Perceptive analysis of bearing defects "Contribution to vibratory monitoring of bearings"

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Abstract

The objective of present work is improving the bearings monitoring through a perceptive study, allowing the search a correlation between sound perception and the vibratory analysis of rotating machines. In present situation, an experimental bench was designed to simulate the different defects of rotating machines (bearing defects, gears and alignment). Current study was carried out in three stages; the first consists of processing the signals of the simulated defects on the test bench using the different vibration analysis techniques. The second step is performing a perceptive test by listeners, using the noises generated by the simulated defects. The results obtained by this test will be treated by the multidimensional analysis (MDS) to determine the sound dimensions. The final step of this study is to search the dimension correctly representing the evolution of the degradation of simulated defects and correlate this dimension with classical vibratory indicators.

1 Introduction

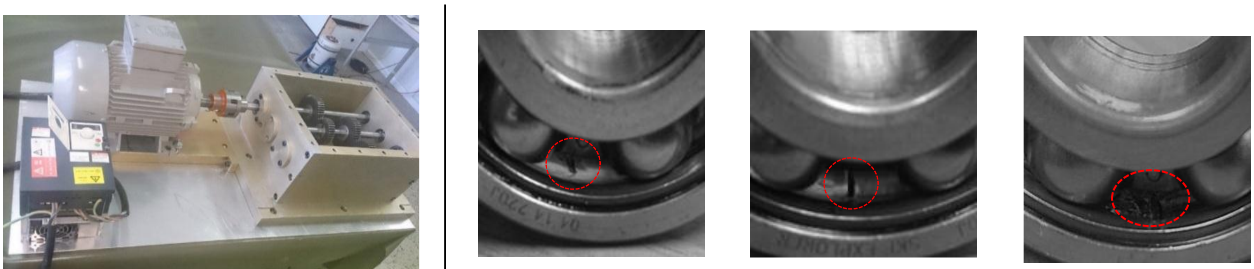
Rotating machines are an important part of today's world, due to the presence of machines in all industrial fields such as mechanical manufacturing, automotive and aeronautics… This has led researchers to develop numerous maintenance techniques in order to guarantee and ensure the safety of products and people, to optimize maintenance operations by performing conditional or predictive maintenance, that ensure the availability of machines and avoid unexpected shutdowns. Consequently, these techniques have allowed minimizing financial losses resulting from the cease of production, as well as repair costs. Vibration analysis is considered among the techniques, conditional maintenance, and indispensable for the monitoring of rotating machines. It ensures the safety of the installation by avoiding major degradations, by monitoring the evolution of specific scalar vibratory indicators such as kurtosis, RMS, crest factor, Very often; these indicators are not sensitive to vibratory change, especially in the case of nascent and aggravated defects. In present work, a perceptive study has been proposed to improve the bearings monitoring, through the development of new vibratory indicators more effective than the conventional indicators.

The perceptive study consists in search of a correlation between the vibratory analysis of the simulated defects on an experimental test bench and the sound perception of the noises generated by these defects. The perceptive study is used by E. Parizet [1], with the aim of improving the acoustic quality, which represents the adequacy between what the noises of the object mentioned and the image that the designers want to give it. We quote the study exploited by E. Parizet [2] in the field of automobile, analysing the noise coming from the closing of the car door. In the field of diagnostics of rotating machines, N. Hamzaoui & M. Kanzari [3] developed a new vibratory indicator for the monitoring of gears via the perceptive study. This indicator was defined as a function of the spectral centre of gravity (SCG). Similarly, through perception, R. Younes [4] has determined a new indicator for the monitoring of gears by the combination of two vibratory indicators: the global level (GL) and kurtosis. The indicator allowed a vibratory, targeted and efficient monitoring of the gear defects.

2 Experimental analysis

2.1 Experimental bench

In order to simulate the various defects of rotating machines such as bearing, gear and alignment defects, an experimental test bench was carried out (see Figure 1). The latter is a two-stage reducer coupled to an electric motor and whose speed is controlled via a variator. This test bench was used as support for the various vibratory and acoustic measurements carried out.



Nascent Aggravated Very aggravated

Figure 1: Test Bench & Simulated Bearing Defects

The vibration and acoustic measurements were performed using the NI 4472B (National Instruments) Dynamic Acquisition Board, an accelerometer and a unidirectional microphone.

2.2 Experimental protocol: Simulated defects

Principle object of present study is to improve the vibration monitoring of bearings. Therefore, we simulated three levels of degradation defects: nascent, aggravated and very aggravated on the outer ring of three different SKF bearings 6305 (see Figure 1). These defects will then be combined with a gear defect; the latter is created on one of the teeth of the drive pinion, on the motor side, to evaluate the validity of the method even in the presence of other defects. Seven (07) cases of defects (see Table 1) were simulated to perform our perceptive study. These defects are divided into two types: simple defects (bearing defect) and combined defects (bearing and gear defect).

WD	Without defects
ND	Nascent bearing defect
ND & G	Nascent bearing defect & gear
AD	Aggravated bearing defect
AD & G	Aggravated bearing defect & gear
VAD	Very aggravated bearing defect
VAD & G	Very aggravated bearing defect & gear

Table 1 : Simulated defects

The acquisition of vibration and acoustic signals was made under software environment "LabVIEW", the treatment was done by "Matlab".

2.3 Vibration analysis

In order to show the importance of the perceptive study, we treated the seven (07) cases of simulated defects (see Table 1) using different vibratory analysis techniques; Global level (vibratory indicators) and spectral (envelope analysis).

In order to clarify the limits of the use of vibration indicators to monitor the degradation of bearings, three indicators were calculated: the RMS value and the two shock indicators (Kurtosis and crest Factor), which are generally used for monitoring bearings.

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(x(n))^2} \tag{1}$$

Where x (n) is the measured time signal, N represents the number of samples was taken from the signal.

$$\text{Crest Factor} = \frac{V_{crête}}{RMS} \tag{2}$$

Where V_{Crest} is the maximum value of |x (n)|.

$$\text{Kurtosis} = \frac{\frac{1}{N}\sum_{n=1}^{N}(x(n)-\overline{x})^2}{\left[\frac{1}{N}\sum_{n=1}^{N}(x(n)-\overline{x})^2\right]^2} \tag{3}$$

Where $\overline{x}$ is the mean value of the amplitudes.

The evolution of the conventional vibratory indicators as a function of the simulated defects has shown that they are very often unable to give correct information on the state of the bearings, particularly, in the case of aggravated defects or combined with other defects (see Figure 2).

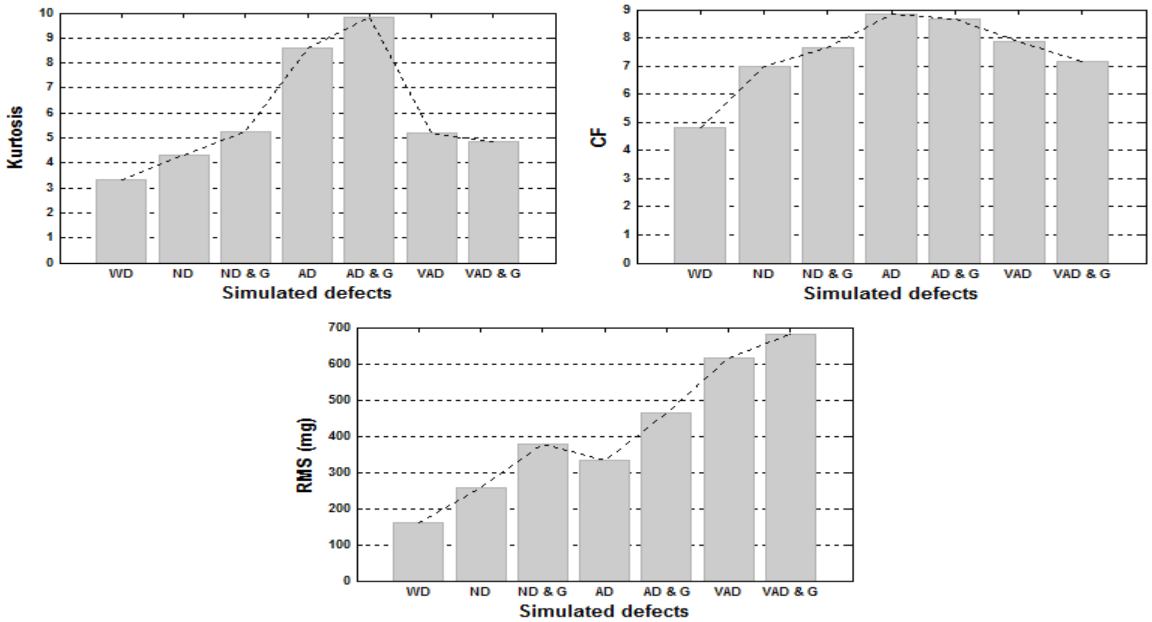
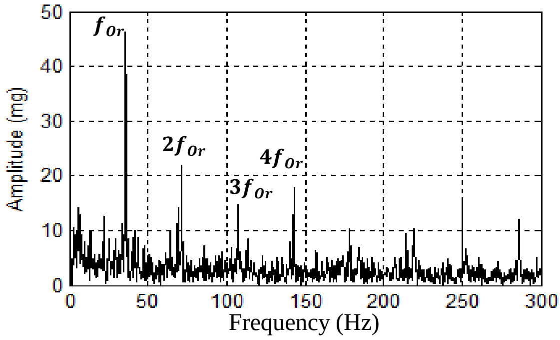
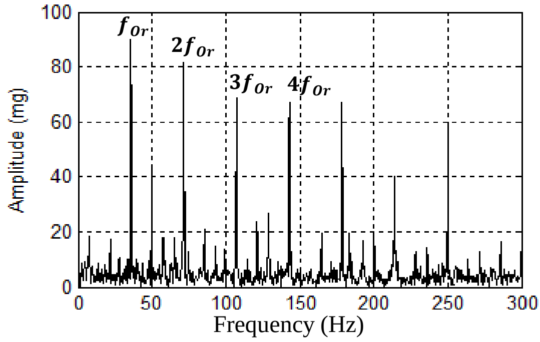


Figure 2: Vibration Indicators

For this reason, additional and complex treatments are necessary to identify very aggravated defects such as envelope analysis. The figure 3 shows that this technique can detect bearing defects, even in the case of nascent defects. As knowing that the rotational frequency of the defective bearing is 14.7 Hz and the frequency of the simulated defect on the outer ring f_{Or} is 37 Hz. This analysis requires a thorough knowledge of the machine kinematics in order to be able to apply it and interpret the results obtained.



Nascent defect (ND)



Very aggravated defect (VAD)

Figure 3: Envelope spectrum

Therefore, the use of scalar indicators is more appropriate. From this effect, a perceptive study has been proposed, to correct erroneous information on the state of the bearing in the case of very aggravated defects or embedded in other defects. This study consists in defining new vibratory indicators that are more reliable and efficient than conventional indicators for monitoring bearings.

2.1 Perceptive study

The perceptive study is based mainly on the human factor, using the auditory sense as an essential element for the improvement of vibratory bearing monitoring by optimizing these indicators. This study consists of performing a perceptive test on listeners by exploiting the noise generated by the simulated defects.

The perception test consists of a pairwise comparison test, which evaluates the dissimilarity between the sounds (noises). An interactive interface has been developed by Matlab (see Figure 4), it allows the pairs of sounds to be presented to the different listeners in a random method. The evaluation of dissimilarity is also evaluated by moving the cursor on a horizontal scale ranging from zero (0) (identical) to one (1) (very different).

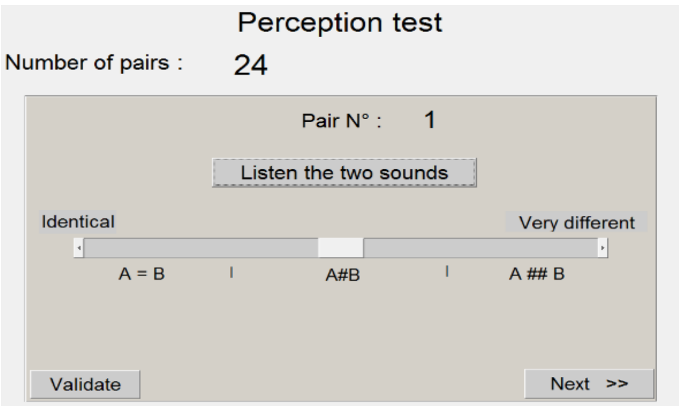


Figure 4: Interface of the perception test

The number of pairs of sounds considered from seven different sounds corresponding to simulated bearing defects is 21 pairs, by adding 03 pairs of identical sounds, the number of pairs to be tested is therefore 24 through 25 listeners.

2.1.1 Perceptive space

The result of the perception test is a superior triangular matrix, each element of which represents the mean value of the dissimilarity evaluated by the listeners between two different sounds.

To exploit the results obtained via the perception test and to correlate them with the classical vibratory indicators, a multidimensional analysis (MDS) was carried out to allow modelling the matrix of dissimilarity in distances; the latter are represented in a perceptive space. The principle of this approach is to evaluate the distances between the different sounds. These distances d_i^{jk} between the stimuli j and k evaluated by the subject i are calculated by specifying the weight each subject allocates to the dimension w_{it} and x_{kt}. x_{kt} being the component of the stimulus k on the dimension t:

$$d_i^{jk} = [\sum_{t=1}^{r} w_{it}[x_{jt} - x_{kt}]^2]^{1/2} \tag{4}$$

In order to verify the results obtained in current study, the Bravais-Pearson correlation coefficient r is used to compare the distances recalculated by MDS with the dissimilarities evaluated by the auditors. As a reminder, r between two variables x and y is given by:

$$r = \frac{\frac{1}{n}\sum_1^n (x_i - \bar{x})(y_i - \bar{y})}{s_x . s_y} \tag{5}$$

Where s_x and s_y are the standard deviations of x and y given by:

$$s_x^2 = \frac{1}{n}\sum_1^n (x_i - \bar{x})^2 \quad \& \quad s_y^2 = \frac{1}{n}\sum_1^n (y_i - \bar{y})^2$$

According to figure 5, we find that the perception test performed is satisfactory. In fact, the correlation coefficient between the result of the dissimilarity and the distances calculated by MDS is greater than 0.85.

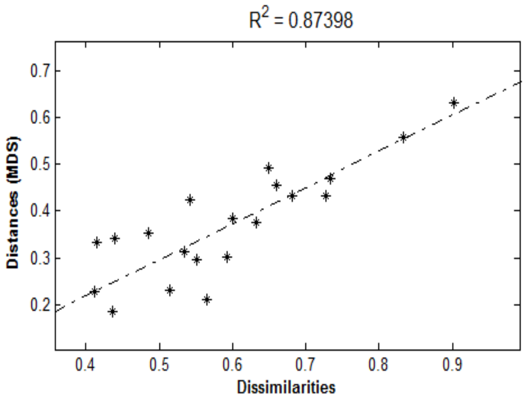


Figure 5 : Correlation between dissimilarities and distances (MDS)

The number of dimensions necessary to represent the results of dissimilarity in perceptive space is determined from the stress curve:

$$Stress = \frac{\sqrt{\sum_{(i,j)\in\Omega}(d_{ij} - \delta_{ij})^2}}{\sqrt{\sum_{(i,j)\in\Omega} {d_{ij}}^2}} \tag{6}$$

δ_{ij} : Dissimilarity measures.

d_{ij} : Euclidean distances.

Usually this number is taken from the first elbow of the stress curve. In present case, this elbow is located at the second point of the curve (see Figure 6). Consequently, the number of dimensions selected is equal to two (2).

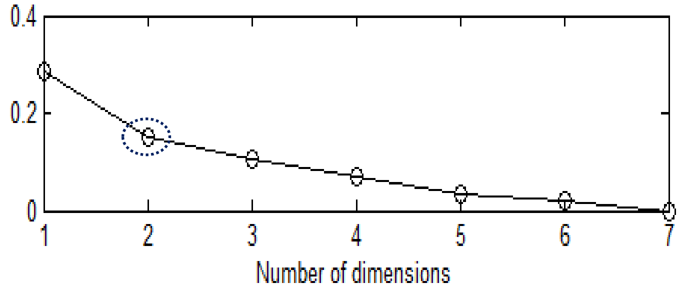


Figure 6 : Stress curve

Table 2 shows the two sound dimensions calculated from the processing of dissimilarity results (perceptive test) using multidimensional analysis (MDS). The components of these dimensions are the coordinates of the seven (7) sounds in perceptive space.

	Dimension 1	**Dimension 2**
Sound 1	-0.2834	-0.0150
Sound 2	-0.2113	-0.0096
Sound 3	-0.0554	0.2202
Sound 4	-0.0428	-0.1485
Sound 5	0.1255	0.1272
Sound 6	0.1237	-0.1975
Sound 7	0.3437	0.0233

Table 2 : Sound dimensions

Figure 7 shows the position of the seven (07) sounds in the perceptive space as a function of the dimensions calculated by MDS. According to the distribution of these sounds, the first dimension correctly indicates the evolution of the degradation of the simulated defects whether this is in the case of simple defects or combined with a meshing defect. The dimension 1 thus represents the desired indicator.

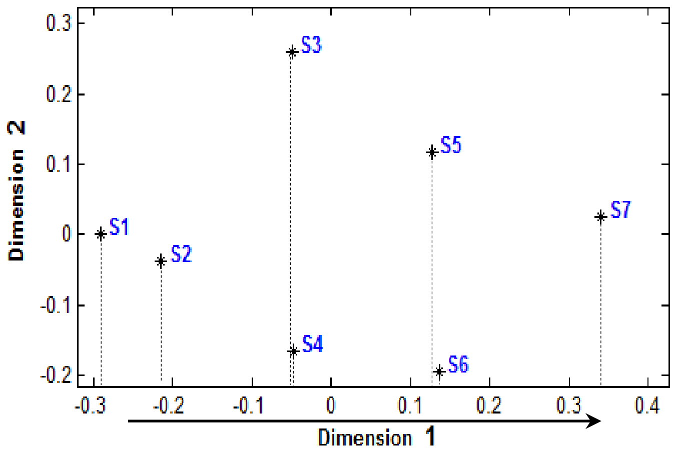


Figure 7 : Perceptive space

2.2 Determination of new indicators

The aim is to find a correlation between the subjective dimension 1 and the objective or classical vibratory indicators. An ascending linear regression was used to define the dimension 1 as a function of the classical indicators. We will thus retain the indicator with the highest correlation factor as a new indicator of bearing monitoring.

The results obtained from the correlation with a single indicator not represented in this article, although interesting results were obtained in terms of correlation coefficient (0.93). Indeed, very often the indicators defined with a single classical indicator follow the evolution of the latter. Nevertheless, the correlation with two classical indicators was more effective, the latter was therefore retained. It consists in expressing the dimension 1 representing the evolution of the degradation of simulated defects as a function of two classical indicators.

The application of a linear regression allows us to define dimension 1 as a function of Kurtosis and RMS (mg), with a correlation factor of 0.96, as shown in Figure 8.

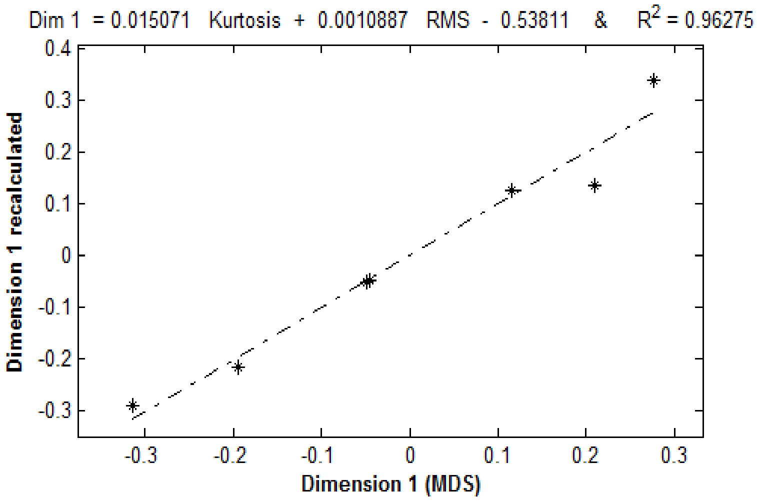


Figure 8 : Correlation with two indicators

In reality, as shown in Figure 9, the new indicator thus defined through the perceptive study represents the evolution of the degradation of the simulated bearing defects, even in the presence of a gear defect. This is not the case with classical indicators; RMS, Kurtosis and FC (see Figure 2).

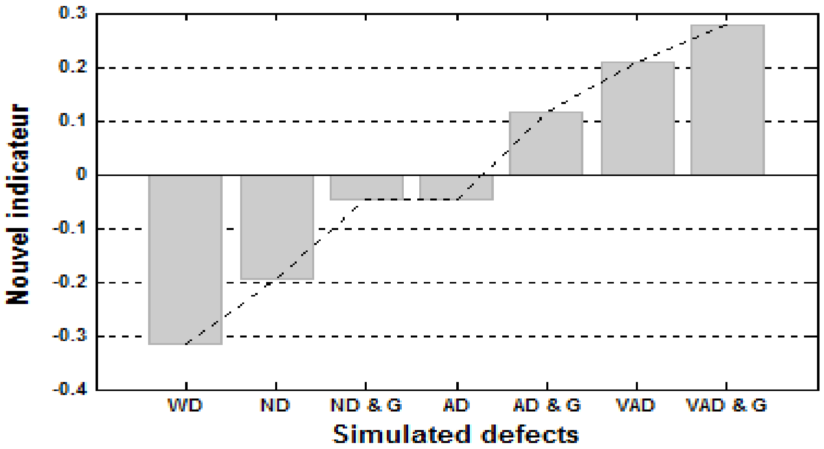


Figure 9: Evolution of the new indicator

3 Evaluation

To evaluate the results obtained, the new indicator was tested on vibratory signals measured on another test bench (see Figure 9). These signals correspond to the six cases of new simulated bearing defects; simple or combined with an unbalance defect (see Table 3), in addition to the case without a defect.

WD	Without defects
ND	Nascent bearing defect
ND & UB	Nascent bearing defect & unbalance
AD	Aggravated bearing defect
AD & UB	Aggravated bearing defect & unbalance
VAD	Very aggravated bearing defect
VAD & UB	Very aggravated bearing defect & unbalance

Table 3 : Simulated defects

Figure 10 : Test bench

Figure 9 shows the proportional relationship between the evolution of the new indicator and the degradation of defects (see Figure 12), which is not the case for RMS and kurtosis (see Figure 11).

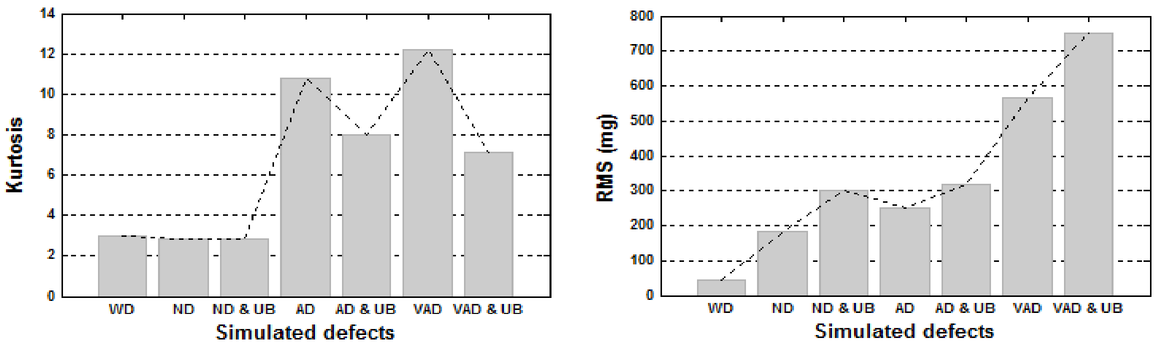


Figure 11: Vibration indicators

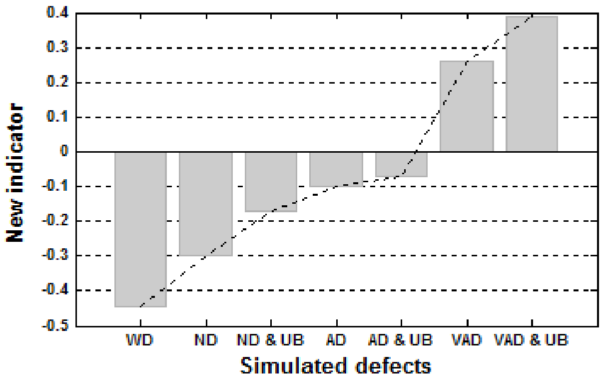


Figure 12: New indicator

This evaluation confirmed the reliability and effectiveness of this new indicator for bearings vibration monitoring, in contrast to conventional indicators.

Conclusion

The present work allowed us to develop a method to find new indicators, which are more efficient than conventional indicators for the vibrational monitoring of bearing defects. This method is based on the correlation of the vibratory analysis with the sound perception (of the listeners) of the noises resulting from the vibration of the machines affected by these defects. Based on the evaluation of results, we clearly showed that the indicator correlated with two indicators (Kurtosis and RMS (mg)) better responds to bearings monitoring than conventional indicators or correlated with a single indicator.

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