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CHARACTERIZATION OF OIL VISCOSITY ALTERATIONS IN A GEARBOX THROUGH VIBRATION SIGNAL ANALYSIS

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Abstract: The last few years have seen an increased interest in maintenance techniques. Maintenance management strategies based on reliability (RBF) , and new techniques for conditioning monitoring have shown that, in many industrial equipment, the best performance is accomplished when preventive or corrective maintenance are replaced by predictive maintenance techniques.

The most used technique applied for monitoring and diagnosis of rotating machinery is vibration analysis. Despite the fact that many rotating machinery problems are caused by lubrication failure, very little is known about the relation between the vibration signature and the lubrication condition. This work presents a study of this relation. It is presented here an investigation for detecting lubricant viscosity alteration in a gearbox, using vibration signals. The experiment was made using different kinds of lubricant oils, with different viscosities and considering several shaft speeds. The temperature of the lubricant was also monitored. The results show that it is possible to define a vibrational characteristic that is strongly related with the viscosity variation.

Keywords: predictive maintenance, vibration analysis, lubrication, oil viscosity.

1. Introduction

In the last few years the industrial environment has seen a growing usage of predictive maintenance techniques. The complexity of the equipment is growing and therefore a non programmed stop in the production line may result in high costs due to machinery repair and production losses (Taylor, 2000 and Almeida et all, 2001b,).

The use of predictive maintenance techniques demands each day more knowledge about non intrusive methods for characterization of the state of the machinery. One of the more used and explored methods of predictive maintenance applied to rotating machinery is vibration analysis (Jones, 1994).

The fact that many industries have been, using vibration analysis, for some time now, in order to monitor rotating machinery status (Tandon, 1994 and Kimura, 1997), makes any study to extend and improve predictive maintenance tools very important, since it can result in a more reliable and faster diagnostic.

Lubrication failure has been an important cause of machinery breakdown (Gerges, 1999). In many cases the lubrication failure is due to oil degradation by contamination with dust, water, etc… (Carreteiro 1998). In the context of predictive maintenance the lubrication state is usually monitored through physical and chemical oil analysis.

Despite the spread use of this two techniques (vibration analysis and oil analysis), very few knowledge is available about the effects of the lubrication or the lubricant on the vibration machinery signature (Almeida, 2001a) and most of the few papers at this subject are about rolling bearings (Su, 1992 and Campbell , 1994).

The most important characteristic of the lubricant oil is its viscosity (Carreteiro 1998). This work presents the initial results of an experiment that seeks to characterize the effects of the lubricant oil viscosity in the vibration signature of a gearbox.

This work explores the effects of the lubricant oil viscosity on several well known parameters of gearbox vibration signal. It will show that it is possible to obtain a parameter that has a strong correlation with the oil viscosity and will also show a vibration signal characteristic that seems to be correlated with the contact area.

2. Experimental rig.

The spur gearbox had two pairs of gears, reaching a 6.32:1 ratio, connected to an electric motor of 0.34 kW. The equipment was manufactured by the Cestari Corporation. A frequency variation device was used to obtain several different shaft speeds.

In these tests, two different pinions were used at the first reduction stage: a pinion without any defect (denominated normal gear) and one with ten teeth scratched, characterizing a damaged surface pinion (denominated scratched gear).

In these initial results, no external load was applied to the gearbox.

Two piezoelectric accelerometers were used: an accelerometer B&K 4393 was positioned in the vertical direction and an accelerometer PCB 353b02 was positioned for taking measures in the axial direction. Both accelerometers were positioned over the first gear pair regarding the input shaft . The accelerometers were connected to an amplifier, with a low-pass analog filter of 10 kHz cut-off frequency. The filtered signal was sampled, with a sampling frequency of 21 kHz for an A/D converter card mounted in a personal computer. The signal was represented by 43000 points.

For each one of the experimental conditions, nine samples of signals were collected to assure good statistical representation.

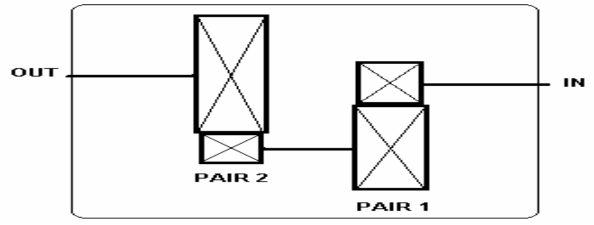

Figure 1-gearbox scheme.

An electronic trigger was used in the outer shaft of the gearbox in a way that its signal was used to control the acquisition process in order to obtain all signals with the same phase (regarding the shaft position). Using the trigger signal it was also possible to measure the shaft speed.

The overall temperature of the gearbox oil lubricant was measured using a thermocouple positioned at the bottom of the gearbox. This signal was measured but not digitalized.

3. The Oils

The oils used in the experiment were obtained by mixing two basic oils (oils without any addictives) supplied by Petrobras: the OB470 (viscosity 435cSt at 40°C) and the OB96 (viscosity 112cSt at 40°C). The oils obtained by the mixing procedure were named as follow: 96, 200, 300, 400, 470 (with their viscosities indicated in Table 1).

The oil were used in two different temperatures. In Table 1 the letter “f” indicates the cold condition of oil temperature (30°C) and the letter “q” the hot condition (40°C).

Before being used in the gearbox the oils have their viscosity evaluated by an oil analysis laboratory. The results are shown in Table1.

Table 1-Oils viscosity order.

Oils ordered by its viscosity				
oil denomination	viscosity (cSt)	Viscosity order	line color	line style
96q	96	1	magent	dot
96f	168	2	magent	continuous
200q	217	3	blue	dot
300q	328	4	red	dot
200f	358	5	blue	continuous
400q	364	6	black	dot
470q	435	7	green	dot
300f	643	8	red	continuous
400f	680	9	black	continuous
470f	861	10	green	continuous

The raising viscosity order is indicated in the third column in Table 1. This table will be referred when comparing the obtained results.

A special experimental condition was also employed in order to characterize a critical lubrication failure by the use of the gearbox without any oil in it.

It is worth to point out that the nominal oil viscosity indicated by the gearbox manufacture is approximated 300 cSt and also that this oils have almost the same specific mass.

4. Experimental conditions

The experimental database is composed by a combination of the following experimental conditions:

- Five oils 96,200,300,400,470 at 30°C (cold condition “f”) and 40°C (hot condition “q”) and no oil (s/o), resulting in 11 different viscosities.
- Two different gears: a normal one and a scratched one.
- Six different shaft speeds: 600, 800, 1000,1200,1400,1600 rpm.

- Acceleration signals measured in the vertical and axial directions.

5. Traditional statistical methods for signal processing

Three widespread statistical techniques, which are used for machinery diagnosis purposes, are statistical moments of order two, three and four. The mathematical definition of the RMS, Skewness and Kurtosis are presented below.

5.1. RMS

The RMS value is related to the energy of the signal. In many cases the arising of the defect is directly detected by the increasing of the machine vibration level. This means that RMS calculated in a certain frequency band can be used for detection of a defect. The results of RMS can be compared with normalized values or even with values previously collected. It is common to use RMS to detect defects in industry (Tandon , 1994). The RMS value is calculated in the following way:

$$RMS = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i)^2} \tag{1}$$

where x_i is the signal amplitude and N is the signal number of points.

5.2. Skewness

Skewness is the third order statistical moment, normalized by the standard deviation to the third power.

$$s = \frac{1}{Ns^3}\sum_{i=1}^{N}[x_i - m]^3 \tag{2}$$

Where σ is the standard deviation, *m* is the average of the signal and x_i are the amplitudes of the signal. This statistical moment indicates the asymmetry of the probability density function (pdf), measuring the deviation degree from the symmetry of a distribution.. The skewness is being studied as a parameter for machinery defect diagnosis (Almeida , 2001b).

5.3. Kurtosis

Kurtosis is defined as the fourth statistical moment, normalized by the standard deviation to the fourth power, which is shown below.

$$K = \frac{1}{Ns^4}\sum_{i=1}^{N}(x_i - m)^4 \tag{3}$$

Kurtosis represents a measure of the flatness of the density probability function near the average value. A well-known value of the Kurtosis for the normal distribution is 3.

As a parameter for diagnosing faults in rolling bearings, the values of the Kurtosis increase with the growth of the defect. This fact is a consequence of the increase on the vibration pulses generated by the passage of the rolling elements over the defect (Silva, 1999).

6. Traditional spectral analysis

Despite the importance of the statistical tools, specially the RMS used for alarm purposes, the most important techniques used for vibration analysis in rotating machines are based on the spectral analysis.

6.1. The PSD

One of the most common ways to visualize the signal spectrum is the Power Spectral Density (PSD), mainly in the case of noisy signals, particularly vibration signals.

The PSD is defined as the Fourrier Transform of the autocorrelation function of the signal. For a good statistical spectrum representation, the spectrum is estimated in this work by using the Welch method (Proakis, 1996) that considers the periodgram techniques. Equation 4 gives an idea of this calculation.

$$X[f] = \frac{1}{L \times M \times U} \sum_{i=0}^{L-1} \left| \left(TF\left[x_M{}^i[t] \bullet g_M[t] \right] \right) \right|^2 \qquad (4)$$

where:
M is the size of the time window.
x_M^i is the signal amplitude at the i time window of length M.
L is the total number of time windows.
γ_M is the time window (in the results presented in this article, it was used a Hanning window)
U is a normalization factor related with the time window energy.

6.2. The spectrum of the envelope of the signal

In many cases the signal contains many modulation frequencies, mainly when dealing with rotating machinery. To study this modulation the envelope technique is generally used (Jones , 1994). The envelope of the signal is the overall shape of the amplitude maxima of the signal. A way to visualize the modulation frequencies is by calculating the envelope spectrum. In this article the envelope spectrum was estimated using the Welch method.

6.3. The gearmesh frequencies

The gearmesh frequencies are an important parameter used for gearbox analyses (Taylor, 2000). It can be calculated as shown at Eq. (5).

$$fe = np \cdot fr \qquad (5)$$

where:
fe- gearmesh frequency , *np*- number of gear teeth. and *fr* is the rotation frequency.

In predictive maintenance the multiples of the gearmesh frequencies (harmonics) are also usually important (Taylor, 2000 and Jones, 1994). The gearbox used in this work has two fundamental gearmesh frequencies (for each one of the gear pairs).

7. Results and analysis

This discussion presents the results accomplished by the use of the described signal processing techniques. The results show that despite the fact that some of these parameters have a good correlation with the viscosity; this correlation is not consistent, failing in several important experimental situations.

From the spectral analyses, it will be shown that a particular frequency band is strongly correlated with the oil viscosity. Calculating the energy level at this particular band it was possible to create a parameter expressing this correlation. It will be shown that this new parameter is very sensible to alterations in the lubricant oil viscosity.

Despite the good relation between viscosity order and the parameter values this good result do not repeat when the scratched gear is used. This fact indicates that the parameter (and the associated frequency band) should be correlated with the contact area as will be discussed later in this article.

7.1. Statistical characteristics

The results obtained with the kurtosis and skewness show that the oil viscosity has no correlation with these statistical parameters.

Figure 2 presents the results for the vertical acceleration, in a condition of a constant torsional load using the normal gear. The number in parenthesis, in the figure legend, indicates the viscosity rising order as described in Table 1(this will appear at all the figures presented in this work).

From Figure 22, it can be notice that, regarding the viscosity, no order is achieved. The same behaviour can be observed for kurtosis and skewness in all the other experimental conditions.

Figure 3 presents the results for the RMS, vertical acceleration, no load and normal gear. It can be noticed that the RMS has a better correlation with the viscosity order, than with skewness and kurtosis parameters

This result is not a surprise since RMS is related to the vibration energy, and the greater is the viscosity, the greater the expected damping effect (Campbell, 1994). Consequently, a decrease in global vibrations levels is also expected. Despite this correlation being good, the viscosity order fails in many experimental conditions. Perhaps the most clear example of this failure can be observed in Figure 3 when, for low shaft speeds, the oil 470f has greater RMS values than the oil 470q.

It also worth pointing out that the values of the kurtosis and the RMS for the scratched gear are much higher than that for the normal one. This fact shows that these parameters are useful for defect diagnostic, but not for oil viscosity alteration monitoring.

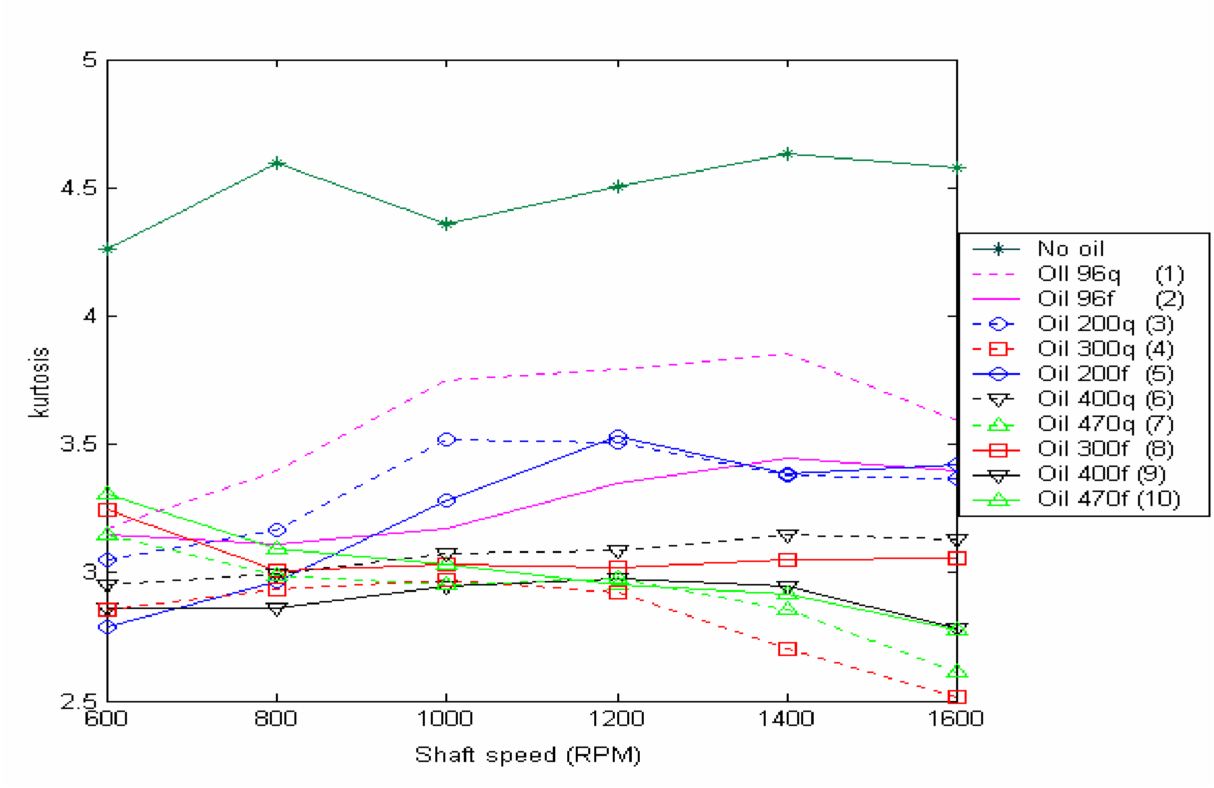

Figure 2-kurtosis ,vertical acceleration, normal gear.

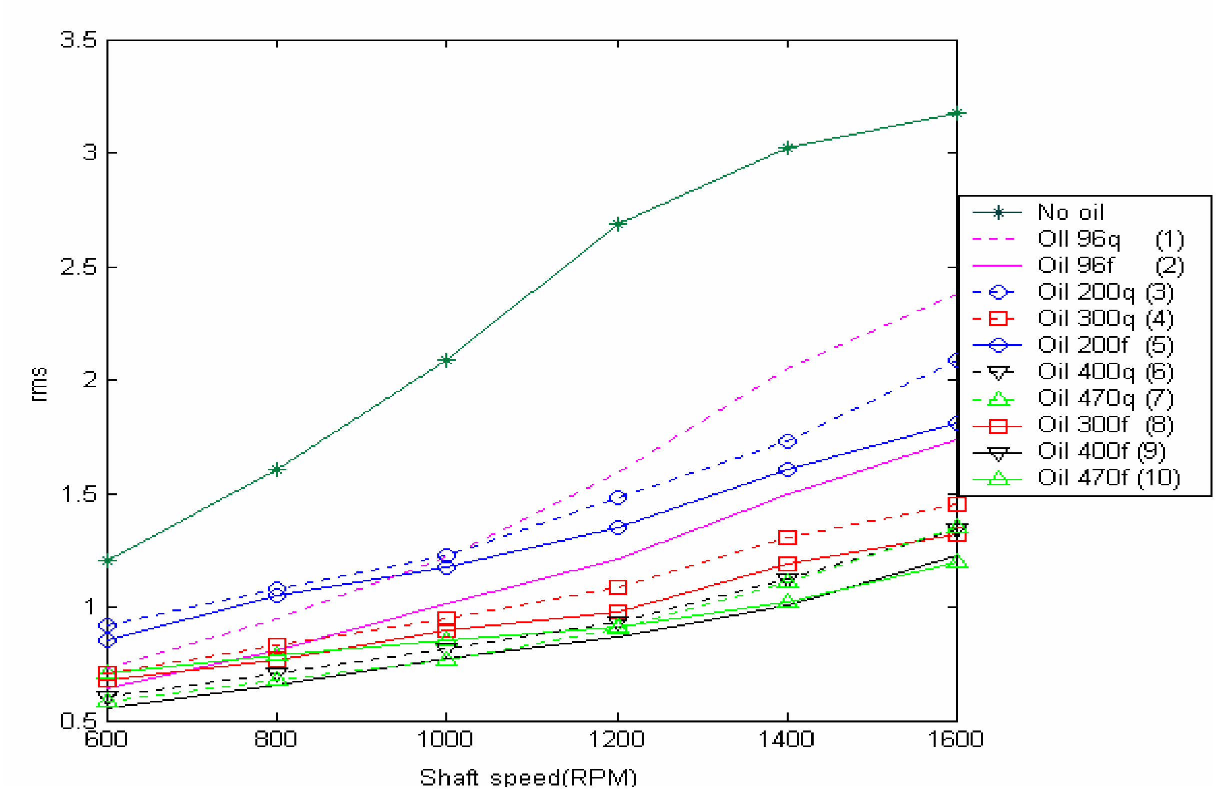

Figure 3-RMS, vertical acceleration, normal gear

7.2. Gearmesh frequencies.

As in the RMS case, for the gearmesh frequencies it is also expected that the greater the oil viscosity, the smaller the energy at the gearmesh frequencies, since these frequencies are generated by the contact of the gear teeth and the lubricant oil actuating on the contact area.

The gearmesh frequencies can be identified, for each one of the gear pair, by analysing the signal spectrum. To compare the energy associated with these frequencies, the spectrum was integrated in a narrow frequency band centred at these frequencies. The parameters so created reflect the energy around these frequencies and were denominated: IpBf1 and IpBf2 for the first and second gear pair respectively.

Figure 3 shows the results of IpBf2 for axial acceleration, normal gear. The parameter ipBf2 represents the energy of the gearmesh frequency of the second gear pair in the axial direction. It worth pointing out that in fact no correlation with oil viscosity can be seen. The same results were obtained for the other experimental conditions.

Some harmonics of the gearmesh frequencies were also identified and analyzed, but no correlation could be observed with the oil viscosity.

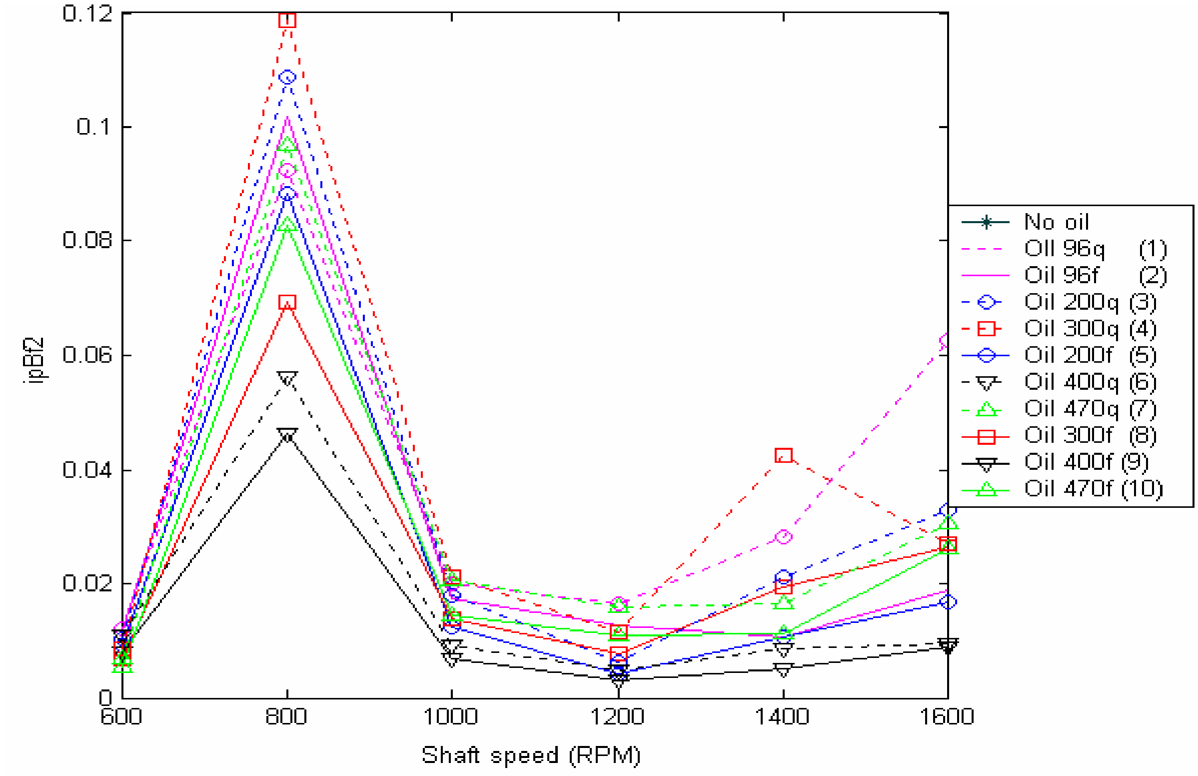

Figure 4- IpBf2 parameter for the first gearmesh frequency, axial acceleration, and normal gear.

7.3. The spectrum

Figure 5 shows the spectrum of the vertical acceleration signal against viscosity. It shows the behavior of the spectrum when the viscosity of the oil is changed. This kind of graphics was made for both the signal and the envelope of the signal spectrum. The analysis of the envelope spectrum clearly revealed the gearmesh frequencies and the rotation speed but , from that, it was not possible to find a characteristic that was correlated with the oil viscosity.

In the signal spectrum, however, it was noticed (Figure 5) that the frequency band from 2300 Hz until 7000Hz has a strong correlation with the oil viscosity, what suggests the possibility of using this information for oil viscosity monitoring. This band presents two major problems and some care needs to be taken in its analysis: it is a wide band and has low energy level when compared to other bands of the spectrum. The hole frequency band was initially divided in 3 frequency bands: B1 from 0 to 2300Hz , B2 from 2300 to 7000Hz and B3 from 7000 to 10000Hz. Then the spectrum was integrated in each of these bands. This resulting parameters was denominated respectively according to the bands: EB1,EB2,EB3.

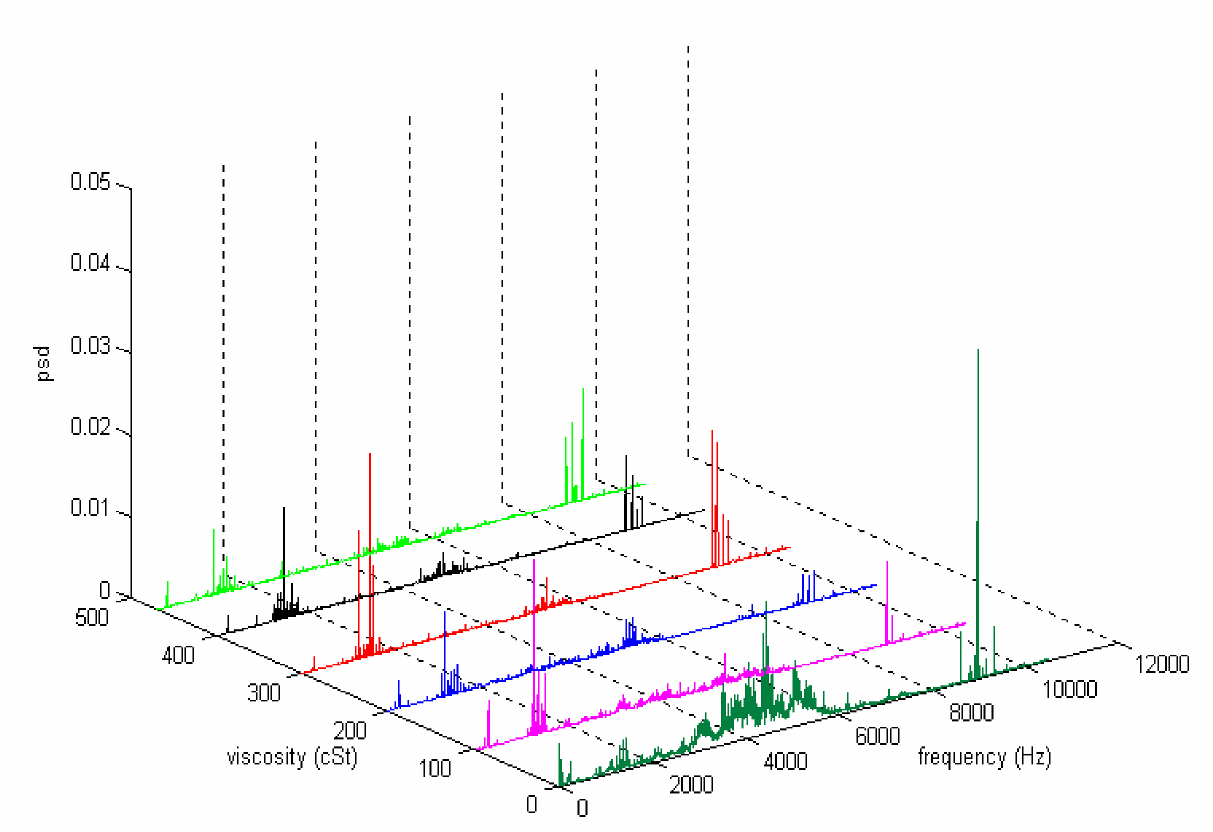

Figure 5-Spectrum x viscosity, 1600RPM,vertical acceleration, normal gear.-

7.4. The EB2 parameter

The results for IB1 and IB3 are not significant. IB1 revealed some correlation with the oil viscosity but with worse results than the RMS ones. IB3 have not shown any relation with the oil viscosity.

The result for the IB2, using the normal gear, without load and vertical acceleration can be seen in Figure 6 (a logarithmic scale was used for better visualization).

It can be seen in Figure 6 that the correlation with the oil viscosity is excellent in almost all of the experimental conditions. In fact, if the viscosities order (Table 1) and the parameter EB2 values are compared, the order is not respected only in the case of the oil 200f and oil 400q. The viscosity difference, in this case, is approximately 2%, what is higher than the experimental errors. In fact, it is interesting to notice that two different oils, which have close viscosities values because of the different temperatures, have the same value of the EB2 parameter, what indicates that the parameter is related to the viscosity and not to another oil characteristic.

The results obtained for the axial acceleration direction were worse than those presented in Figure 5 and will not be shown.

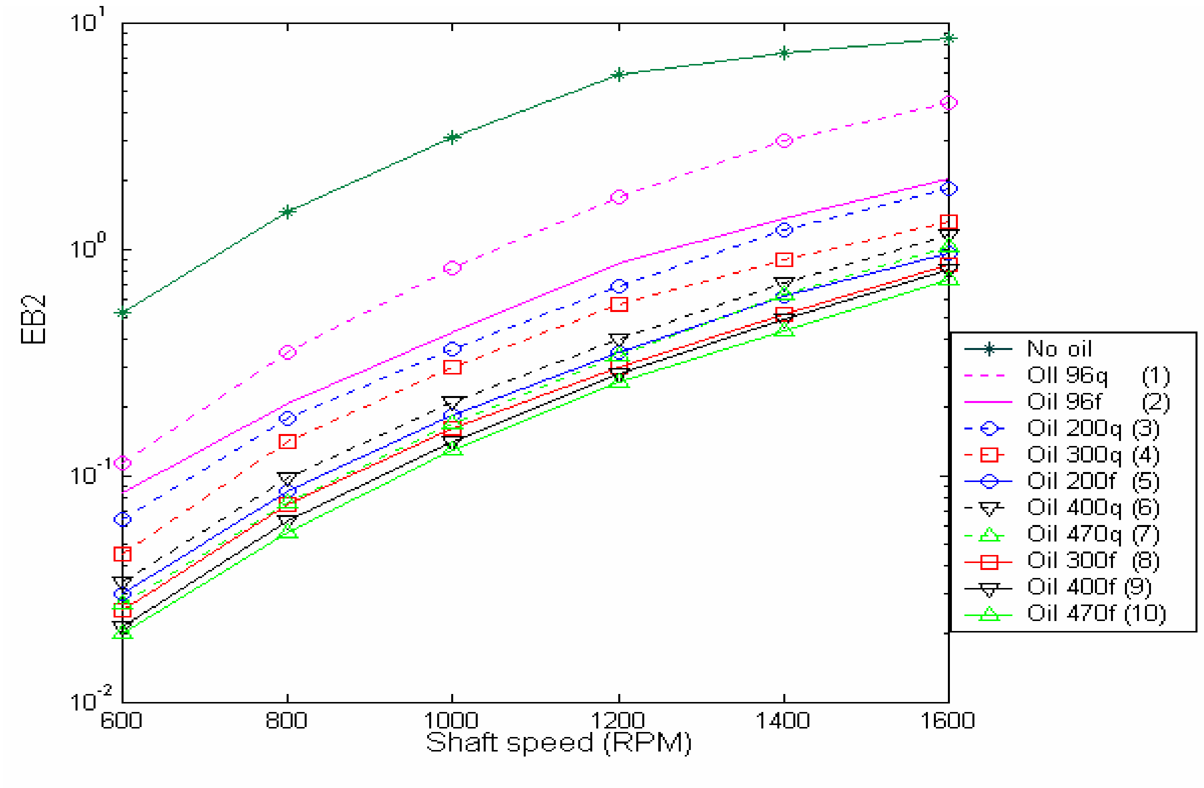

figure 6-EB2 parameter, vertical acceleration, normal gear.

7.5. The scratched gear and the parameter EB2

Figure 7 shows the results obtained for the EB2 parameter when the normal gear is replaced by the scratched gear.

Figure 7 shows EB2 values higher than those for the case with normal gear, indicating that more energy is being dissipated at the B2 band. It also presents worse results concerning the viscosity order, the general order is maintained but there are many cases where the order is not respected. This fact brings a suspect that this particular band is related with the contact area.

The results for the normal gear show that the oil viscosity modulates the intensity of the frequency band B2. A model for understanding this behaviour can be developed by assuming that the oil film has dynamic characteristics (Su, 1992) and acts like a filter that affects some frequencies at the B2 band when these frequencies are transmitted to the gearbox surface (where the accelerometer is positioned) .

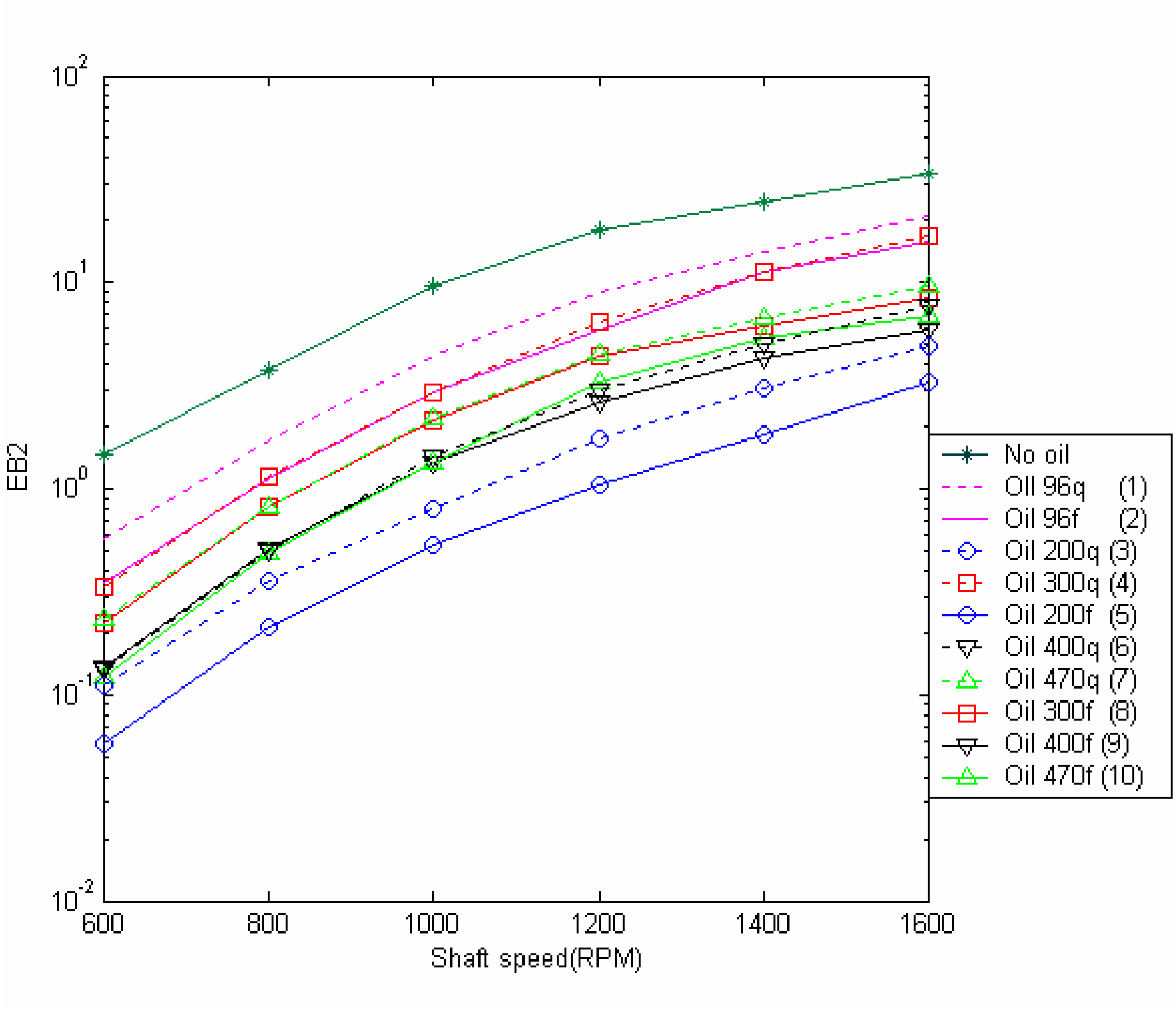

Figure 7-EB2 parameter, vertical acceleration, scratched gear.

8. Conclusion

This paper presents an experimental study in the effects of the lubricant oil viscosity in the vibration behaviour of a gearbox. Oils of different viscosities were used in the gearbox, and vibration was measured, at many gearbox operational conditions. Several signal parameters were developed to try to detect these viscosity changes.

One of parameters used is the RMS, which shows that in many experimental cases the global vibration level do not decrease with an increase in the oil viscosity. In fact this correlation with the RMS failed at some important experimental conditions such as cases where the same oil was at different temperatures.

On the order hand, the EB2 parameter (a parameter that is related to the vertical signal power at a particular spectral band) is strongly related to the lubricant viscosity. These good results where not repeated in the case of a scratched surface gear. In this case the general viscosity order is respect but it fails at many experimental conditions. The general EB2 values are bigger than in the normal gear case. This behaviour seems to indicate that the EB2 band is related with the contact area.

The results show that the shaft speeds modulates the energy at the B2 band but do not alter the spectral composition of this band, indicating that this band is not shaft speed dependent. It means that however changes in the shaft speed modifies the amplitudes of the spectrum it does not modify its spectral composition..

Further studies will explore others experimental conditions, seeking to increase the knowledge of the relationship between lubrication condition and vibration behaviour of gearboxes.

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