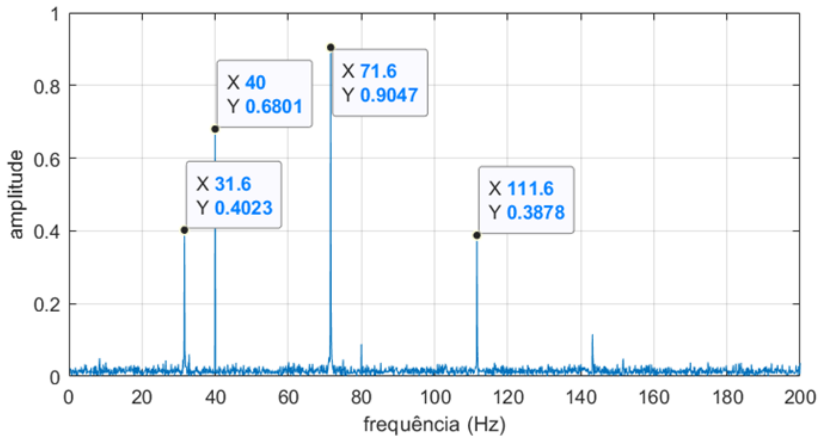

Figure 08: Simulation of the frequency spectrum of the envelope of an outer race defect signal.

In Figure 09, it is possible to observe the frequency spectrum of the envelope of a signal with a defect simulation in the rolling elements. The peaks displayed refer to:

- First harmonic of FR: 40 Hz;
- FER: 46.9 Hz;
- FRE modulation ± 2 x FR: 6.9 Hz and 86.9 Hz.

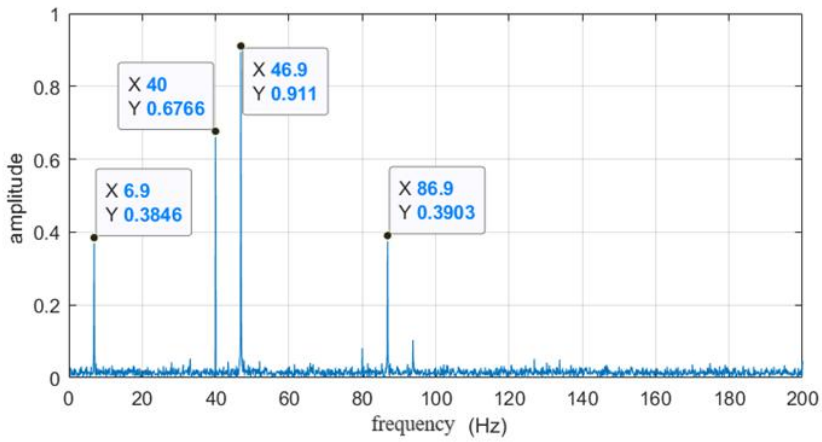

Figure 09: Simulation of the frequency spectrum of the envelope of the rolling elements defect signal.

Figure 10 shows the frequency spectrum of the envelope of a signal with cage defect simulation. Note the presence of four peaks:

- First harmonic of FR: 40 Hz;
- FG: 8.0 Hz;
- FG modulation ± 2 x FR: 32.0 Hz and 48.0 Hz.

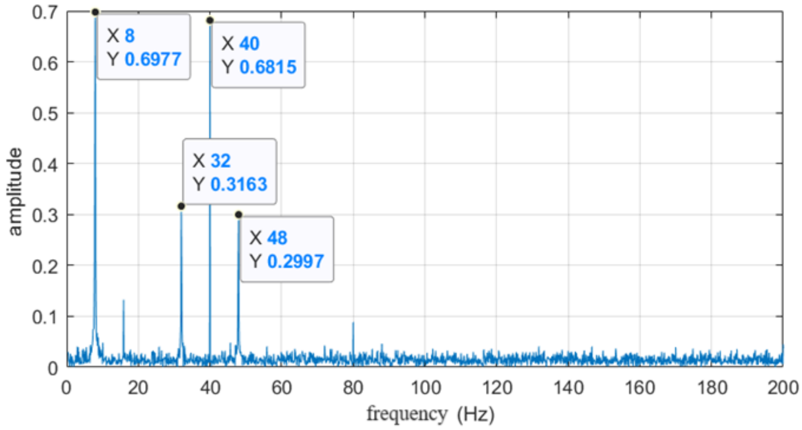

Figure 10: Simulation of the frequency spectrum of the envelope of the cage defect signal.

Figure 11 shows the frequency spectrum of the envelope of a signal with bearing simulation that presents the four defects. The highlighted peaks refer to:

- FG: 8Hz;
- Second harmonic of FR: 40 Hz;
- FER: 46.9 Hz;
- FPE: 71.6 Hz;
- FPI: 108.4 Hz.

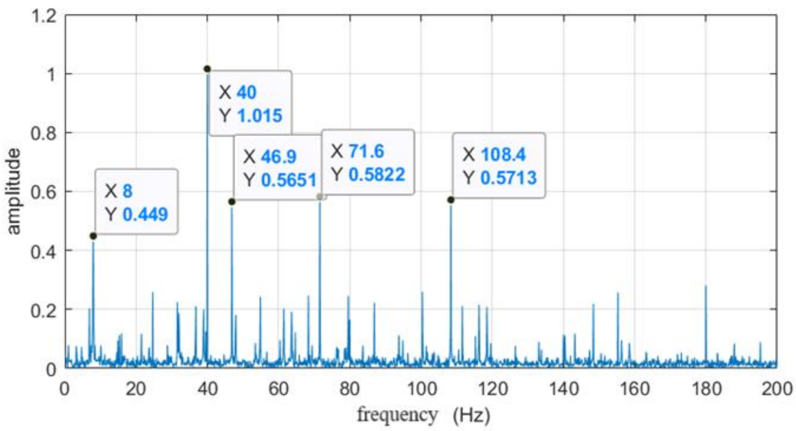

Figure 11: Simulation of the frequency spectrum of the envelope of a signal with four defects.

Thus, after the numerical simulations, the experimental tests began, using the bench and instrumentation described in item 2.5. To this end, the bearing induced a defect, as shown in item 2.6.

It is essential to highlight that the rotation frequency does not remain stable during an experimental test, and, in the present case, it suffered fluctuations of approximately 20 Hz. For this reason, the frequencies of interest highlighted in the following figures may vary slightly.

In Figure 12, it is possible to observe the frequency spectrum of the signal envelope with the defect induced in the external track. The peaks displayed refer to:

- The FR and its first, second, and third harmonics: 20.6 Hz, 41.2 Hz, 61.8 Hz, 82.4 Hz;
- FPE: 73.3 Hz;
- FPE ± FR modulation: 52.7 Hz and 93.9 Hz.

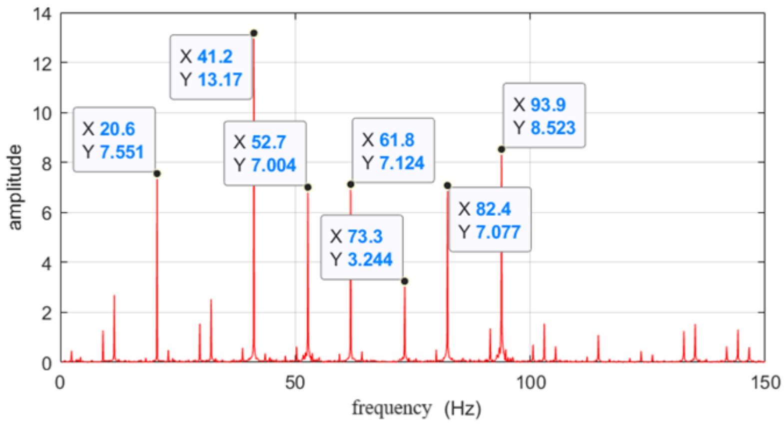

Figure 12: Frequency spectrum of the envelope of a bearing signal with outer race defects.

In Figure 13, it is possible to observe the frequency spectrum of the signal envelope with the defect induced and increased to reach the cage. The peaks displayed refer to:

- FR and its first, second, and third harmonics: 20.6 Hz, 41.2 Hz, 61.8 Hz, 82.4 Hz;
- FG: 8.1 Hz;
- FPE: 72.8 Hz;
- FPE ± FR modulation: 52.7 Hz and 93.9 Hz;
- FPE modulation ± 2 x FR: 41.2 Hz and 114.1 Hz.

There is a peak at the frequency of 103.0 Hz, but to conclude if this frequency is induced by the internal race, the defect was aggravated a little more, to be sure that the cut reached the internal race.

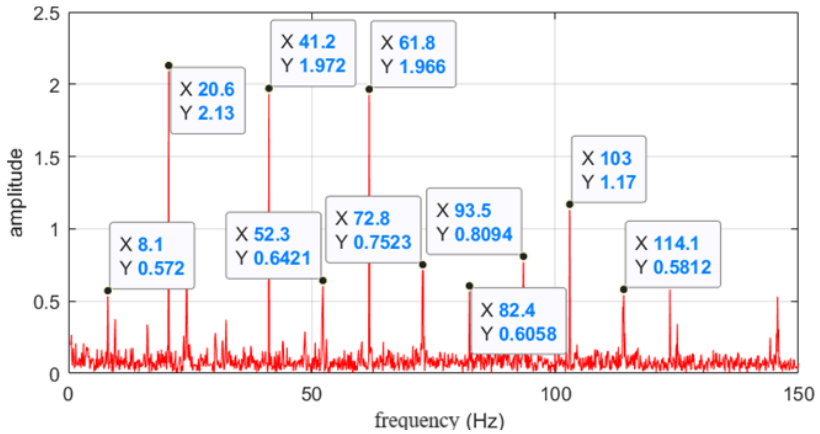

Figure 13: Frequency spectrum of the envelope of a bearing signal with outer race and cage defects.

In Figure 14, the frequency spectrum of the signal envelope is shown with the defect increased, aiming to reach the internal track. The peaks displayed refer to:

- FR and its second and third harmonics: 20.6 Hz, 61.8 Hz, 82.5 Hz;
- FG: 9.0 Hz;
- FPE: 73.4 Hz;
- FPI: 103.1 Hz;
- FPE ± FR modulation: 52.8 Hz and 94.1 Hz;
- FPE modulation ± 2 x FR: 32.2 Hz and 114.7 Hz;
- FPE modulation ± 3 x FR: 11.6 Hz and 135.3 Hz.
- FG ± FR modulation: 11.6 Hz and 29.6 Hz;
- FPI ± FR modulation: 82.5 Hz and 123.7 Hz.

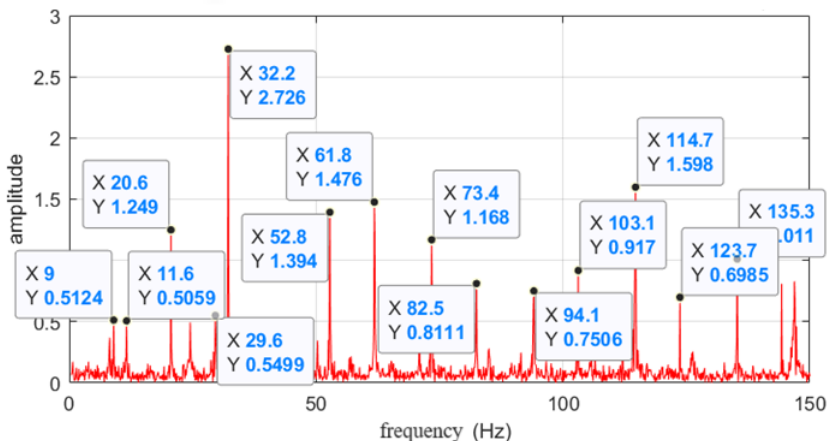

Figure 14: Frequency spectrum of the envelope of a bearing signal with outer race, cage and inner race defects.

4 CONCLUSIONS

The present work proposed the development of a didactic module to apply a methodology to identify failures in bearings used in rotating motors to present a predictive maintenance strategy. The method chosen and studied was spectral analysis together with the envelope technique. As a result, the implementation of the technique highlights the characteristic failure frequencies in the outer and inner race, rolling elements, and cage, among the other system frequencies.

The envelope technique was initially applied to a mathematical model to know the respective frequencies of the types of failures and compare them with the signal obtained experimentally.

A The application of the HFRT technique to the mathematical model and the acquired signal proved effective in identifying bearing defects, emphasizing the characteristic frequencies of the bearing components and the modulations caused by the rotation frequency. The development and results of the experimental analysis validate the application of the principles described by Randall (2011).

The effectiveness of the technique was proven in the identification and measurement of the defects applied to the bearing, which reinforces the conclusion that spectral analysis derived from the envelope technique constitutes one of the main tools in the predictive maintenance of rotating machinery in industries. As Choudhury (1999) highlights, although effective, the methodology has limitations in scenarios of advanced wear of rolling elements, as the characteristic fault frequencies can be masked by background noise generated by the machine's own operation.

The didactic module proved to be a practical and fundamental tool for practical application and teaching. Its use allows students and professionals to visualize theoretical concepts through controlled simulations. As a suggestion for improvement for future replicas of the module or in subsequent academic works, it is recommended to:

- Simulate the operational signals of a rotating system;
- Estimate the characteristic frequencies of the components;
- Modulate the signals of rotating components using the rotation signal to simulate defects;
- Apply the envelope technique to identify the simulated failures;
- Analyze the frequency spectrum of the envelope of the simulated signals;
- Develop or use a didactic module for vibration signal analysis in rotating systems;
- Implement experimental tests on equipment operating in real industrial environments to enable validation and adjustment of detection parameters, ensuring greater reliability and precision.

Therefore, it is concluded that spectral analysis combined with the envelope technique is an essential tool in the predictive maintenance of rotating motors in industries, making it possible to present them in a practical application using the teaching bench presented in the work.

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