Vibration Analysis in Rotating Machinery

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SUMMARY

Due to the constant industrial development and the new techniques in the area of Predictive Maintenance being implemented in companies, this article has the general objective of demonstrating the benefits of one of them, which is the technique of Vibration Analysis in Rotating Machinery. For this, the concepts of Maintenance Management were explored, discussing their classifications, Preventive Maintenance, Corrective Maintenance and finally Predictive Maintenance, so that it was possible to present some of the most used techniques in this area, ending the article with the deepening of the Vibration Analysis technique. This study is classified as a literature review, with the research carried out from a database (books, websites, articles and academic works) published in the last decades, up to the present time. With the article exploring, from the macro view of the subject, such as the concepts of Maintenance Management, to the deepening of the Vibration Analysis technique, demonstrating the possible failures to be detected, it is important to emphasize the importance of the study and its general objective achieved.

Keywords: Management. Maintenance. Predictive. Techniques.

1 INTRODUCTION

Currently, industries are constantly looking for new methods and advanced technologies that allow for cost reductions in their processes, and for this it is necessary to have advanced and effective maintenance, enabling actions and scheduled work orders before eventual breakdowns or even a stop in the production line, since the Maintenance sector of a company is considered one of the main responsible for the good condition and monitoring of components and Machines.

From the contextualization of Maintenance Management, the area of Predictive Maintenance will be deepened, which is responsible for monitoring and diagnosing machines and components, covering one of the main techniques in this area: Vibration Analysis in rotating machinery.

Vibration Analysis in rotating machinery is one of the most used and implemented techniques in the area of industrial maintenance, making it possible to

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identify failures before a potential breakdown, making it possible to carry out planned maintenance, which is directly related to cost reduction and increase in the useful life of your monitored equipment. Therefore, through the industrial development and consequent advancement in the area of Predictive Maintenance, with the creation of several techniques for supervising equipment and machines, the article and its sharing are justified so that it adds, from the theoretical foundation, to all professionals related to Maintenance Management in industries and to all academics related to the subject, so that it is possible to continue collaborating with industrial development.

Through the above, the problem of the article is reached: how is it possible to obtain supervision and reduction of breakdowns in rotating mechanical components?

Based on the understanding and contextualization of the theme, the area of Predictive Maintenance will be deepened, discussing some of its main techniques that perform the analysis of the state of components and machines, identifying breakage trends, such as: Thermography, Shaft Alignment, Oil Analysis and Vibration Analysis, enabling the focus of the Vibration Analysis technique, presenting the types of failures that can be identified. From these specific objectives, the purpose is to present the general objective of the article: to demonstrate the benefits, based on the theoretical foundation, of the Vibration Analysis technique.

2 DEVELOPMENT

2.1 Maintenance Management

Maintenance has always existed, and it came to be known by this name around the sixteenth century in Central Europe, when the first assembly and service technicians appeared. It developed throughout the Industrial Revolution and took hold in World War II. In the post-war period, Maintenance Engineering was considered a foundation in the industrial performance of the main countries involved (MORO, 2007).

According to Gil Branco Filho (2006, p.59) "part of the company's global managerial function and the actions with which the management of a Maintenance organization follows a certain policy". Describing the term Maintenance Management in this way. Also described, as a continuous improvement process that supervises the operation of machines, avoiding possible breakdowns and stops in production, in addition to avoiding the waste of resources in inefficient maintenance processes

(VOITTO, 2019). In order to achieve effective maintenance, several performance indicators are used according to their Degree of Importance, as shown in Figures 1 and 2:

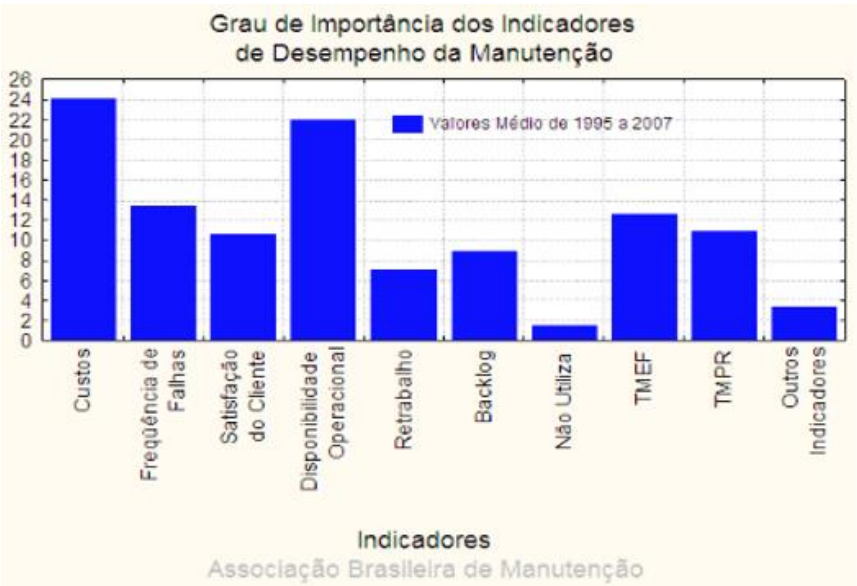
Figure 1 - Degree of Importance of the Main Performance Indicators Used

Principais Indicadores de Desempenho Utilizados (Grau de Importância - GI)								GI 2007
Tipos	1995	1997	1999	2001	2003	2005	2007	
Custos	26,21	26,49	26,32	25,91	21,45	21,96	20,33	1
Frequência de Falhas	17,54	12,20	14,24	16,22	11,66	12,17	9,75	6
Satisfação do Cliente	13,91	11,01	11,76	11,86	8,62	8,11	8,93	7
Disponibilidade Operacional	25,20	24,70	22,60	23,24	19,58	19,81	18,51	2
Retrabalho	9,07	5,65	8,36	8,96	6,06	6,68	3,97	8
Backlog	8,07	6,55	8,98	10,41	9,32	6,92	11,57	5
Não Utilizam	-	2,09	2,79	1,22	1,63	0,72	0,33	10
TMEF (MTBF)	-	-	-	-	11,89	11,69	14,21	3
TMPR (MTTR)	-	-	-	-	9,56	11,46	11,74	4
Outros Indicadores	-	11,31	4,95	2,18	0,23	0,48	0,66	9

Source: ABRAMAN (2007).

From Figure 1, demonstrating the degree of importance of the main indicators in the period from 1995 to 2007, it is possible to obtain the average values of each indicator, as shown in Figure 2:

Figure 2 - Degree of Importance of Maintenance Performance Indicators



Source: ABRAMAN (2007).

2.1.1 Key Indicators

Based on Figures 1 and 2, it is possible to define some concepts:

Costs: it is the sum of various costs, such as: spare materials used, man-hours, training and administration of the Maintenance team. In addition, there may be costs related to loss of production (FILHO, 2006).

Failure Frequency: it is the recurrence of a failure, and in order to avoid this, several studies and methodologies are used within maintenance, one of the best known and implemented is FMEA (*Failure Mode Effect Analysis*), a tool used to analyze and identify potential failures in machines and components (KARDEC; NASCIF, 2012).

Customer Satisfaction: indicator to obtain the evaluation of the service provided, enabling improvements or reforms in the maintenance plan and management.

Operational Availability: according to the Brazilian Association of Technical Standards, NBR 5462 (1994, p.2) is the "ability of an item to be in a position to perform a certain function at a given moment or during a certain time interval".

Rework: it is defined by the repeated work resulting from some failure in a machine, which should be working normally (FILHO, 2006).

Backlog: it is conceptualized by the amount of time necessary, with the factory stopped, for all pending maintenance activities to be performed by the team (ROSA, 2018).

MTBF (*Mean Time Between Failures*): means the frequency between failures, for example, if a machine worked for 10 hours and had 2 failures in this period, taking 1 hour for each failure to be corrected, its MTBF will be the number of total hours available minus the number of hours of maintenance performed, divided by the number of failures, as the formula below (WINDTEC, 2019) demonstrates:

Total operating time = 10 hours

Total Maintenance Time = 2 hours

Number of failures = 2

MTBF = (10-2) / 2

MTBF = 8 / 2

MTBF = 4 hours

That is, in the example described above, the MTBF indicator shows that the average time between failures is every 4 hours of operation.

MTTR (*Mean Time To Repair*): according to Gil Branco Filho (2006, p.87) it can be conceptualized as "mean time to repair". That is, following the previous example, if a machine had two failures and each failure took 1 hour for maintenance to be performed, its calculation will be the sum of the total maintenance time divided by the number of failures, as shown in the formula below (WINDTEC, 2019):

Total Maintenance Time = 2 hours

Number of failures = 2

MTTR = 2 / 2

MTTR = 1 hour

From the above calculation, it can be seen that the MTTR indicator shows an average repair time of 1 hour.

2.1.2 Preventive Maintenance

Preventive Maintenance, according to the Brazilian Association of Technical Standards, NBR 5462 (1994, p.7) is the "Maintenance performed at predetermined intervals, or according to prescribed criteria, aimed at reducing the probability of failure or degradation of the functioning of an item".

Therefore, it is extremely important to have an efficient and organized Preventive Maintenance so that components and machines can always maintain their good working order. This maintenance classification is always carried out in a planned manner, so that it does not interfere with or interrupt the production line and the continuity of manufacturing processes.

2.1.3 Corrective Maintenance

The concept of Corrective Maintenance is defined as the service performed, in an unplanned manner, by the Maintenance team, resulting from a failure or stoppage in the production line, with the purpose of returning the machine, equipment, operating system, unit or item to normal operation as soon as possible (FILHO, 2006).

In addition, this maintenance classification is considered the most expensive and harmful to companies, due to the need for quick action, stoppages in the production line, breakdowns of machines and components, among other factors (ENGETELES, 2018).

2.1.4 Predictive Maintenance

According to the Brazilian Association of Technical Standards, NBR 5462 (1994, p.7) is the "Maintenance that allows to guarantee a desired quality of service, based on the systematic application of analysis techniques, using centralized supervision or sampling means".

With this, Predictive Maintenance becomes capable of diagnosing and monitoring the state of components and machines, making it possible to detect possible failures (NEPOMUCENO, 1989).

2.1.4.1 Predictive Maintenance Techniques

Thermography: according to the Brazilian Association of Technical Standards, NBR 15424 (2006, p.4) thermography is conceptualized as:

> "Remote sensing technique that makes it possible to measure temperatures and form thermal images (called thermograms) of a component, equipment or process, from infrared radiation, naturally emitted by bodies, as a function of their temperature".

Therefore, this technique is widely applied in mechanical equipment and electrical systems, as shown in Figure 3.

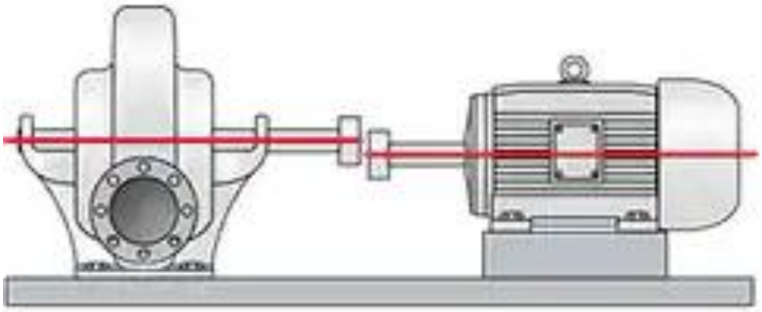
Figure 3 - Thermographic analysis in an electrical system.

Source: Instrutemp (2018).

From this thermographic analysis, it is possible to identify some possible causes of failures, they are: overheating, overload, high energy consumption, lack of thermal insulation, loose connections and power transmission failures. These failures, if not identified and repaired, can generate future problems, unscheduled stoppages and production breakdowns, in addition to offering possible risks to workers and facilities (INSP-THERM, n.d.).

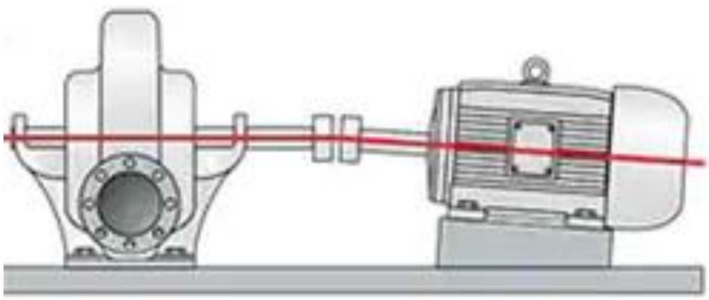
Shaft Alignment: this technique is very important and is used when two shafts coupled in rotating systems are misaligned both horizontally and vertically, with two classifications, parallel misalignment (Figure 4) or angular misalignment (Figure 5) (SKF, n.d.):

Figure 4 - Parallel misalignment.



Source: SKF (n.d.)

Figure 5 - Angular misalignment.



Source: SKF (n.d.)

Shaft misalignment failure can result in increased vibration and noise, breakage in shafts, bearings, couplings, lubrication leakage. This failure is considered responsible for up to 50% of all costs related to rotating machinery downtime (SKF, n.d.).

Oil Analysis: all mechanical and rotating machines have components that need adequate and constant lubrication, so that their best operating performance is achieved. Therefore, the Oil Analysis technique is considered one of the most important and used within Predictive Maintenance, performing the extraction of lubricants and later, laboratory analyses, so that the conditions of the lubricants used in the machines are accurately evaluated (ALS, 2018). In Figure 6 it is possible to see one of the steps of the technique.

Figure 6 - Sample removal of lubricating oil.

Source: Abecom (2021).

This technique has four types of analysis, they are (ALS, 2018):

Physicochemical analysis: evaluation of lubricants carried out on a one-off or periodic basis.

Contamination analysis: aims to identify the presence of any contamination, which may be caused by equipment wear or chemical reactions.

Spectrometry: more precise analysis, carried out through a combustion process, which causes the lubricant to disintegrate to its atomic level, making it possible to identify chemical elements in lubricants.

Ferrography: performed from particles found in lubricants, identifying the degree and reason for wear of components and machines.

From Oil Analysis, it is possible to obtain a plan for its change, avoid unwanted stops, predict breakdowns and wear of machinery components, increasing the useful life and availability of components (ALS, 2018).

2.1.4.2 Vibration Analysis in Rotating Machinery

All rotating machines have shafts, bearings, gears, among other rotating components that emit a "normal" level of vibration from their movements. From this level of vibration, the Vibration Analysis technique is applied, making it possible to detect failures and defects in machines through sensor measurements (SCHEFFER; GIRDHAR, 2004).

When the machine has vibrations outside its normal parameters, it is a sign that some type of failure may be occurring. To perform the analysis of these vibrations, the Fast Fourier Transformation (FFT) method is most often used (SKF, 2000).

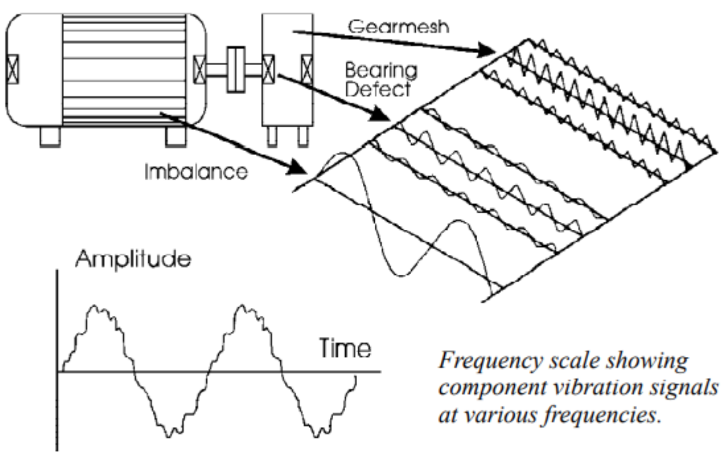
2.1.4.2.1 Fast Fourier Transform (FFT)

The mathematical expression of the Fast Fourier Transform (1) transforms the amplitude in the time domain to the amplitude and signals in the frequency domain (ENSUS, 2016).

$$F\,(\omega) = \int_{-\infty}^{\infty} f\,(t) e^{-i\omega t} dt \qquad (1)$$

In addition, in non-mathematical terms, the FFT method can have its concept explained in a signal decomposed into specific amplitudes at different respective frequencies of the machine components (SKF, 2000).

Figure 7 - Frequency of waveform components.

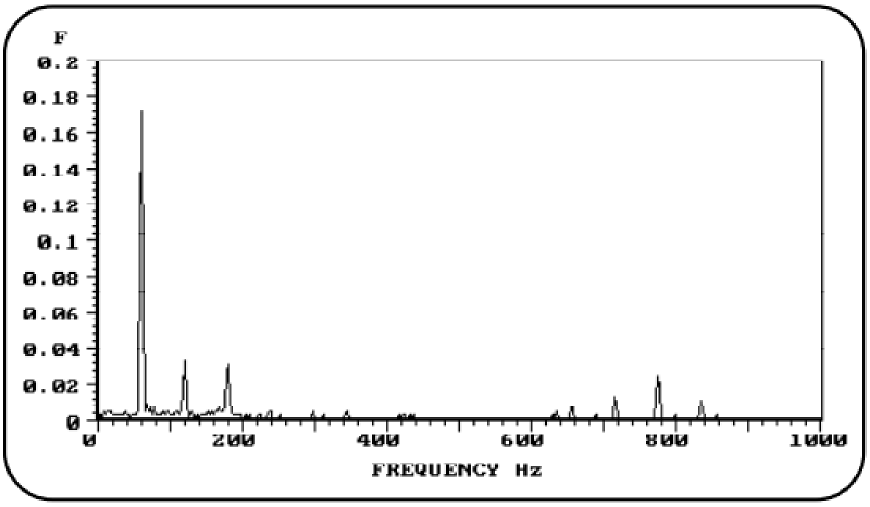


Source: SKF (2000).

As shown in Figure 7, different frequencies are represented, related to Imbalance, *Bearing Defect*, and *Gearmesh*, which are represented in the form of a waveform of the specific amplitude in the time domain (SKF, 2000).

From the vibration measured in waveform (amplitude with time domain), the amplitudes of the signals in different frequency scales are collected, so that the values collected in the time domain can be transformed into the frequency domain, thus generating the so-called FFT spectrum (Figure 8) (SKF, 2000).

Figure 8 - FFT spectrum.



Source: SKF (2000).

After the Fast Fourier Transform process and how its spectrum is performed, it can be analyzed through pre-stipulated values such as machine rotation, number of teeth of a gear, bearing model, among other parameters, as shown in Figure 9.

Figure 9 - Relationship between frequency and causes of vibration.

CAUSA	FREQÜÊNCIA	VARIÁVEL	AMPLITUDE	OBSERVAÇÃO
Desbalanceamento	1 X rpm	d	Proporcional ao desbalanceamento. Maior no sentido radial	Geralmente aparece no primeiro harmônico
Desalinhamento ou eixo torto	1/2/3/4 X rpm	d	Grande em direção axial (maior que 50% da amplitude, radial)	Desalinhamento entre mancais ou entre ambas metades do *"manchón"*
Folga nos mancais	½ X rpm	d	Grande no sentido vertical	Como a freqüência é menor que ½ rpm a fase pode ser variável
Falta de firmeza mecânica	2 X rpm	d	Instável	Geralmente afeta o alinhamento
Correias frouxas	1 X rpm	d	Instável	
Engrenagens defeituosas	alta, número de dentes X rpm	a/d	*"blips"*	Freqüência entre 15000 e 40000 rpm
Almofadas antifricção deterioradas	Alta	a	*"blips"*	A freqüência alcança valores maiores do que os registrados para engrenagens ou rolamentos
Rolamentos deteriorados	Alta	a	*"blips"*	Freqüência entre 15000 e 40000 rpm
Lubrificação	Alta	a	-	A amplitude se modifica notadamente em função da lubrificação
Eixo torcido	1 X rpm	d	Grandes valores no sentido axial	A amplitude pode se apresentar de forma pulsátil

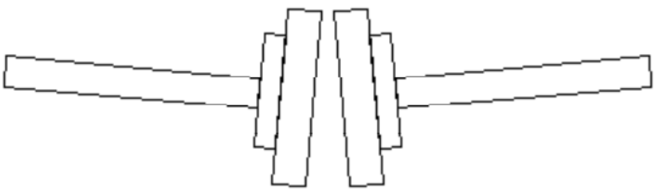
Source: Cyrino (2017).

With this, it becomes possible to visualize the cause for excessive vibration of the equipment, because in each cause and defect, the spectrum will demonstrate its corresponding value, and it is possible to conceptualize some of them:

- **Misalignment**

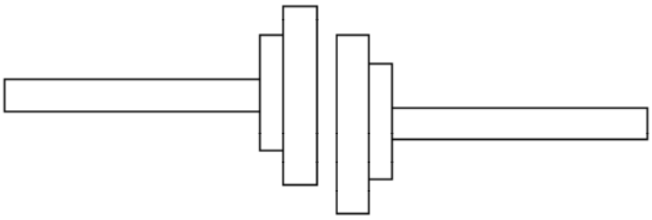
Misalignment failure occurs when, according to SKF (2000, p.14) "the shafts, couplings and bearings are not properly aligned along their centerlines", angular misalignment (occurs when two axes do not have their parallel centerlines – Figure 10), parallel misalignment (when the centerlines are parallel, but are misaligned – Figure 11) or the set of both (SKF, 2000).

Figure 10 - Angular misalignment.



Source: SKF (2000).

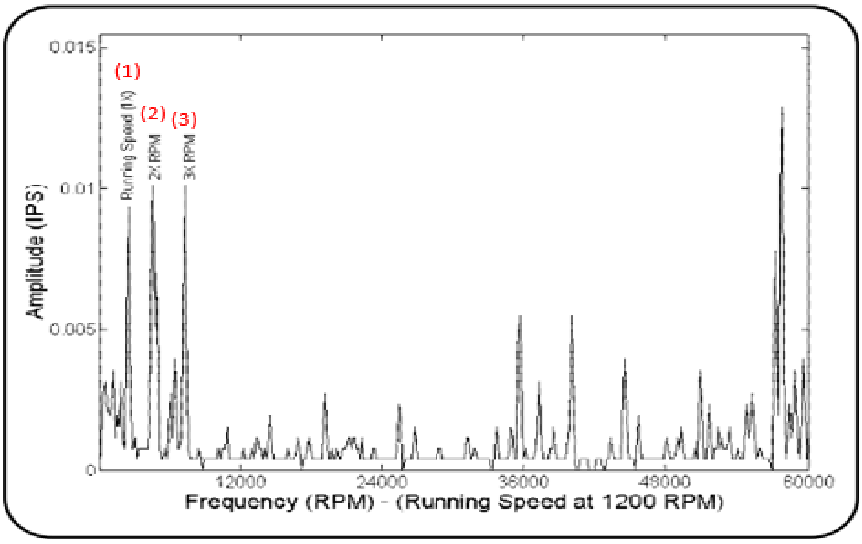
Figure 11 - Parallel misalignment.



Source: SKF (2000).

When the misalignment failure occurs, a spectrum similar to that of Figure 12 will be generated from the parameters presented in Figure 9:

Figure 12 - FFT spectrum - Misalignment.



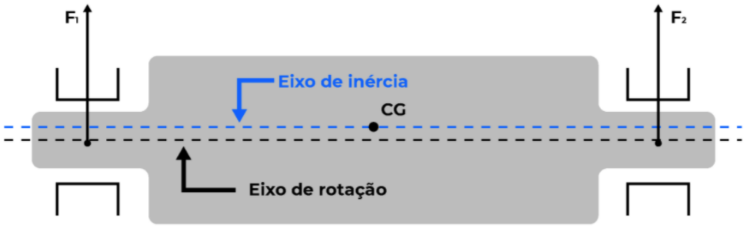
Source: SKF (2000).

Where, in this example, a machine with a rotation of 1,200 RPM (Revolutions Per Minute), FFT spectrum with a maximum amplitude of 0.015 (IPS) and a total frequency range of 60,000 RPM, will point to three peaks in amplitude, the first peak being at the frequency of 1,200 RPM (1), the second peak at the frequency of 2,400 RPM (representing 2 x RPM) (2) and the third peak at the frequency of 3,600 RPM (representing 3 x RPM) (3).

- **Imbalance**

Unbalance failure occurs when the center of mass does not coincide with the center of rotation of the shaft, and there can be different types of unbalance. They are static unbalance (Figure 13), conjugate unbalance (Figure 14) and dynamic unbalance (Figure 15) (TRACTIAN, n.d.).

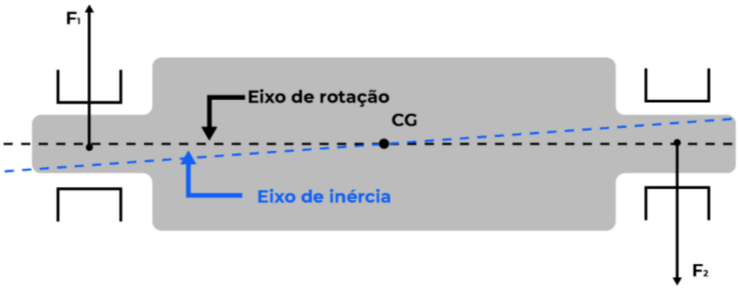
Figure 13 - Static unbalance.



Source: Tractian (n.d.)

It occurs when the axis of inertia and the axis of rotation of the machine are parallel, but do not coincide (TRACTIAN, n.d.).

Figure 14 - Conjugate unbalance.



Source: Tractian (n.d.)

It happens when the axis of inertia and the axis of rotation are not parallel but coincide in the center of gravity of the rotor (TRACTIAN, n.d.).

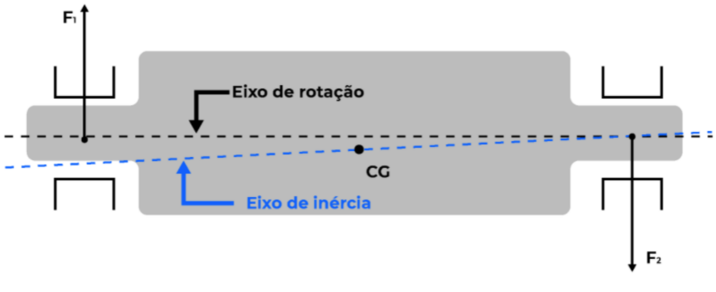
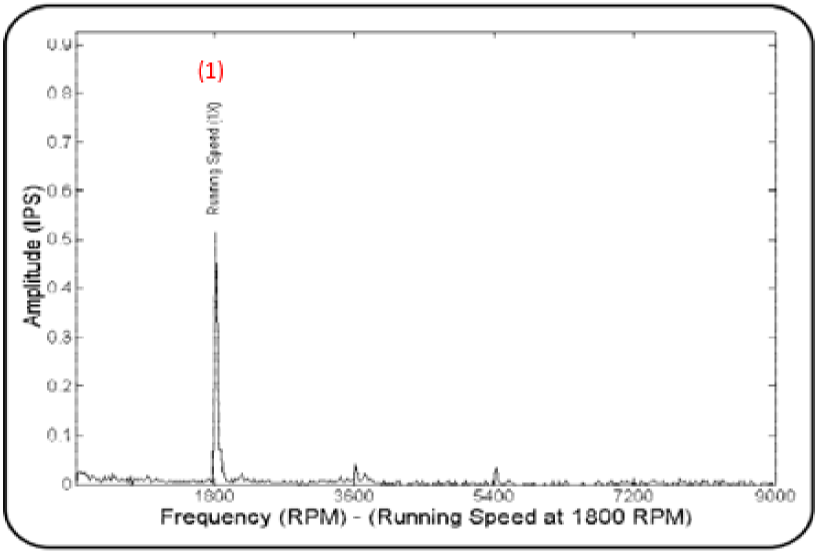


Figure 15 - Dynamic unbalance.

Source: Tractian (n.d.)

It occurs with the combination of the two previous types of unbalances, when the axes are not parallel or coincide in the center of gravity (TRACTIAN, n.d.). When the unbalance failure occurs, a spectrum like that of Figure 16 will be generated from the parameters presented in Figure 9:

Figure 16 - FFT spectrum - Unbalance.



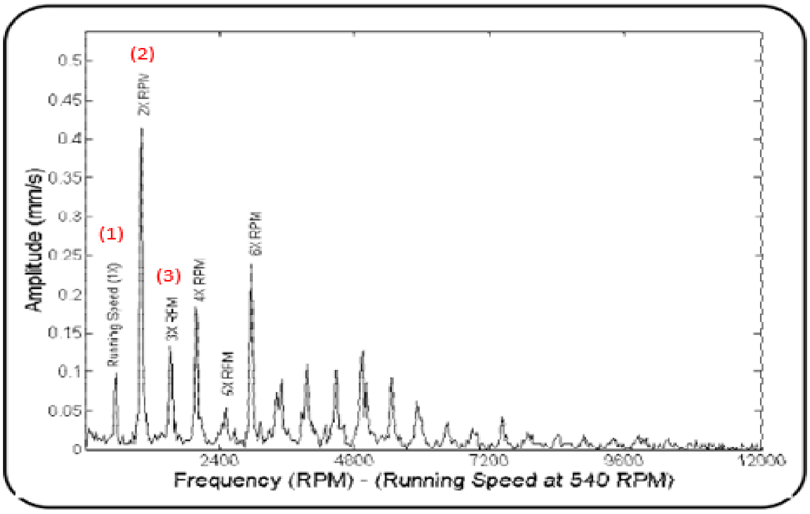
Source: SKF (2000).

Where, in this example, with the machine having a rotation of 1,800 RPM, the FFT spectrum with a maximum amplitude of 0.015 (IPS) and a total frequency range of 9,000 RPM, will indicate only one peak in the amplitude, being the peak at the frequency of 1,800 RPM (1), respective of the rotation frequency of the machine.

- **Mechanical Backlash**

This type of failure happens when mechanical components of the machine have inadequate adjustments, presenting mechanical clearances. When this type of failure occurs, harmonics of its rotation frequency will be generated in the FFT spectrum, and harmonics may also present harmonics at 1/2 frequency of its rotation (SKF, 2000).

Figure 17 - FFT spectrum – Mechanical clearance.



Source: SKF (2000).

With a machine at a rotation of 540 RPM, this fault has harmonics in the frequency of its rotation, such as: 1 x RPM (1), 2 x RPM (2), 3 x RPM (3) and so on, as shown by the spectrum (Figure 17).

- **Bearing Failures**

Bearing failures occur due to several factors, such as misalignment, unbalance, bearing clearance, lubrication, among other factors. These faults are identified at very high frequencies and low amplitudes (SKF, 2000).

To detect the faults in a bearing, frequencies are classified into four types (BASTOS; JUNIOR, 2010):

- Cage Frequency (FFT - *Fundamental Train Frequency*): used to detect defects in the cage;

- Indoor Track (BPFI - *Ball Pass Frequency Inner Race*): used to detect defects in the inner track;

- Outer Track (BPFO - *Ball Pass Frequency Outer Race*): used to detect defects in the outer track;

- Ball Spin Frequency *(BSF*): used to detect defects in rolling elements.

To calculate the respective frequencies, Figure 18 presents the equations:

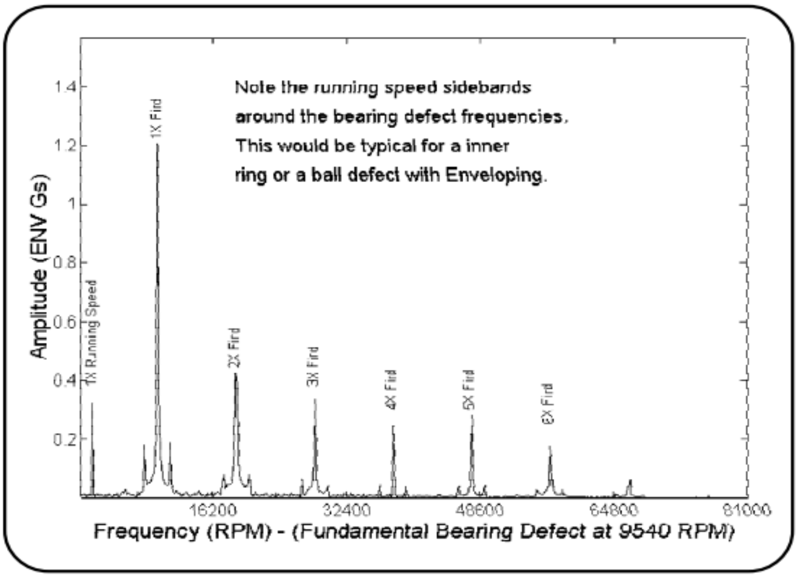
Figure 18 - Equations for calculating failure frequencies in bearings.

Freqüências	*Equações*
Freqüência da Gaiola	$f_g = \frac{f_{pe}}{2}\left(1 + \frac{D\cos\beta}{d}\right)$
Freqüência de Defeito na Pista Interna	$f_{dpi} = \frac{N_e f_{pe}}{2}\left(1 + \frac{D\cos\beta}{d}\right)$
Freqüência de Defeito na Pista Externa	$f_{dpe} = \frac{N_e f_{pe}}{2}\left(1 - \frac{D\cos\beta}{d}\right)$
Freqüência de Defeito na Esfera	$f_{de} = \frac{d\, f_{pe}}{2D}\left(1 + \frac{D^2\cos^2\beta}{d^2}\right)$

Source: Bastos; Junior (2010).

Each bearing will present its failure frequencies, as parameters such as ball diameter, contact angle, primitive diameter, among other factors (BASTOS; JUNIOR, 2010).

Figure 19 - FFT spectrum – Internal raceway failure in radial bearing.



Source: SKF (2000).

From Figure 19, it is possible to analyze a spectrum demonstrating an example of a typical internal runway failure. Where, the modulation frequency is the speed of execution (1x) and is found on the far left of the FFT spectrum (SKF, 2000).

2.2 METHODOLOGY

The methodology of the article carried out was a literature review, where information and research were collected and explored from a database such as: books, websites, articles and academic papers. The period of the literature review collected were the documents published in the last decades, up to the present time. The article was carried out with a focus on the keywords of the work, which were "Maintenance Management", "Predictive Maintenance" and "Vibration Analysis".

2.3 RESULTS AND DISCUSSIONS

In view of the literature review in the area of Maintenance Management, it was possible to analyze the concept of Maintenance, discussing its classifications, Corrective, Preventive and Predictive, the latter considered the focus of the article. From the concept of Predictive Maintenance, some of its main techniques were explored, such as Thermography, Shaft Alignment, Oil Analysis and, finally, Vibration Analysis.

With the more in-depth study of the Vibration Analysis technique, some types of faults were presented, which can be detected and thus repaired before worse damage. It was possible to understand and "answer" the research problem, which was how to obtain supervision and reduction of breakdowns in rotating mechanical components.

In addition, from this literature review, specific objectives were achieved, such as the understanding of Maintenance Management concepts, analysis of failures that occur due to excessive vibrations and the presentation of techniques in the area of Predictive Maintenance. In order to achieve the general objective, which was to demonstrate all the benefits of the Vibration Analysis technique. It should be noted that this review did not aim to deepen the area of bearing failures, but rather to superficially present this field of study.

3. CONCLUSION

This literature review was initiated by exploring the concepts of Maintenance Management, presenting some of the main Performance indicators and Maintenance classifications, namely: Preventive, Corrective and Predictive.

After the introduction of each classification, the article focused on the area of Predictive Maintenance, presenting the techniques of Thermography, Shaft Alignment, Oil Analysis and Vibration Analysis, which focus on monitoring and diagnosing the condition of the components and machines analyzed.

Subsequently, the article emphasized the Vibration Analysis technique, demonstrating some of the possible faults to be identified, with an example spectrum related to each fault. With this, achieving the general objective of the article, which was to demonstrate the benefits of the Vibration Analysis technique from the literature review.

Therefore, the study carried out in the field of Maintenance Management is concluded, with the aim of sharing information and data so that it is possible to continue collaborating with industrial development and all academics related to the area.

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