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Maintenance of Reducers with an Unbalanced Load Through Vibration and Oil Analysis Predictive Techniques

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1. Introduction

Among the techniques for Predicitive Maintenance of Reducers, the most used are the oil analysis and vibration analysis, and the simultaneous use of both of these provides accurate results about the condition of a system under test.

The principle of the vibration analysis is based on the idea that the structures of the machines excited by the dynamic efforts (power action) give vibrational signs, whose frequency is equal to the frequency of the exciting agents. An imbalance in a machine component will cause increased vibration, once it causes an imbalance in the system and consequent increase in the power. Thus, observing the progression of the level of vibration, it is possible to obtain information on the state of the machine (Gonçalves and Campos-Silva, 2011).

The oil analysis enables identifying the first signs of wear of a component. The identification begins with studying the amount of particles, size, shape and composition, which provide accurate information on the conditions of the moving surfaces without having to disassemble the entire set that these parties belong to. These solid particles are generated by the dynamic friction between the parts in contact. According to the study of these particles the wear situations of the set can be related and attributed to physical and chemical conditions, (Barraclough et al, 1999), (Anderson et al, 1999). The oil analysis is achieved through laboratory techniques involving, reagents, instruments and equipment..

2. Analysis of the lubricants

The lubrication is introduced between two sliding solids by the addition of a lubricant at the interface, in order to reduce friction and wear, remove heat and particles generated by the contact.

Normally, the lubricants are liquids, but can also be solid, and pasty and gaseous, according to its physical state. Liquid lubricants are characterized by their liquid viscosity, but other properties are also important. Lubricating oils have names designating these properties. This type of lubricant can be subdivided into: mineral oils, fatty oils, composite oil, aditivated oils and synthetic oils..

2.1 Viscosity

Viscosity is the most important property of lubricating oils and essentially it can be defined as the flow resistance that fluids present. It is defined as the shear stress in a plane of the fluid per unit of normal velocity gradient to the plane. Viscosity can be expressed in terms of kinematical viscosity (mm²/s or cSt) or absolute viscosity (dynamics) whose unit is the Pa.s. Hutchings (1992) defines the Newtonian viscosity of fluids, in terms of shear deformation by:

$$\tau = \eta \cdot \frac{\partial \gamma}{\partial t} \tag{1}$$

τ = shear stress [Pa],

η = dynamic viscosity [Pa.s],

$\frac{\partial \gamma}{\partial t}$ = shear deformation rate

The kinematical viscosity Z is defined according to Equation 2.

$$Z = \frac{\eta}{\rho} \tag{2}$$

Where:

Z = viscosity in cSt or mm²/s;

ρ = specific mass.

2.2 Viscosity monitoring

Monitoring viscosity is an important component of many programs for the analysis of oil. Even small changes in viscosity can cause major damage to the lubrication. The Limits of typical industrial oils are set at 5% for precaution, and 10% for critical situations, although applications at high loads and extremely critical systems should also have an alarm system (POA, 2002).

Significant reduction of viscosity	Significant increasing of viscosity
• Loss of the oil film causing excessive wear; • Increase of mechanical friction causing excessive consumption of energy; • Generation of heat due to mechanical friction; • Internal or external leaks; • Increased sensitivity for contamination of particle due to the reduction of the oil film; • Failure of oil film for high temperatures, high loads or during starting and stopping.	• Excessive generation of heat resulting in the oxidation of oil, sludge and development of varnish; • Gaseous cavitation due to inadequate flow of oil to pumps and bearings; • Lack of lubrication due to inadequate oil flow; • Oil whipping in the radial bearing; • Excessive consumption of energy to overcome the friction of fluid; • Poor demulsibility; • Weak pumping during cold starting.

Table 1. Depicts the effects of using a lubricant with inappropriate viscosity.

When a significant change in viscosity is observed, the root cause of the problem should always be investigated and corrected. Changes in the viscosity can result from a change in the basic chemistry of the oil (a change in the molecular structure of the oil), or due to ingression of contaminants. Change in viscosity requires additional testing, such as: number of acids (AN) and infrared spectroscopy with the Fourier transform (FTIR) to confirm the incipient oxidation; contaminant tests to identify the presence of water or soot, or another less commonly used assay, which is the gas chromatography test (GC) to identify any changes in the basic chemistry of the oil.

2.3 Wear in lubricated system

Wear can be defined as a progressive loss of material, as a result of mechanical interaction between two surfaces in contact, lubricated or not. In general these areas are in relative movement (sliding or slipping) and with applied loads.

Various authors characterize wear mechanisms differently but, according to the Modern Tribology Handbook (2001) there are 4 main forms of wear: adhesive, abrasive, corrosive and by fatigue, as well as some sideline cases often classified as wear forms. Oxidation, erosion, erosion by cavitation and impact, are sometimes classified as types of wear, although Rabinowicz (1995) finds that in fact none of them are forms of wear.

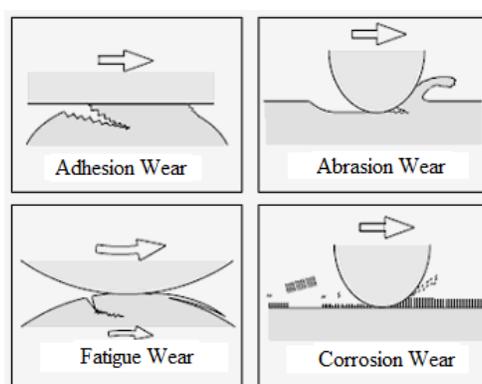These four types of damage are shown in Figure 1.

Fig. 1. Schematic Figures of four types of wear (Kato and Adashi, 2001).

These types of wear will provide precise information during the lubricant's analysis, as the particles generated mix with this analyzed lubricant.

2.4 Physical tests

The most common physical tests used with spectrographic programs and analysis programs of wear metals are: viscosity, total acid number (TAN) and determination of the water rate.

The method ASTM D445 is used for identification of viscosity, the method ASTM D 974 or D 664 is to determine the total number of acids and ASTM D 1744 to determine the water concentration by titration(Gonçalves, Padovese, 2010).

In cases where the water is at levels above 0.05 vol.%, infrared spectrography can be used. Although the limits of control for each of these parameters need to be adjusted depending on the type of lubricant and equipment, variations in viscosity of ± 10%, TAN greater than 3 mg/g, and water exceeding 100 to 500 ppm are usually sufficient for an intervention or at least for further investigation.

2.5 Spectrographic analysis of metals

The spectrographic methods include atomic absorption (AA), atomic emission spectrography (AES), inductive coupled plasma emission spectroscopy (ICPE), and X ray fluorescence (XRF). Of these methods, AES and ICPE, which are based on the detection of light emitted by the elements, are the most popular because of cost, speed, and other factors (Kimura and Gonçalves, 2009).

The spectrographic analysis of metals determines the concentration of metals and particles of up to 10 microns in size, such as moderate wear (benign sliding) and the advanced stages of fatigue, since in these wear modalities the predominant distribution of particles is within the detectable scale (<10 microns).

2.6 Particle count

The particle count is the monitoring of the number of particles of a given size by fluid volume, it is used as a preliminary monitoring tool combined with other analytical methods. The counting of particles and direct reading ferrography of direct-reading detect the onset of severe wear with a rapid increase in the quantity and size of the particles. The counting of particles detects all the particles, given that the direct reading ferrography indicates only particles of ferrous wear.

Many sensitive optical instruments are used in the counting of the number of particles in different size ranges. This counting informs the number of particles larger than a given size found in a specified volume of fluid.

For the counting of particles the standard SAE AS 4059, NAS 1638 (National Aerospace Agency), or ISO can be used (Gonçalves and Padovese, 2010).

The ISO 4406 norm (International Standard Organization) is the most widely used. Most of the versions commonly used of this technical standard refer to the number of particles larger than 4, 6, and 14 micrometers in 1 ml of fluid. The number of particles 4+ and 6+ are used as a particles point of reference. The 14+ size indicates the amount of large particles present, which contribute greatly to the possible catastrophic failure of the machine.

Figure 2 and Table 2 below represent a measurement example, where the result is obtained by an ISO code. Table 2.6 shows the various numbers of ISO 4406 code.
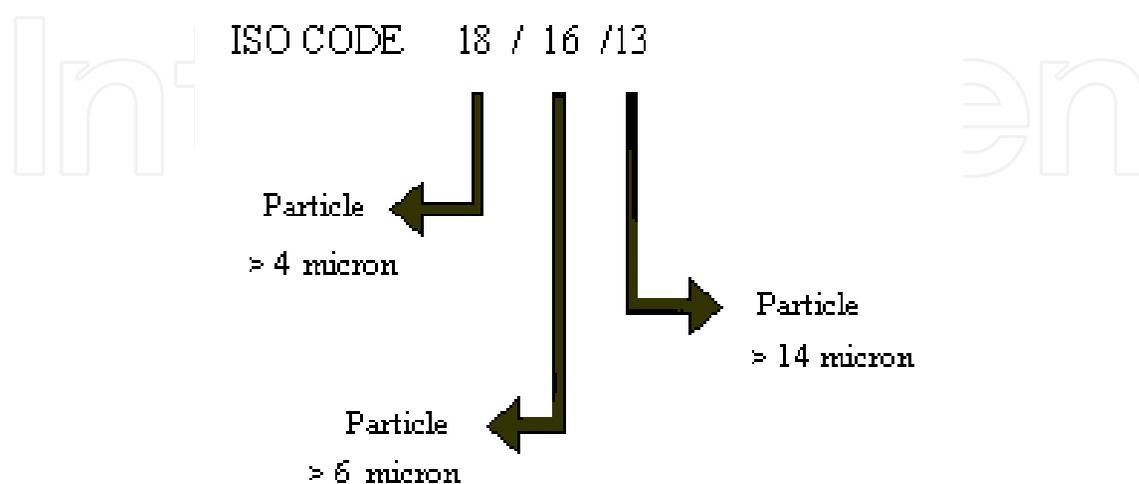

Fig. 2. Example of an obtained ISO Code, (Parker Catalog, 2000).

Range Number	Micron	Actual particle Count range (por ml)
18	4+	1,300 – 2,500
16	6+	320 – 640
13	14+	40 - 80

Table 2. Classification and definition by ISO (Parker Catalog,2000).

2.7 Ferrography

The ferrographic techniques are divided into two levels of analysis. A quantitative one, which is an evaluation technique of the wear conditions of the components of a machine, by quantifying the particles in suspension in the lubricant, and an analytical one, which uses the observation of particles in suspension in the lubricant.

The analytical ferrography is also known as direct reading ferrography. This one measures the concentration of ferrous particles in a fluid sample. With this technique one can get information on the degree of severity of wear in the machine under analysis.

To establish exact guidelines for the oil condition, samples are regularly taken from carefully selected positions of the machine system, preferably during normal operation (Lockwood and Dalley, 1992). In the ferrographic examination of direct reading the optical density is used to quantitatively measure the concentration of the wear particles in lubricating oil or in a hydraulic fluid. The particles are classified according to their sizes in DL (large particles, larger than 5 mm) (large particles), and DS (small particles, smaller than 5mm) (small particles). The wear particle concentration (WPC) and the percentage of large particles (PLP) are derived like this.

The following are equations to calculate the WPC and PBP:

$$WPC = DL+DS \tag{3}$$

$$PLP = [(DL - DS) / (DL + DS)] * 100 \tag{4}$$

The RPD (rotary particle depositor) is a type of device for direct ferrography where an index that represents the magnetic density in a given volume of lubricant is measured.

When the quantitative ferrography indicates an abnormal wear tendency, the analytical ferrographic techniques can be used to specifically identify the nature of the machine's potential problems. This enables a thorough study of particles whose size is between 1 and 250 μm (Arato, 2004). A ferrogram is built and then it can be analyzed aided by optical and electron microscopy, identifying the morphology of the particles, hence identifying any anomaly.

The ferrograms consist of transparent slides where the magnetic particles are deposited, they are separated by sizes by means of a magnetic field, other particles are randomly placed in the "barriers" formed by magnetic particles.

A first type of ferrogram is obtained by passing a flow of diluted lubricant on a plaque by gravity (the plaque is inclined). The plaque is placed on a magnet that attracts the ferrous particles and allows its adherence to the plaque, as illustrated in Figure 3.

Due to the magnetic field the particles are lined up in horizontal chains along the plaque, the larger particles are deposited first and there is a size decrease along the plaque. The non-ferrous particles are randomly placed throughout the plaque. The absence of ferrous particles actually reduces the efficiency of the analysis of non-ferrous particles.
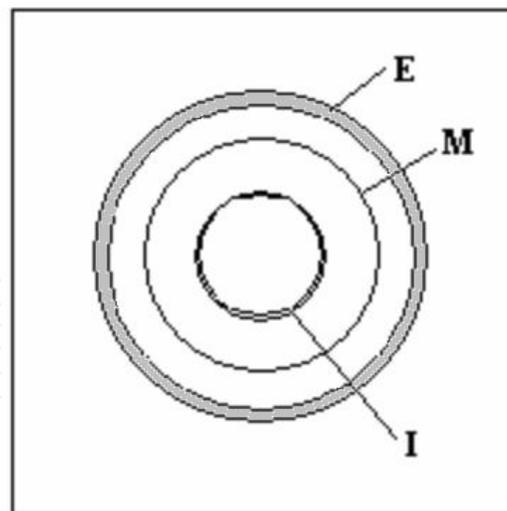
Fig. 3. Obtaining the ferrogram.

3. Analysis of vibrations

Vibration analysis is based on the idea that machine structures, excited by dynamics efforts, give vibratory signs whose frequency is identical to those of the efforts that provoked them; and the global measure in some point is the sum of vibratory answers of the structure to the different excitator efforts (Wang and Willing, 1995).

It is possible, with captors placed in private points, to register the transmitted vibration to the machine by the structures, and with its analysis, to identify the origin of the efforts which it is submitted. Vibration monitoring provides information about the macroscopic behavior inside the machine (Diana and Chelif, 2005).

In that way, as soon as it is obtained, the "vibration signature" of the machine when it is new or reputed as in good state, it will be possible for comparison , to appreciate the evolution of its state and to identify the appearance of new dynamic efforts, serial to a degradation in development process (Azoutsev, 1998).

The measure of a vibration transmitted by a structure under the effect of dynamic efforts will be function of multiple parameters:

a. Mass, rigidity and damper coefficient of the structure that transmits the vibrations;
b. Characteristics of machine fixation on the ground that opposes reactions to vibrations and modifies the intensity;
c. Position of measure point;
d. Position and fixation of the sensor (captor) on the machine;
e. Characteristic of sensor;
f. Pre amplification and transmission of the sign;
g. Performance of analyzed apparels;
h. Rotation and absorbed potency;
i. State of the connection of the cinematic chain (alignment, balancement, engagements, rolling, etc);

In a spectrum all the components of a vibratory level are represented under the form of "picks" and it can follow individually a variation of amplitude, without the masking effect that occurs in a global measure. Figure 4 shows an example of a spectrum.
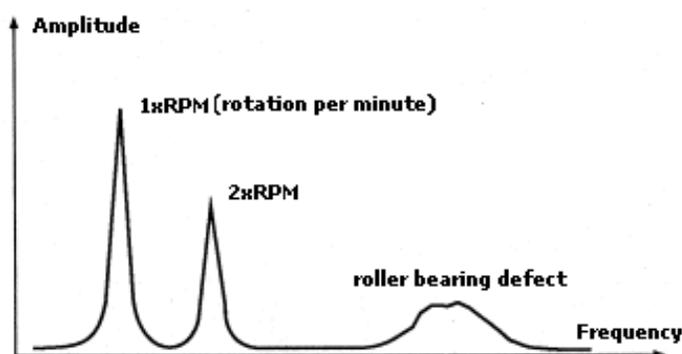
Fig. 4. Typical example of a roller bearing with problem (Mirshawaka, 1991).

The measure of the global value is an approximate analysis method of the sign that makes abstractions of the frequential parameters, expressing the evaluated amplitude in different ways. That takes into account:

a. The pick to pick value. It is measured the maximum amplitude of the fundamental wave that is useful, for example, when the vibratory displacement of a machine is critical in relation to restrictions of maximum load or clearance;
b. Crest value (or pick value). It is an important measure to indicate, for example, the level of a shock of short duration; and
c. Effective value. Measurement that takes into account the evaluation of the value of harmonic components directly related to the vibration energy content.

From the analysis of vibration signals it is possible to make decisions whether or not to intervene in the operation of the machine, so that it can be "available" as much as possible, reducing maintenance costs, time-stop of the machine, reducing the stock and improving safety, among others.

Thus, it is possible from the vibration signs at certain points of the equipment, to identify the emergence of new dynamic efforts or the abrupt increase of the magnitude of the response, which are indicators of the appearance of defects or deterioration of the operation.

Vibration data can be measured with accelerometers and processed by a signal analyzer. The signal can be analyzed in the time domain or in the frequency.

3.1 Description of time domain

A vibration signal can be presented by constructing a graph for magnitude values of the signal as a function of time, from a given moment regarded as zero time. The vibration magnitude can be represented by acceleration, velocity or movement.

The wave forms are analyzed by comparison with the wave forms previously collected, and observed by repetitive impulses that can report the frequencies of the bearings, the gears or other components. In Figure 5, the vibration signal caused by imbalance is the dominant signal. It has high magnitude when compared with the defects of bearing or gears. For this reason, the lower magnitude of the wave form is superimposed on the waves caused by imbalance (Green, 2003).

The vibration elements can be divided depending on the period of repetition, finite or infinitely long, in: periodic vibrations, random vibrations and transient vibrations.

• Periodic Vibrations - Vibrations that are repeated according to a given period of time.
• Random Vibrations - Vibrations that are unpredictable as to its instant value, for any future moment.

• Transitional Vibrations - Vibrations that exist only in a limited space in time, and null at any other time.
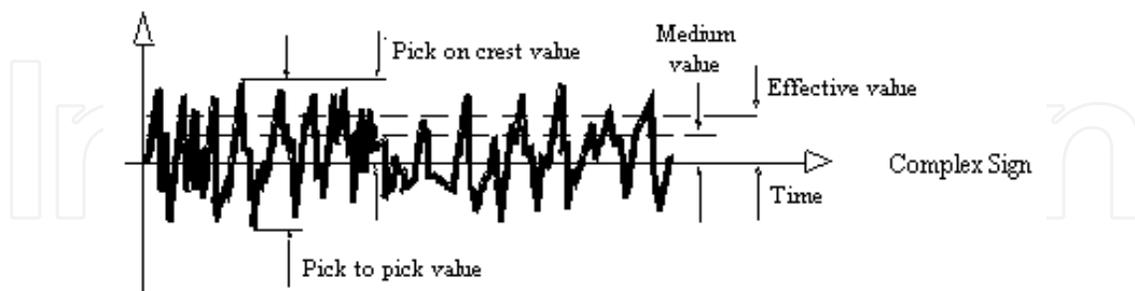

Fig. 5. Vibration Signal in time domain (Arato,2004).

3.2 Description of the frequency domain
The fast Fourier transform (FFT) can derive a wave form in time and present it in the frequency domain as shown in Figure 6. This process is the breaking of all vibrational signals into individual components of the vibration signal and plotting it in a frequency scale. This signal in the frequency domain is called frequency spectrum and provides valuable information about the condition of a machine.
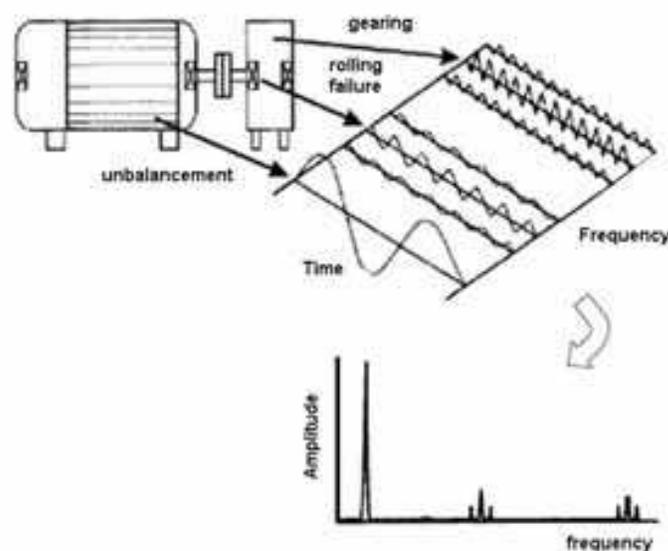
Fig. 6. Vibratory Signal in the frequency domain(Green, 2003)

The frequency spectra are used to obtain information that help determine the location of the problem, the cause of the problem and the time for the problem to become critical. This depends on the type of machine and is always relative to the level of vibration of the machine's proper operation. The frequency at which the vibration occurs indicates the type of failure and it provides an indication of what is causing the failure.

In FFT transformation, a small section is extracted from the time signal (the so-called time window) and the frequency spectrum is calculated using the FFT algorithm. During this

process the instrument assumes that the signal in this time window (time data set) is continuously periodical, that is, it is repeated over time, as seen in Figure 7.
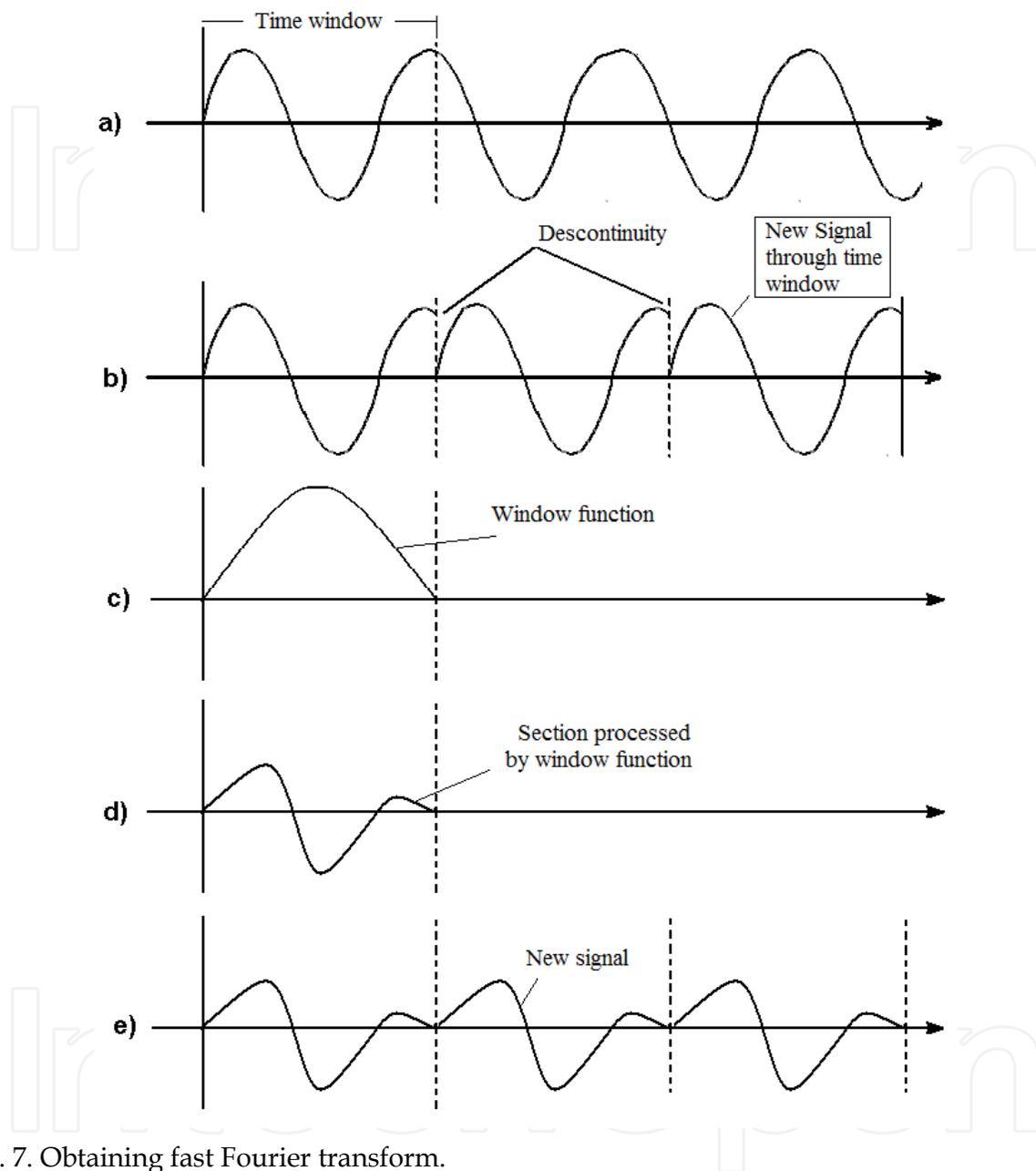
Fig. 7. Obtaining fast Fourier transform.

Depending on the structure and circumstances of the signal, some interruptions in the sequence can occur at the edges of the time window - which will reflect on the visual components of vibration.

These sequence interruptions always occur when the number of periods of the sign in the time window is not an integer. To eliminate such interruptions, a weight function is applied to the signal within the time window. As a rule, this is done so that the values of the signal at the beginning and end of the time window are reduced to zero.

Then, when the time signal on the computer is rebuilt, all the interruptions in the signal sequence are removed.

Evidently, because of this "manipulation", the machine's original vibration signal is distorted. To correct this, the results of the transformation are multiplied by a correction factor so that the exact values of magnitude are maintained, after processing.

3.3 Vibration analysis by global levels

In the case of application for predictive maintenance, the international technical standards, including the ISO, define two criteria for the adoption of a global value. One method assesses the severity of vibration by absolute measurement of non-rotating parts. The other one assesses conditions of the machine by direct measurement of oscillation of the shaft. (Gonçalves et all, 2007).

According to NBR 10082 a rating of acceptable levels of vibration severity for similar machines is established and grouped into classes. Table 3 shows the guidance offered by this standard, where:

Class I - Small machines activated by directly coupled electric motor, maximum power of 15 kW.

Class II – Mid-sized machines, class I type, with power greater than 15 kW, up to 75 kW. Motors or machines rigidly mounted up to 300 KW.

Class III - Large driving machines and other large machines (> 75 kW) with rotating masses mounted on rigid and heavy foundations, which are relatively rigid in the measuring of vibration.

Class IV - Machines of the Class III type, mounted on relatively flexible foundations in the measuring of vibration, for example, a set of turbogenerators.

Range of vibration severity		Avaliation of quality for differents machine classes			
Range	Velocity in limits (mm/s)	Class I	Class II	Class III	Class IV
0.28	0.28	A	A	A	A
0.45	0.45	A	A	A	A
0.71	0.71	A	A	A	A
1.12	1.12	B	A	A	A
1.8	1.8	B	B	A	A
2.8	2.8	C	B	B	A
4.5	4.5	C	C	B	B
7.1	7.1	D	C	C	B
11.2	11.2	D	D	C	C
18	18	D	D	D	C
28	28	D	D	D	D
45	45	D	D	D	D
71	upper 45	D	D	D	D

Table 3. Classification and assessment of machines by vibration severity levels.

Where:
A = Proper conditions;
B = Acceptable for continued operation;
C = Tolerable Limit;
D = Non-permissible.

For rotating machines with rotation speeds in the range of 600 to 12,000 rpm (10 to 200 Hz), ISO norm 2372, VDI Richiline 2056, and in Brazil by NBR 10082, take the value of effective vibration speed, known as rms speed of the signal, as the unit of measure for identifying the severity of vibration (Arato, 2004).

The parameter to be measured is the absolute velocity of vibration on the machine parts, preferably the bearings. In this case, the global value chosen as the unit of measure to indicate the vibration severity, the effective value, or simply RMS speed (V_{ef}) is not represented by a single scale of values. This is due to the great diversity of forms, mass, assembly and operational conditions of the equipment, which results in the RMS speed values for different levels of acceptable severity, (Gonçalves et all , 2007).

3.4 Demodulation

In more complex situations, where there is a combination of more than one source of excitement added to the noise transmitted through the support and foundations of the machines, the obtained spectrum of frequencies can present difficulties in the analysis (Arato, 2004).

In cases like this it is necessary to use other more dedicated techniques, such as the technique of demodulation, which enables identifying noise sources responsible for the excitation of resonant responses in the structure, hence allowing to monitor defects that are responsible for impacts of the repeated excitation type, in addition to others that produce modulator signals, even if the level of energy of the source does not allow a direct identification of its frequency in the general spectrum, as it generates amplitudes of minor significance, which remain hidden in the level of background noise.

Taking into consideration, by generalization, that the modulation in magnitude of a signal is defined as the multiplication of one sign for another, a nonlinear inherent process that creates new frequencies are not present in any of the signals involved. The identification of the noise source associated with the defect requires identifying the frequency of the modulating signal, (Arato, 2004).

The process of identifying the modulating frequency of a modulated signal is known as demodulation, and includes the following steps, (Arato, 2004):

a. Filtering of the signal by band-pass filter for the frequency range identified as modulated;
b. Detection of the modulator signal;
c. Spectral analysis of this detected modulator signal.

For the detection of the modulator signal there are several techniques. Application of the Hilbert transform that can be obtained from X (f), which is the Fourier transform of the filtered signal x(t) , according to the equations below.

$$x_{re}(t) = \text{Re}\left[2\int_{0}^{\infty} X(f)e^{i2\pi ft} df \right] \tag{5}$$

$$x_{im}(t) = \text{Im}\left[2\int_{0}^{\infty} X(f)e^{i2\pi ft} df \right] \tag{6}$$

Obtaining the signals $x_{re}(t)$ and $x_{im}(t)$ from which an analytical signal $z(t) = x_{re}(t) + ix_{im}(t)$ (Bendat(1986) can be constructed, (apud Arato & Silva, 2000), which can be represented by

Equation 7, where A(t) is the envelope and $\phi(t)$ is the instantaneous phase of the signal x(t), according to Equations 8 and 9.

$$z(t) = A(t) \cdot e^{i\phi(t)}$$ (7)

$$A(t) = \sqrt{x^2(t) + x_1^2(t)}$$ (8)

$$\phi(t) = tg^{-1}\left(\frac{x(t)}{x_1(t)}\right)$$ (9)

4. Materials and methods

In this work, to verify the effectiveness of the techniques studied, a reducer of the worn drive type was monitored. For this monitoring a test bench was built, where the reducer, coupled with its entry shaft to an electric motor, by means of an elastic coupling, had a load of an unbalanced mass in its output shaft.

A photograph of the bench is shown below in Figure 8. The electric motor used is a WEG, 220 V, 60 Hz, three-phase power with 0.5 CV power and 1720 rpm.

Fig. 8. Test bench for verification of the studied techniques.

The reducer used was a Macopema, ZM reducer, worn thread, with a reduction of 1:30, 0.53 CV at the entry and 0.31 CV at the output, with oil capacity of 0.25 liters.

Rolling element bearing (www.skf.com)			Shaft rotation		Engagement
Model	6008	6204	exit	entry	
f_{ip}	197 Hz	142 Hz			28.67 Hz
f_{ep}	147 Hz	87.5 Hz			
f_{rp}	191 Hz	114 Hz	0.95 Hz	28.67 Hz	
f_{gp}	13.2 Hz	11 Hz			

Table 4. Preferred vibration frequencies of the reducer.

At the output of the reducer a bearing was attached and after the bearing a 7.5 kg mass with a 195 mm arm.

The preferred vibration frequencies of the reducer analyzed were calculated, as illustrated in Table 4.

Where:

f_{ip} = defect frequency of inner race.

f_{ep} = defect frequency of outer race.

f_{rp} = defect frequency of rolling bearing elements.

f_{gp} = defect frequency of cage.

The tests were conducted after a running period of 168 hours, for four weeks, and each week (168 hours) oil samples were collected.

Oil recommended by the manufacturer was used; beyond oil with several percentages of liquid contamination and oil with various percentages of solid contamination.

This work presents results obtained from the first four weeks of testing, with ISO 320 oil that was recommended by the manufacturer of the reducer.

The vibration measurements were collected in the three directions of the reducer. Analyses were performed in time and frequency in order to determine the beginning and severity of the active wear where the sensors were placed for collection of the vibration signs. Figure 9 shows the points along the reducer where the sensors were placed for collection of the vibration signs.
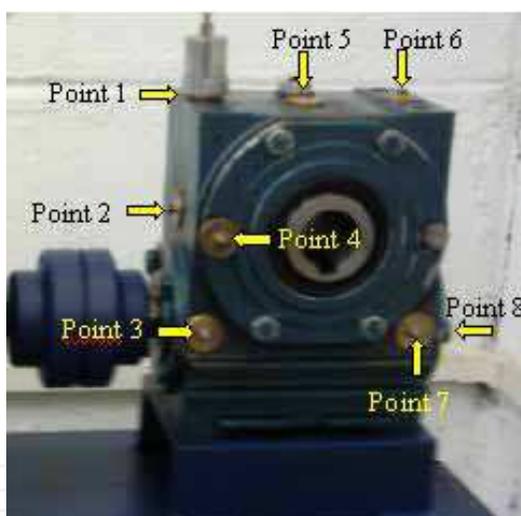
Fig. 9. Collection points of vibration signals.

According to the norms the bearings should be monitored first, thus points 3 and 7 were chosen. Points 2 and 5 represent the other two directions. These points contain all the information provided by points 1, 4, 6 and 8.

The time vibration signals were obtained by measuring the vibration speed of the reducer. For such measures piezoelectric accelerometers, a 4-channel Conditioner/ Amplifier, data acquisition system DaqBooK and a Notebook were used. The sampling frequencies were of 500 Hz, 1 kHz, 5 kHz and 10 kHz, and the corresponding analog filters were of 141 Hz, 281 Hz, 2250 Hz and 4500 kHz. For each frequency 10 samples were taken out of 2048 points.

The time vibration signals obtained were processed using the algorithm FFT (Fast Fourier Transform), and analyzed in the laboratory through the "software" DASYlab.

As the accelerometer measures the vibration speed of the reducer, using a reading indicator, the measured value of greatness is obtained directly, that is, the value of the effective vibration speed for each distinct sampling frequency. The value of the vibration severity however, is obtained when a vibration signal of a sampling frequency of 5000Hz is read, but subjected to a high-passed filter of 10 Hz and a low-passed of 1000 Hz. Both the effective value of the vibration speed and the severity of vibration were obtained using the "software" DASYlab, which contains numerous tools as: reading indicators, filters, etc.

The vibration analysis was achieved by spectral analysis, analysis by demodulation and the values of the effective vibration speed and vibration severity.

For demodulation of the signal it was necessary to use a computational routine on the Matlab platform called DEMOD, created by Arato (2004) and responsible for the calculation of Hilbert transformed.

Only the time signals obtained in points 2 and 5, when subjected to high frequencies of sampling were demodulated, due to the fact they are the only signals demonstrating frequencies that can be resonant. After demodulation the signal was processed to obtain the spectrum of the demodulated signal.

Oil samples were prepared in the rotary particle depositor (RPD), and then examined and photographed using the optical microscope Neophot 21 with adapted light transmitted. In the RPD lamina the particles are arranged in three separate rings, depending on the size of the particle, due to this, it was necessary to capture the images by observing these three rings separately.

Using the automatic monitor of ferrous particles, the PQ index of the samples was obtained. Also the viscosity, water content, the acidity index and atomic absorption of the oil samples were obtained at the end of each test.

5. Results and discussions

5.1 Analysis of lubricant
Initially, the inner elements of the reducer were photographed for a subsequent comparison and verification of wearing.

Fig. 10. Inner elements of the reducer. On the left is the worn screw and on the right the crown gear.

Figure 11 shows the photographs after the first week of the experiment.

In the figure above it can be seen severe wear particles (1A), bronze particles (2A), laminar particles (3A) and cutting particles (4A).

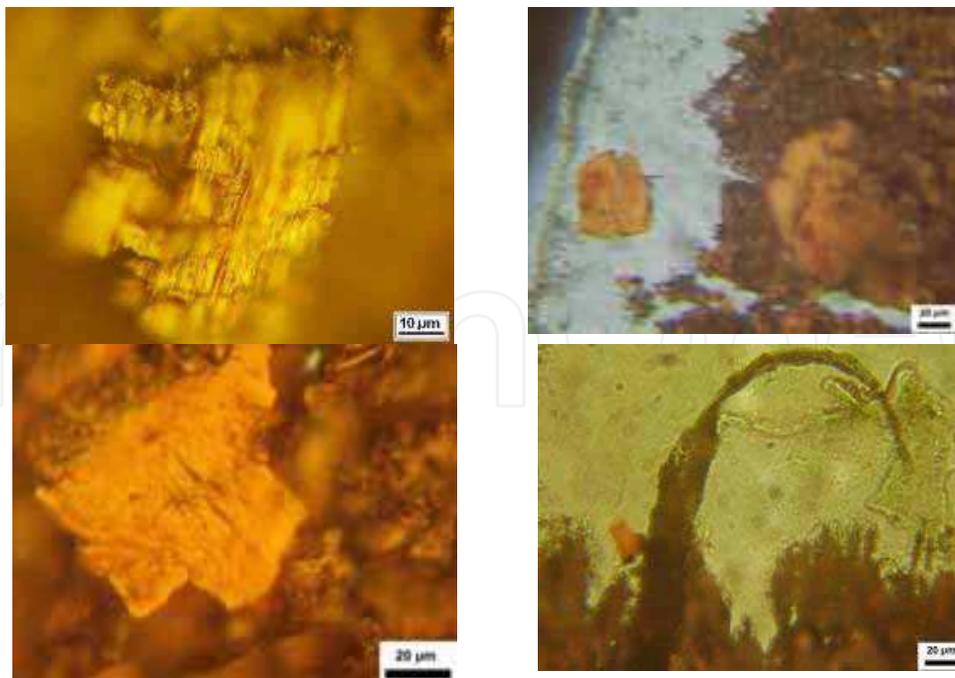Figure 12 shows the photos obtained after the second week of the experiment.

Fig. 11. Wear particles generated in the first week of the first experiment with transmitted and reflected light. First picture: inner ring of the RPD. Second photo: outer ring. Other photos: intermediary ring.
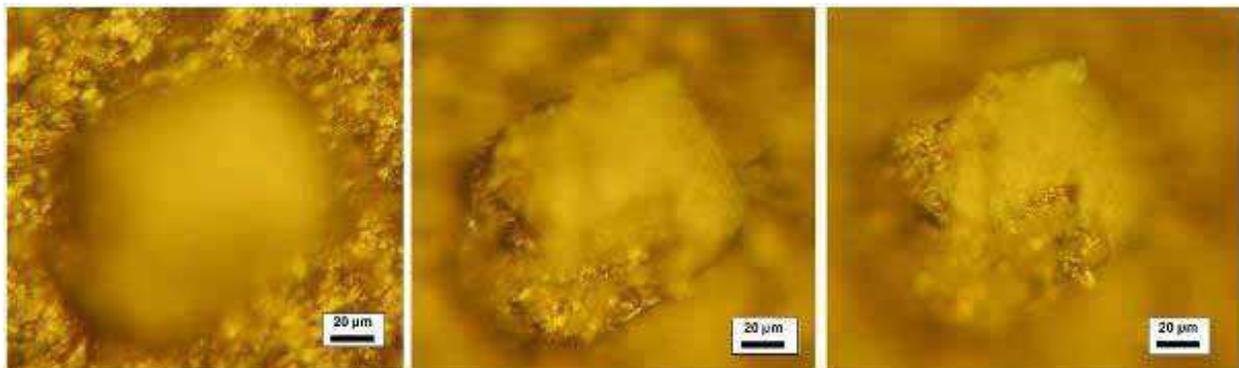

Fig. 12. Wear particles generated in the second week of the first experiment with reflected light and in the inner ring of RPD. The three photos are from the same field of vision but with different focal heights.

By Figure 12 the visual difficulty of the laminar particles can be perceived.

Figure 13 illustrates the photos obtained after the third week of the experiment.

Through Figure 14 the presence of oxide (1A), laminar particles (2A), bronze detained between the ferrous particles (3A) and parts difficult to focus can be seen (4A and 5A). The last two figures also show the need to vary the type of light in the verification of the particles.

Table 5 presents the tests values of TAN, viscosity at 40^0C and 100^0C, after the end of the last week of the first experiment. Table 6 shows the result of the atomic absorption at the end of this experiment. Table 7 shows the figures obtained in the direct ferrography during the experiments, represented by the PQ index of the magnetic particles counter. Figure 15 shows the state of the reducer after the experiments.
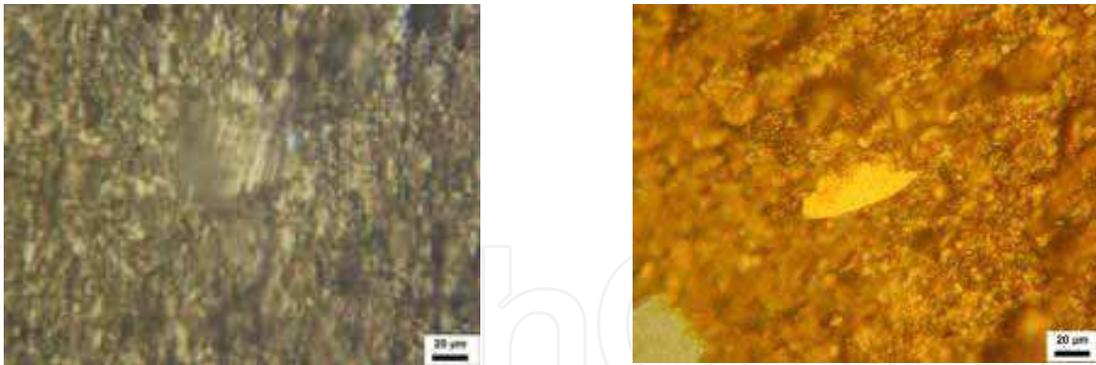
Fig. 13. Wear particles generated in the third week of the first experiment with reflected and transmitted light in the intermediary ring of RPD.

Through the figure above the severe wear particles represented by striation (1A) and the particles overlapping the others (2A) can be seen.
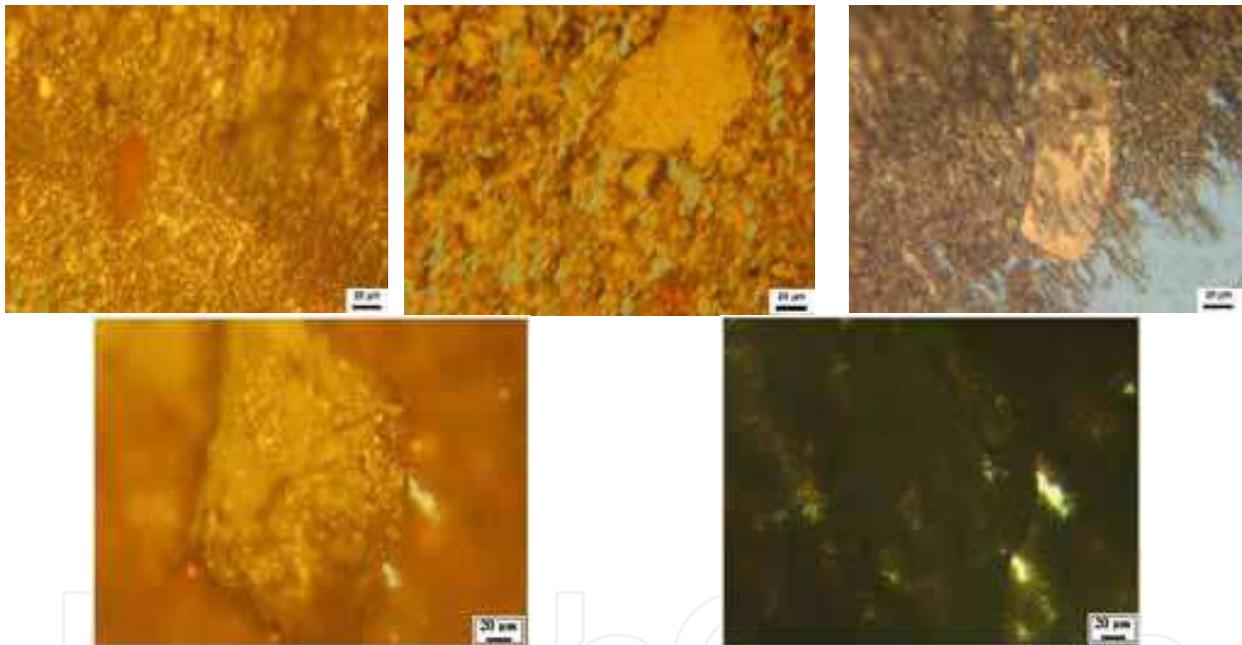In Figure 14 the photos obtained after the fourth week of the experiment are shown.

Fig. 14. Wear particles generated in the fourth week of the first experiment The first photo is of the inner ring of RPD observed with transmitted and reflected light. The second photo is of the outer ring with the same lights. The third one is the intermediary ring with the same lights. The last two are also of the intermediary ring; the second to last is with transmitted and reflected light and the last one with only transmitted light.

Water	TAN	Viscosity at 40^0C	Viscosity at 100^0C
ASTM D 95	ASTM D 664	ASTM D445	ASTM D 445
(%)	mg KOH/g	cSt	cSt
0.00	1.17	295	42

Table 5. Tests conducted on the oil at the end of the experiment.

Atomic absorption						
Cu	Si	Al	Fe	Pb	Cr	Ni
Ppm	ppm	ppm	ppm	ppm	ppm	ppm
580	18	4	142	0	0	7

Table 6. Atomic Absorption conducted on the oil at the end of the experiment. Atomic absorption

Test A			
1st Sample	2nd Sample	3nd Sample	4nd Sample
670	1680	3050	4000

Table 7. PQ Rates obtained on the particle monitor.

Fig. 15. Inner elements of the reducer after the first test.

Through Table 5 it was noticed that the viscosity at 100 ^{0}C increased from allowable range (27.9-33.3), according to the specifications of the new oil, to 42.03. This means an alert since the 10% of the permissible range was exceeded. This may be an indication of oxidation of the oil.

In Table 6 large amounts of Cu was noticed in the bronze of the crown and Fe in the alloy steel from which the pinion is manufactured. The Si is an indicator of external contamination.

In Table 7 the gradual wear of the pinion can be seen. As the samples were not changed during the first experiment, the quantity of metallic particles accumulated during the weeks of this first experiment.

5.2 Analysis of vibrations

Several vibration measures were taken at various points of the reducer. In the following Figures some measures taken at some points are presented. Table 8 shows the effective value and the severity value of the vibration velocities.

	Vibration effective value (mm/s)			Vibration Severity
	500Hz	5000Hz	10KHz	NBR 10082
Point 2	0.27	0.71	0.99	0.64
Point 3	0.34	0.43	0.54	0.51
Point 5	0.37	0.44	1.09	0.42
Point 7	0.51	0.64	0.68	0.61

Table 8. Effective value of vibration speeds (mm/s) and severity values of vibration by the NBR 10082 norm, (10 to 1000Hz), at the end of the last week of the first experiment.
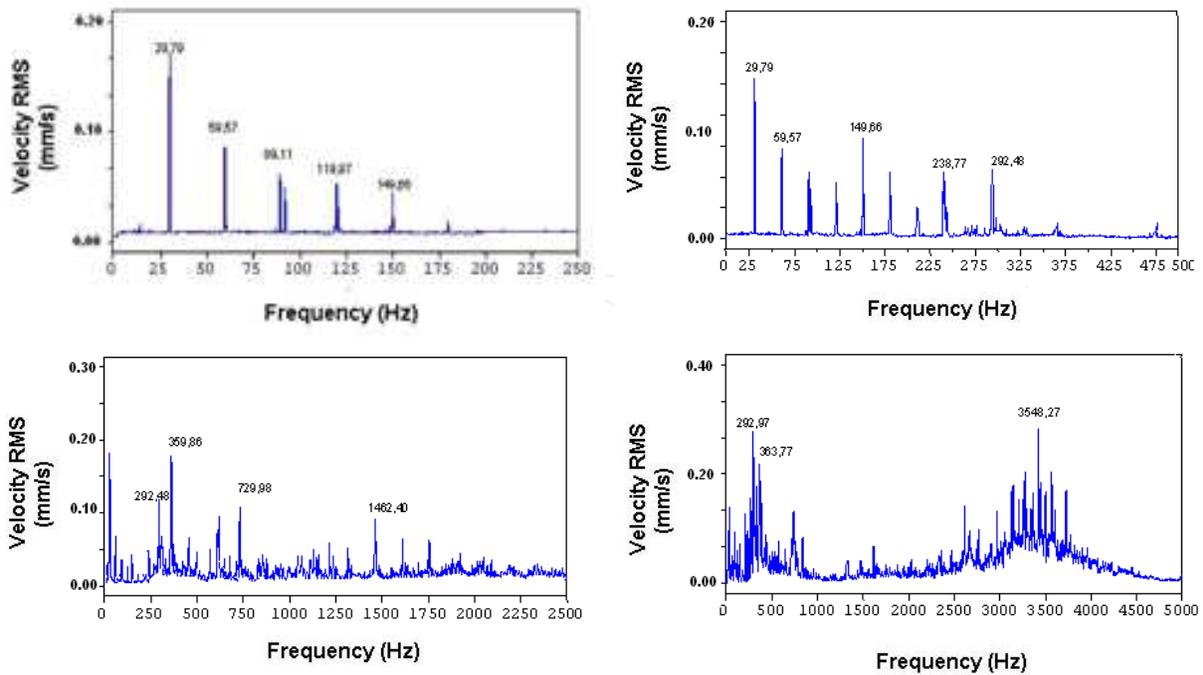
Fig. 16. Vibration spectra obtained at point 2, for sampling frequencies of 500, 1000, 5000 and 10000 Hz with analog filters of 141, 281, 2250 and 4500 Hz respectively, at the last week of the first experiment.
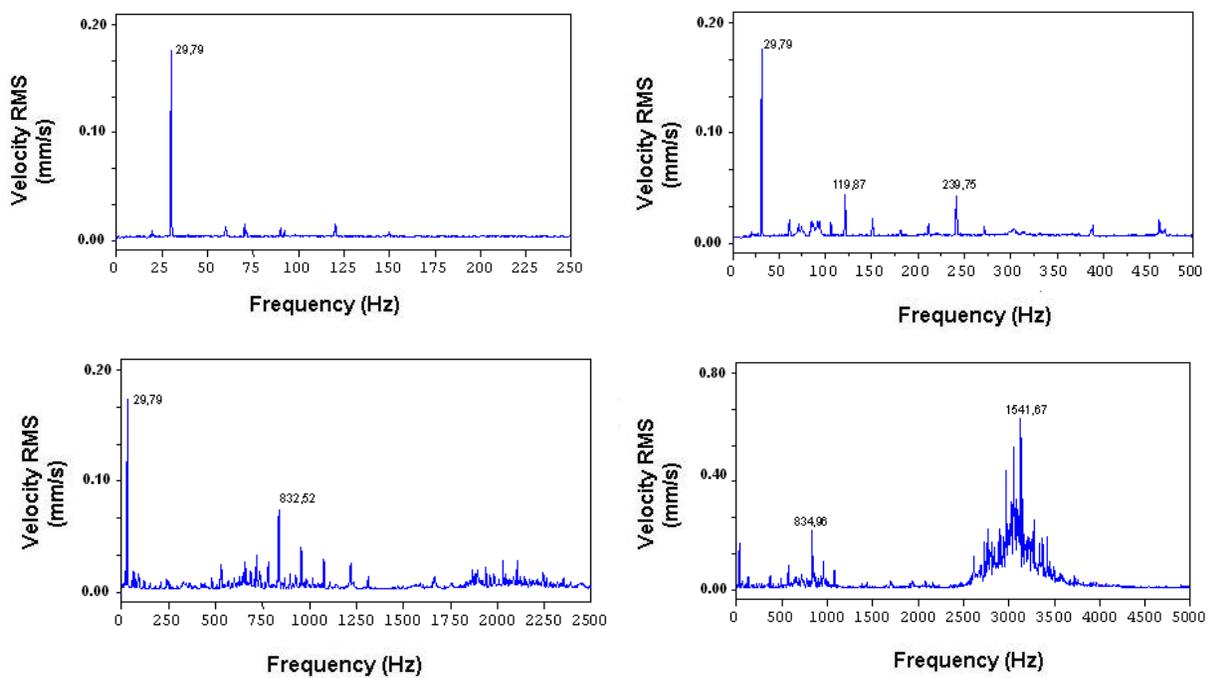

Fig. 17. Vibration spectra obtained at point 5, for sampling frequencies of 500, 1000, 5000 and 10000 Hz with analog filters of 141, 281, 2250 and 4500 Hz, respectively, after the last week of the first experiment.

Figure 18 presents a graph showing the trend of the values obtained in the four weeks of the first test for points 2, 3, 5 and 7.
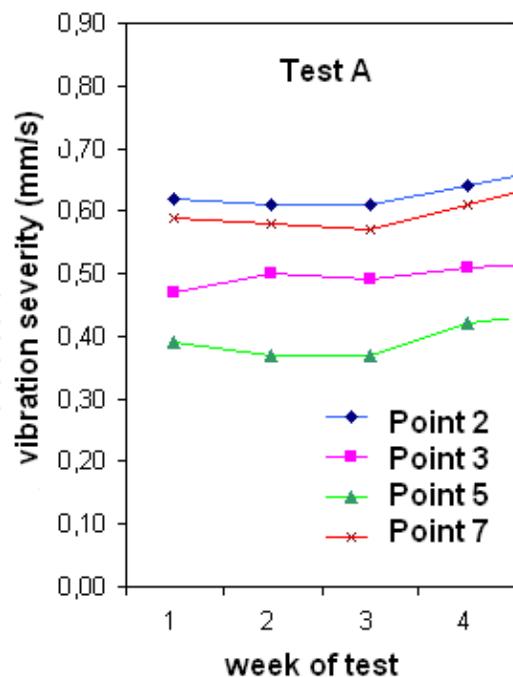
Fig. 18. Evolution of the vibration severity in accordance with the NBR 10082 norm.

Considering that our experiment fits in Class I of the NBR 10082 norm, we found that all the values are within the range considered to be in good conditions, that is, within the range A of Table 3.

Resonant frequencies were found in points 2 and 5 of the reducer. These were demodulated when subjected to a sampling frequency of 10kHz.

Figure 19 shows Point 2 with a cutoff frequency of 250 and 450Hz, where demodulation was performed on the sampling signal of 10 KHz at the end of the first experiment.
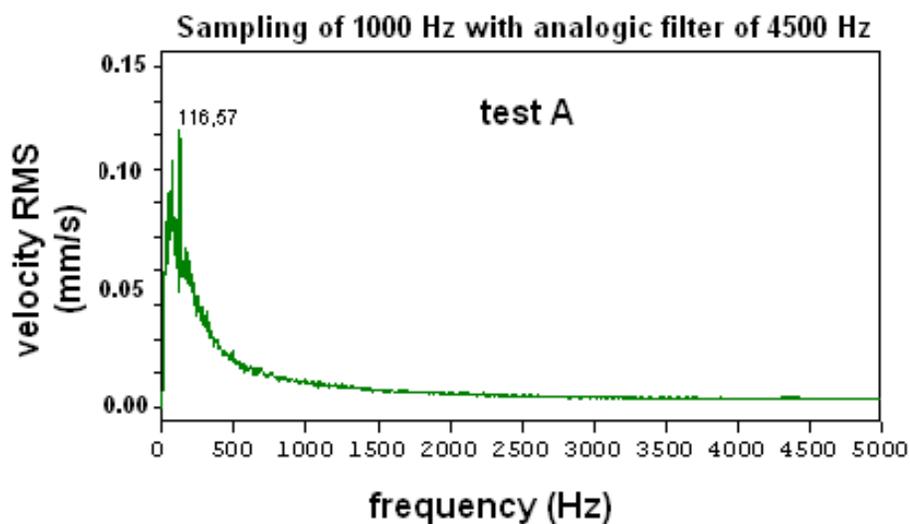
Fig. 19. Filtered time signal around the resonance frequency using a cutoff frequency of 250 Hz and 450 after demodulation by the program DEMOD followed by its spectrum.

Figure 20 shows Point 5 with a cutoff frequency of 2900 and 3300Hz, where demodulation was done on the sampling signal of 10 KHz at the end of the first experiment.

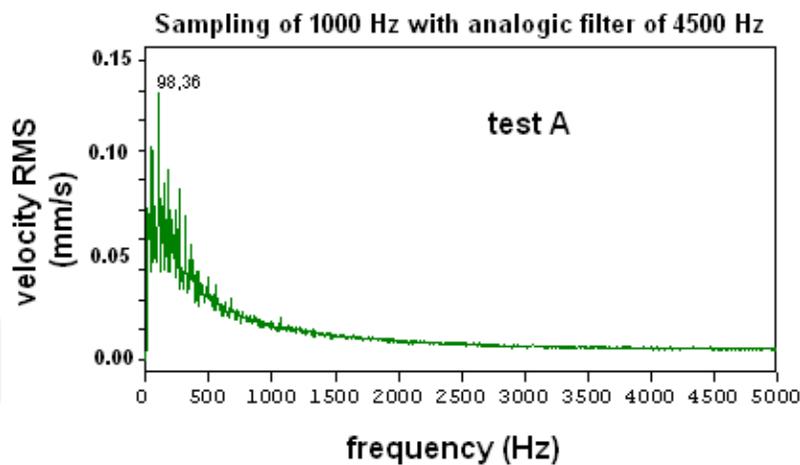Sampling of 1000 Hz with analogic filter of 4500 Hz

Fig. 20. Filtered time signal around the resonance frequency using a cutoff frequencies of 2900 and 3300 Hz, after demodulation by the program DEMOD followed by its spectrum.

Through demodulation of the signal it was observed that these frequencies are not related to bearing defects.

6. Conclusions

The type of reducer used, worn drive, is difficult to analyze because in this case there is a low rotation shaft (exit of the crown, which in our case is of 0.95 Hz) and the engagement frequency coincides with the rotation shaft frequency, given that the worn screw has a single entry.

In the studied reducer the oil analysis showed a certain advantage, given that since from the beginning this operation demonstrated the reducer's improper operation, while the vibration analysis was difficult to use given that the rotation shaft and engagement coincided.

The experiments also demonstrated that if in a system an abnormal occurrence takes place, for example an extra load during a certain period of time, the subsequent vibration analysis may not perceive what took place if no permanent damage occurred, however the oil analysis will acknowledge that there was such a problem during the operation.

No bearing defects were found in the spectra and neither in the demodulation.

After disassembling the reducer it was found that the axis bearings of the worn screw were loose. The literature shows that the loose bearings are represented by the frequency of the spin axis and its harmonics, which is the same case as the wear. This fact was difficult to check because of the coincidence of such frequencies.

One of the simplest tests, the counting of particles through the automatic monitor of PQA particles, showed a high generation of magnetic particles from the first sample.

The atomic absorption performed at the end of each test also provided important information about the tribological condition of the system, where a large amount of copper particles can be noted from the crown and iron resulting from the pinion.

The reducer's incorrect operation can also be verified by a visual inspection of the particles. Most of the photos demonstrate the presence of many ferrous particles and some copper particles. We also found many wear particles by friction (laminar particles) and severe wear particles by sliding, which are particles with striation.

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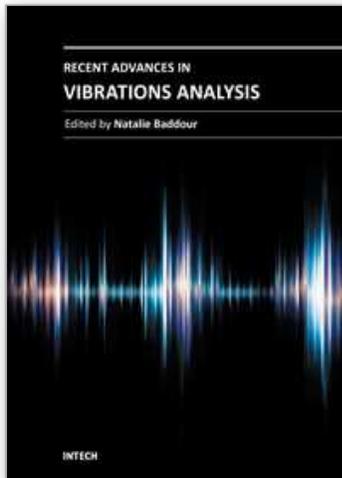
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