"TALAF" AND "THIKAT" AS INNOVATIVE TIME DOMAIN INDICATORS FOR TRACKING BALL BEARINGS

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ABSTRACT

The aim of this paper is to analyze the sensitivity of fault scalar indicators extracted from time domain signals to bearing damage manifested through an increase in size and in the number of localized defects. Six scalar indicators are considered: Peak, RMS, Crest factor, Kurtosis, Impulse factor, and Shape factor. A new software application, called BEAT (BEAring Toolbox), was developed in order to simulate bearing vibratory response to the excitations produced by localized defects. The predictability of the simulation model has already been confirmed by previous comparisons with the results of experiments performed on a bearing test rig. Simulation results show that these time indicators can be used for the early prediction of a fault during the initial stages of degradation. However, they become less sensitive as the damage increases and become very severe. Two new descriptors called TALAF and THIKAT, which combine conventional descriptors, are developed in order to improve diagnosis up to the point where the ultimate signs of catastrophic failure are observed, to diagnose the severity of degradation in four stages, and to help managers schedule their maintenance operations.

Key Words: Ball Bearing, Localized Defects, Numerical Simulation, Time Domain Signal, Fault Indicators.

1. INTRODUCTION

Various diagnostic tools exist for diagnosing damage in machinery, the most common being vibration-based tools. Using vibration data collected from defective components, algorithms are developed to detect when bearing damage has occurred. Over the past 25 years, numerous vibration-based algorithms for bearing damage detection have been developed. Unfortunately, to this date, a complete database of existing vibration algorithms and their capabilities and limitations is not available. A pertinent review of vibration measurement methods for the detection of defects in rolling element bearings is presented by Tandon and Chandhury [1]. The monitoring methods applied to bearings can be achieved in a number of ways [2, 3], with some of the methods being simple to use, and others requiring sophisticated signal processing. Shocks are usually created in the presence of faults and can be analyzed either in the time domain [4] (RMS and max-peak amplitude of vibration level, Crest factor and Kurtosis, detection of shock waves and Julien method [5], statistical parameters applied to the time signal, Cepstrum); or in the frequency domain (spectral analysis around bearing defect frequencies [6, 7], frequency spectrum in the high frequency domain, Spike energy [8, 9], high frequency demodulation [10], acoustic emission [11], adaptive filtering, artificial neural networks, time-frequency [12, 13], etc).

In this paper, a numerical study is conducted on the influence of the bearing spread damage with respect to the variation of time scalar indicators and their ability to trace the size increase and number of localized defects. Simulation results show that these conventional time indicators can be used for the early prediction of a fault in the initial stages of degradation. However, when the damage becomes very severe, these usual parameters, after reaching a maximum, then decrease. Consequently, they cannot be used alone without the RMS level or spectrum analysis in the last stages of bearing degradation. This paper demonstrates that an appropriate combination of conventional scalar indicators may lead to two additional suitable parameters that could be applied solely to predicting future failures and tracking defects from the first signs of degradation to the last signs of catastrophic failure. The first parameter, called *TALAF*, describes the evolution of the damage in four distinct stages, while the second parameter, called *THIKAT*, shows the degree of confidence relative to the use of the bearing in the presence of deteriorating fault conditions.

2. CHARACTERISTICS OF A BALL BEARING

As shown in Figure 1, a rolling-element bearing is an assembly of several parts: an inner race, an outer race, a set of balls or rollers, and a cage or separator. The cage or separator maintains an even spacing of the rolling elements. Important geometrical quantities of the bearing comprise the number of rolling elements N_b, the ball diameter B_d, the average (pitch) diameter P_d and the contact angle α.

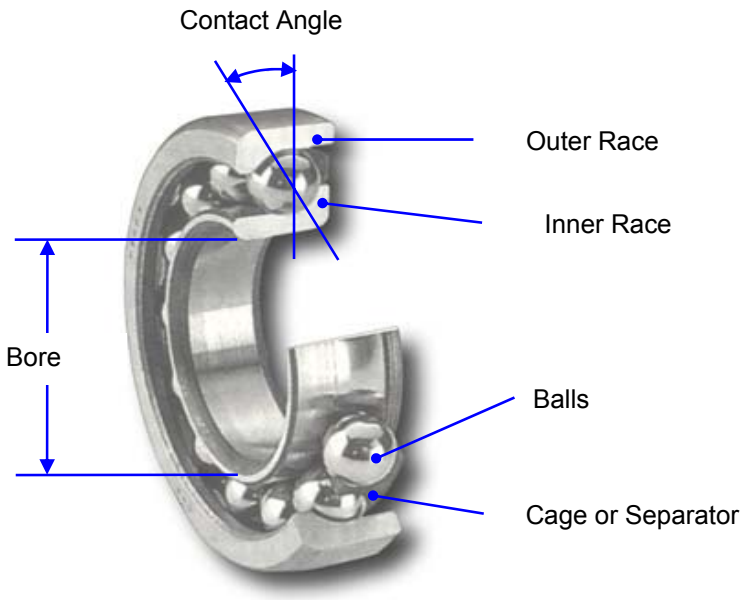


Figure 1: Structure and Loading of a Ball Bearing

3. MONITORING OF MACHINE HEALTH WITH SCALAR INDICATORS

The supervision and condition monitoring of a machine require that a certain number of indicators be chosen beforehand. An indicator must characterize the reliability of a machine, and may be aimed at the early identification of the appearance of anomalies and the tracking of their evolution; it could also be used to target the pausing or stopping of the installation. Its evolution in time must be meaningful to the appearance or the aggravation of a defect. The temperature of

housing, the rate of concentration of metallic particles in the lubricant, the amplitude of vibration, etc., are indicators that can present the state or the performance of a piece of equipment and follow its evolution in time.
Any machine in operation induces vibrations. As direct expressions of the dynamic loads generated by moving parts, such vibrations occupy a privileged position among the parameters to be considered when monitoring a machine. Vibration signal processing techniques make it possible to define a wide list of surveillance indicators that are more or less sensitive to the severity of a fault, to the identification of its source, and to its localization.
Moreover, surveillance indicators could be classified also under two major categories:

- ✓ Scalar indicators, which follow the evolution of a parameter linked to the amplitude of the vibration signal, in the time domain;
- ✓ Spectral indicators that simultaneously follow the evolution in frequency and in amplitude of each of its components.

There is no unique and universal indicator capable of the early detection of any defect likely to affect a machine, and it would be utopian to believe in the existence of a pre-defined alarm threshold whose value is independent of the nature of the defect, the machine, and its operating conditions.
A scalar indicator extracted from the time domain gives a scalar number which may not necessarily be intrinsically significant. However, the evolution in time of this value indicates the level of aggravation of a defect. The evolution in time of a scalar indicator is more important than its intrinsic value. Scalar indicators may provide information not only on the defect area and on its gravity, but also on the strategic decisions concerning any immediate replacement of the damaged bearing.
Defining a scalar indicator in the time domain requires choosing:

- ✓ A kinematics parameter representative of the vibratory movement (acceleration, velocity, displacement) according to the frequency content of the vibratory signal;
- ✓ A parameter representative of the signal amplitude (RMS value, Max-peak amplitude, Crest factor, Kurtosis…);
- ✓ A bandwidth over which the retained parameter will be evaluated;
- ✓ A duration of analysis.

The six most commonly used statistical scalar parameters for bearing diagnosis are Peak, RMS, Crest factor (CF), Kurtosis (Ku), Impulse factor (IF), and Shape factor (SF) [14, 15, 16]. These parameters are defined in Table 1.

4. NUMERICAL SIMULATION OF BEARING VIBRATION AND EXPERIMENTAL VALIDATION

To gain a detailed insight into the dynamic behavior of rotating bearings when they are affected by localized defects, a powerful simulation software application called BEAT® (the Bearing Toolbox), has been developed for predicting vibratory behavior and diagnosing localized damaged bearings [14,15].

Qualitative and quantitative comparisons of several results (in the time and frequency domains) obtained from experimental and simulation signals clearly shows that the model developed provides realistic results which are very similar to those given by a sensor during experimental measurements.

Table 1: Scalar indicators specific to bearing vibration detection

(*for a signal array* a *of* k *samples*)

Peak	$a_{peak} = \sup_{1 \le k \le N} \lvert a_k \rvert$	(1-a)
Average	$\bar{a} = \frac{1}{N} \sum_{k=1}^{N} a_k$	(1-b)
Root Mean Square	$a_{RMS} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} a_k^2}$	(1-c)
Crest Factor	$CF = \frac{a_{peak}}{a_{RMS}}$	(1-d)
Kurtosis	$Kurtosis = \frac{\frac{1}{N} \sum_{k=1}^{N} (a_k - \bar{a})^4}{a_{RMS}^4}$	(1-e)
Shape Factor	$SF = \frac{a_{RMS}}{\frac{1}{N} \sum_{k=1}^{N} \lvert a_k \rvert}$	(1-f)
Impulse Factor	$IF = \frac{a_{peak}}{\frac{1}{N} \sum_{k=1}^{N} \lvert a_k \rvert}$	(1-g)

In particular, the comparison between the experimental value of scalar indicators (as defined in Table 1), calculated from data directly downloaded from the Bearing Data Center (B.D.C.) Website of Case Western Reserve University, Cleveland, Ohio, USA [17] and those obtained from 100 numerical simulations is presented in Table 2. The bearing considered is of type SKF 6205. It has nine balls and a pitch diameter-to-ball diameter ratio of 4.9. The faults are located on the inner race. The maximum damage size is 0.72 mm, the rotor speed 1750 rpm, and the radial force applied to the bearing is maintained in a fixed direction.

Table 2: Comparison between time domain indicators collected from BDC test rig and simulated on BEAT

	Experimental results (from one measurement)	**Numerical results (BEAT) (from 100 simulations)**	**Error (%)**
PEAK	10.1	10.26	1.6
RMS	2.1	2.09	0.5
C.F.	4.9	4.91	0.2
KU	3.9	3.66	6.2
I.F.	6.4	6.27	2

S.F.	1.3	1.28	1.6

The average values of these parameters computed for 100 simulations and compared to the experimental trial show a very good agreement, with a maximum error of 6.2 %.

5. NUMERICAL INVESTIGATION OF SCALAR DESCRIPTORS

Given the high confidence level in terms of the accuracy of the numerical results, the developed software called BEAT, was used to generate results that may help to understand how time domain health indicators, as defined in Table 1, as well as their sensitivity, are linked to the evolution of localized defects and their size inside the bearing, and how they can be used to track bearing degradation.

Usually, the shocks within a rolling bearing generate impulsive vibrations. Whenever a defect is present on one surface of a bearing, it strikes another surface and generates an impact. The produced shock excites not only the resonances of the bearing but also the overall mechanical system. Thus, the pulsation generated by rolling bearing defects excites vibration at specific defect frequencies as well as a high-frequency response in the overall machine structure. The scalar indicators determined from time domain signals are physical parameters specially adapted to the recognition of the vibration origin in order to identify its nature and its degree of severity.

5. 1. Time response evolution due to a defect on the outer race

Figure 2 shows the evolution of a typical time wave response in acceleration (m/s^2), when a bearing deteriorates on the outer race from a healthy stage (case a) to a small defect of 0.5 mm (case b), and finally, to a large defect of 1.55 mm (case c). For a healthy bearing, surface roughness exhibits very little spatial correlation. As a result, the response is almost a Gaussian noise. Such a noise is characterized by a Kurtosis that is close to 3.

When a defect is produced on the outer race, a succession of shocks appears, with a spacing corresponding to a ball pass frequency outer (BPFO) race, and modulated over a period corresponding to the shaft revolution. As the defect increases, the time waveform indicates heavy amplitude of multiple impacts.

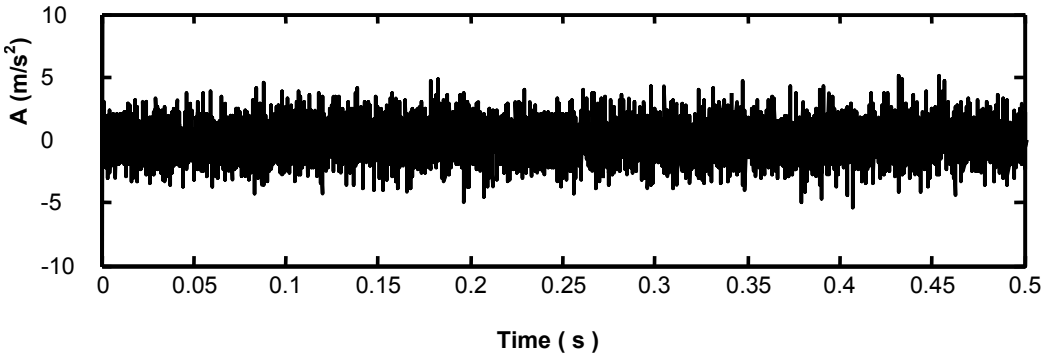
5.2. RMS and peak measurements

Overall level measurements are the most common vibration measurements in use. The peak and RMS values are generally used to indicate the presence and severity of defects. Although the RMS measure is widely accepted in Europe, and is embodied in relevant standards and codes, it is less popular in the U.S.A., where the peak value (or the peak-to peak) is used.

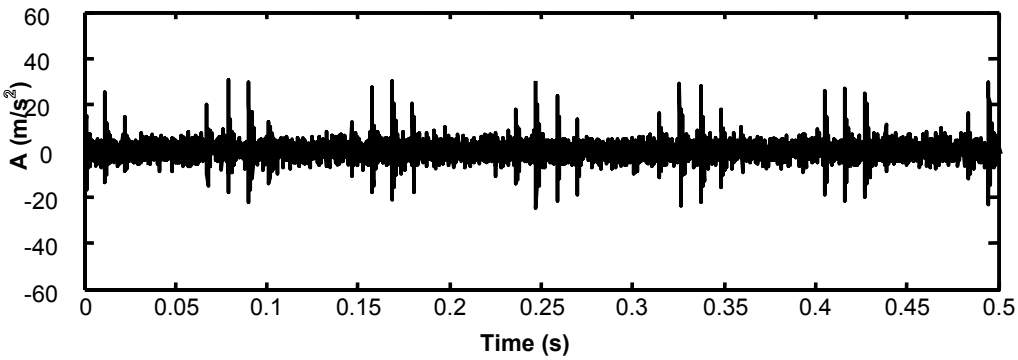
The RMS signal is a simple and inexpensive type of measurement, which is computed by estimating the root mean square level of the time record. It represents the mean energy of the vibratory signal. However, the RMS indicator does not allow the early detection of degradation because the overall level measurements do not change significantly unless a problem becomes severe.

As an alternative to RMS, the peak level of the signal can be used. A baseline "peak" level is defined for a new machine, and any variations from this norm would be indicative of a change in machine condition. It represents the effect of impacts in the signal. Very often, the max-peak

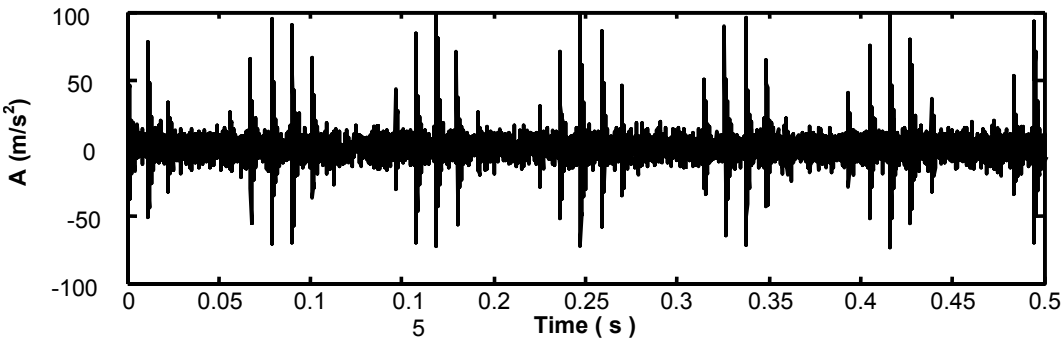
signal is used to detect accidents.



a) healthy bearing



b) small defect of 0.55 mm



c) defect of 1.52 mm

Peak	a) 5.1 b) 26.6 c) 75.7	CF	a)3.7 b) 6.4 c) 7.2	SF	a) 1.2 b) 1.4 c) 1.6
RMS	a)1.4 b) 4.3 c) 10.4	KU	a)3 b) 10.2 c) 15.8	IF	a) 4.6 b) 9.3 c) 11.5

Figure 2: Typical time response evolution of a damaged bearing

Figure 3 shows a typical evolution of peak and RMS values when the outer race of a bearing is deteriorating.

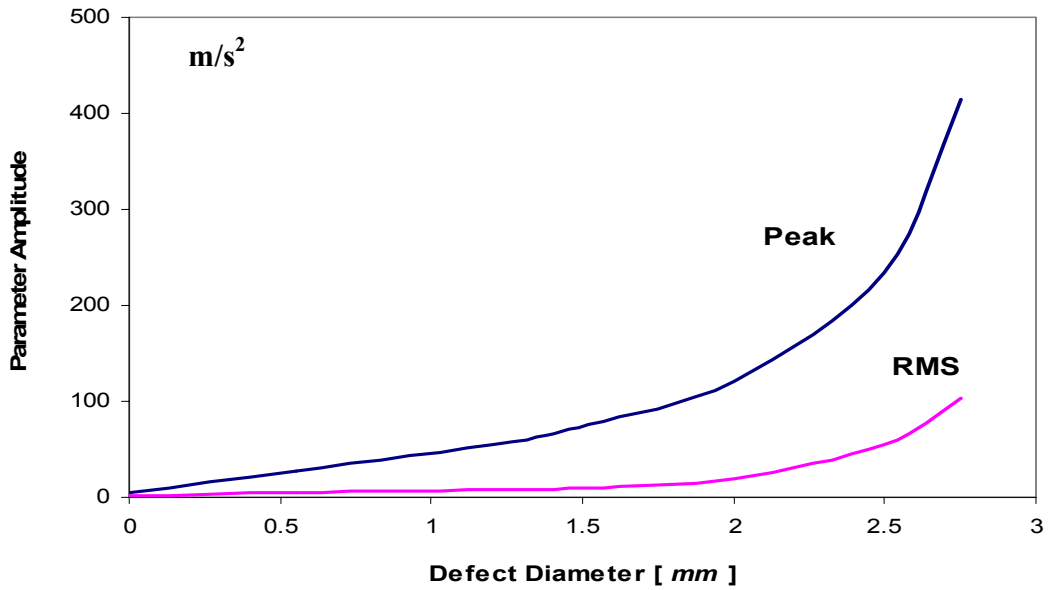


Figure 3: Evolution of the scalar parameters (Peak, RMS) according to the size of a defect on the outer race

Initially, when a localized defect appears, the small resulting shocks increase the peak level considerably, but have only a small influence on the RMS value. As the bearing deteriorates, more significant impacts are generated by each passing ball. Thus, toward the end of the bearing life, the RMS level increases dramatically with the peak level.

5.3. Crest factor, Kurtosis, Impact factor and Shape factor measurements

Among the most suitable scalar indicators used to characterize the vibrations are the Crest Factor and Kurtosis. The Crest factor and Kurtosis are less dependent on the vibration level, but are sensitive to the spikiness of the vibration signals, and they can provide an early indication of significant changes in vibration signals. The Impulse and Shape factors are functions of the redressed signal average.

The Crest factor is the ratio of the peak level to the RMS level of the vibration signal. Monitoring the Crest factor of acceleration time waveforms is a simple technique, as it does not require elaborate signal processing, and its interpretation is relatively straightforward. For a healthy bearing, both the peak and the RMS values have weak amplitudes. Under normal operating conditions, most centrifugal machines generate acceleration waveforms at their bearing housings, which are either a sum of discrete frequency components or random, therefore having a crest factor below 4. When a localized fault appears, a periodic shock also appears in the signal at the frequency of the bearing fault (BPFO and/or BPFI and/or 2 x BSF, etc.). As the fault increases, the waveform becomes far more impulsive with higher peak levels, while the RMS value is not affected in any significant way. Whenever a fault or excessive load is present, the crest factor generally increases above 4.

However, this method has a number of shortcomings. The RMS level may become significantly high in bearings with multiple or spreading defects, resulting in a reduction in the Crest factor

(and other descriptors). Background noise is also a problem because it increases the RMS level, and consequently decreases the Crest factor.

The Kurtosis technique, developed by the mathematician, Pearson, is another method used to indicate the "peakedness" of the signal. Kurtosis (Ku) is a statistical parameter, derived from the statistical moments of the probability density function of the vibration signal. It is the fourth moment, normalized with respect to the square of the variance. A harmonic signal gives a Kurtosis of about 1.5 while a random signal gives a value of about 3. Impulsive signals will yield values above 4. It is usually more sensitive to impacts and degradation than the Crest factor. However, the straightforward physical interpretation of a defect is lost.

Figure 4 describes the evolution of the Kurtosis, Impulse Factor , Crest Factor and Shape Factor with the defect size when the outer race of a bearing is deteriorating.

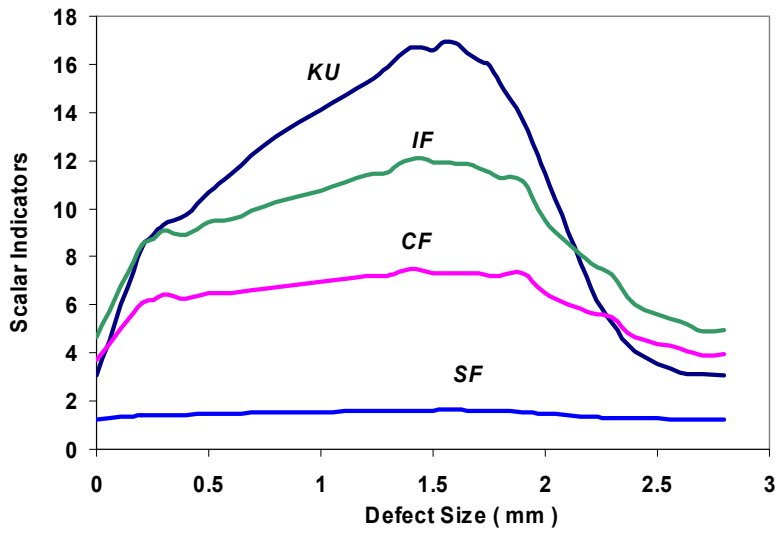


Figure 4: Evolution of scalar parameters (Ku, IF, CF, SF) according to the size of a defect on the outer race

As the size of the defect increases, all the indicators manifest the same behavior, with more or less sensitivity. An increase in the levels of the indicators can be observed at the beginning of the deterioration, when the RMS level is constant; this holds until a maximum is reached, and then a decrease is seen as the bearing deteriorates further and further, because the RMS value increases dramatically. The Kurtosis starts with a value very close to 3 (corresponding to a pure random signal), and increases until it reaches a maximum value close to 16. As the damage increases, the vibration signals become more random, and the Kurtosis, Impulsive factor and Crest factor values decrease down to a level corresponding to the undamaged one, which makes the damage identification impracticable. A comparison between all scalar parameters shows that at the beginning of the deterioration, the Kurtosis is the most sensitive indicator to the damage size, while the Impulsive factor becomes the most sensitive indicator at the end of its life. The Shape factor appears as the least sensitive and cannot be used to detect a bearing defect.

The Kurtosis, the Impulse factor and the Crest factor can be used in a trend chart of a monitoring process until the bearing vibration indicators reach their maximum values. When the trend slope is negative, it means the bearing is approaching the end of its life. When these indicators are weak, the trend should be checked to determine whether the degradation is at its first stage or at the end of its life. It is recommended to complete the diagnosis by making sure that the RMS

value of the vibration amplitude is not in progression, as that would be indicative of a deterioration of the bearing in its terminal phase.

5. 4. Effect of number of defects

When the bearing is subjected to excessive use or is used incorrectly by overloading, over-speeding or lubricant starving, the failure may be accelerated by an increase in the defect size and/or an increase in the number of defects. These are typical warning symptoms of widespread damage. A more general case of multiple defects was numerically investigated by simulating the time response to several defects of 1 mm equally spaced on the outer race. Figure 5 shows the effect of this deterioration on the scalar indicators.

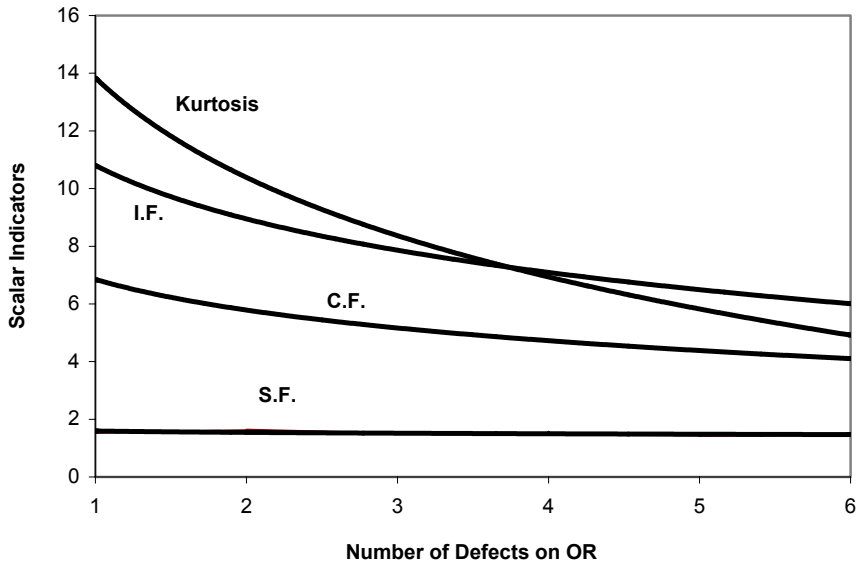


Figure 5: Evolution of scalar parameters (Kurtosis, IF, CF, SF) according to the number of defects on the outer race

Both the peak and the RMS levels are significantly increased in bearings with multiple or spreading defects, thus resulting in a decreasing trend among all the scalar indicators. As seen in Figure 5, as long as the number of defects is moderate, the Kurtosis remains the most sensitive indicator to the increase in signal energy density. However, when the presence of the defects is more pronounced, the Impulse factor becomes the most sensitive indicator. The Shape factor for its part always remains insensitive to damage spread.

6. DEVELOPMENT OF NEW INDICATORS

As already mentioned, the Kurtosis and, to a lesser degree, the Crest and the Impulse factors are three particularly well adapted indicators for detecting the appearance of initial flaking. However, after a certain stage, the evolutions of these indicators are decreasing monotonous functions of the deterioration, and if their trend is not monitored, it is difficult to use them as surveillance indicators without the monitoring of the RMS value. The RMS signal is a monotonous increasing function of the deterioration, but it is only slightly sensitive to the appearance of the first marks of deterioration.

Furthermore, these scalar indicators are unable to detect failures resulting from a large number of defects or widespread damage, or those that occur at high rotational speeds. They reveal fault propagation but do not predict when the fault will become excessive.

Based on the aforementioned trend analysis, it appears that somehow combining the Kurtosis and the RMS parameters may correctly describe the existence of surface defects and their effects, starting from the very first signs of deterioration to the very end when signs of fatal deterioration are observed. Therefore, and based on our numerical experiment, we have defined a new indicator called TALAF:

$$TALAF = \log\left[Ku + \frac{RMS}{RMS_0} \right] \qquad (1)$$

where RMS_0 is the root mean square value defined for a healthy bearing.

If the initial root mean square value RMS_0 is not known or has not been recorded, the method may work by considering any initial value that can be obtained at the beginning of monitoring. This value being a constant, it has no influence on the slope of Talaf but only on its amplitude. When the parameter *TALAF* is plotted as shown in Figure 6, the data from all simulations superpose to give a *four-stage* curve of degradation.

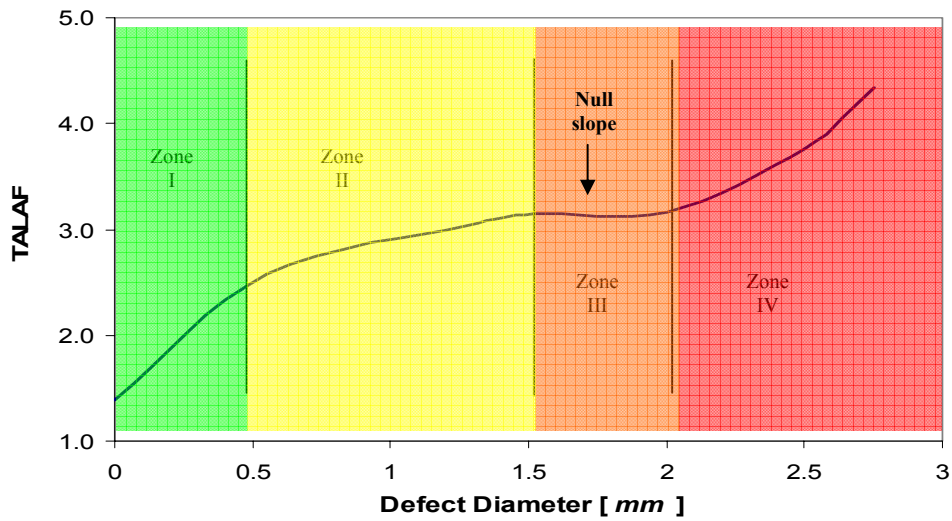


Figure 6: Evolution of the scalar parameter *TALAF* according to the size of a defect on the outer race

The defect appears during the first phase (usually short and unpredictable through vibration measurements), where TALAF exhibits a high slope. The defect grows and shows a weaker slope at the second stage and a null slope at the third phase, which can easily be identified by the null slope of TALAF. When the defect degenerates into final and catastrophic failure at the fourth phase, which is detected after the constant slope, TALAF shows a high slope increase.

The subdivision into four stages is consistent with that proposed by Berry [6], which also calls for the classification of the bearing's degradation into four stages. Whenever the defect size is identified in zone IV as determined by the change in slope from a constant to a high value, failure is imminent, and a shutdown of the production line should be anticipated for shortly thereafter. This is a high emergency case.

It is strongly recommended that once a defective bearing is identified, data should be noted periodically; most managers become puzzled about the evolution of the damage and about the appropriate action to take:

- ✓ When should a machine be taken out of operation in the presence of deteriorating fault conditions, and could it remain reliable and secure until the next scheduled production stop?
- ✓ How long will the damaged bearing last, or should it be repaired immediately?

To answer these questions, another new parameter called *THIKAT*, expressed in Equation 2, has been designed to incorporate data from several parameters (Ku, RMS, CF, Peak) into a single unit of information:

$$THIKAT = \log\left[\left(Ku \right)^{CF} + \left(\frac{RMS}{RMS_0} \right)^{Peak} \right] \qquad (2)$$

The new parameter, *THIKAT*, plotted in Figure 7, informs the user and/or the decision-maker about the degree of confidence in continuing to use any bearing which has already been diagnosed as defective, and enables the confirmation of the preliminary diagnosis carried out with TALAF:

- Whenever the curve is increasing (positive slope), the manager could keep the production going. The bearing is damaged, but could still remain resistant over a comfortable timeframe. It is in its three first stages of degradation.
- However, when the curve starts decreasing (negative slope), the manager should be aware of the gravity of the situation, and an unscheduled and emergency stop should be considered in short order. The bearing is declared to be in its 4th stage of degradation.

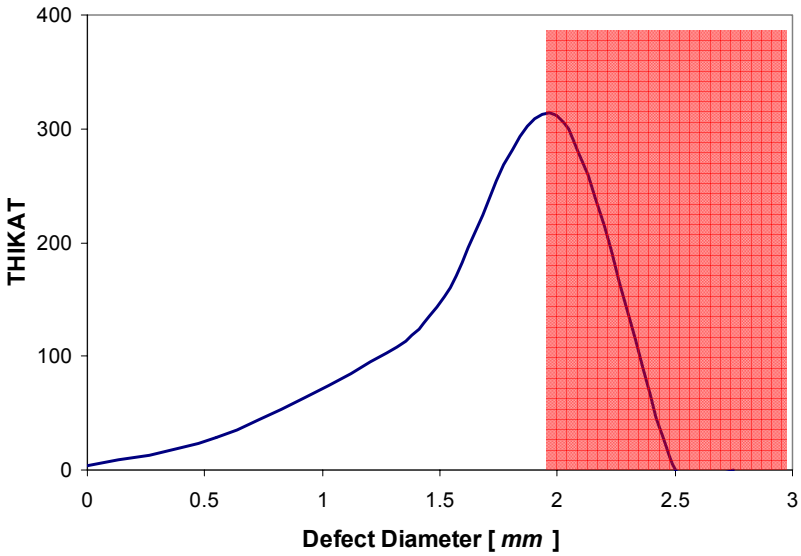


Figure 7: Evolution of the scalar parameter, *THIKAT* according to the size of a defect on the outer race

The main advantage to use Thikat instead of Kurtosis is that Ku would give a too earlier alarm at the end of the stage 2 of degradation while Thikat give an alarm at the end of the third stage of

degradation. When the damage increases dramatically, Thikat becomes null and it is imperative to stop the machine.

Furthermore, a study on the sensitivity of the two new descriptors shows that Thikat increases with the rotational speed of the rotor (Figure 8: the indicators have been normalized by divided their specific value by the value at 1000 rpm) and with the number of defects (Figure 9: several defects of 1 mm equally spaced on the outer race), while Talaf is less affected.

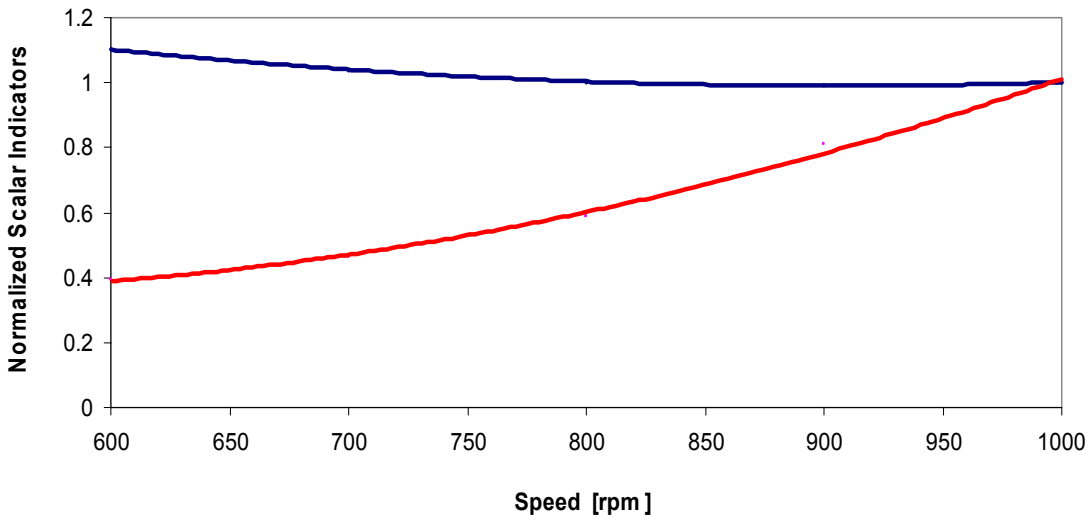


Figure 8: Effect of rotational speed on new descriptors

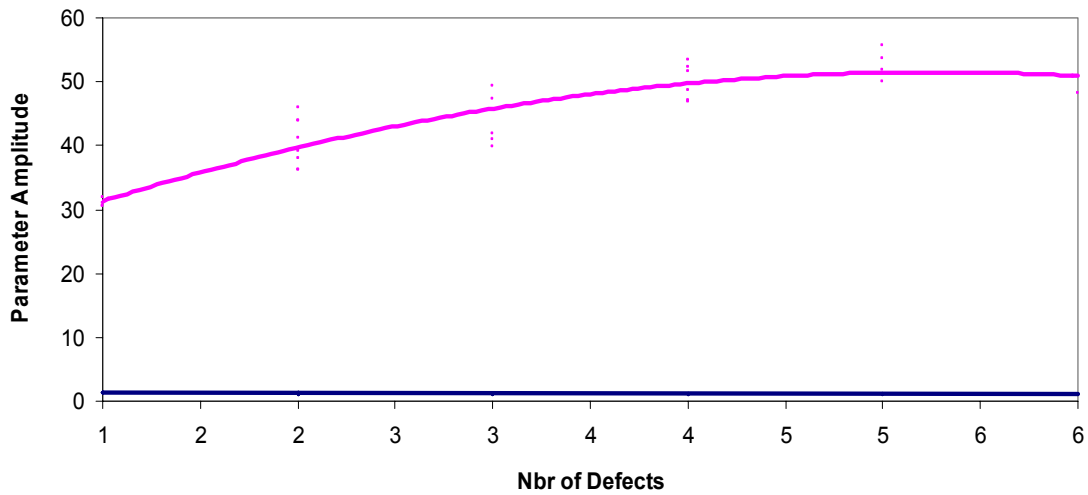


Figure 9: Effect of number of defects on new descriptors

By comparing to Figures 6 and 7, it is clear that Thikat will be able to detect a spreading of the degradation for any rotational speed, while the others descriptors are less sensitive.

7. CONCLUSION

The Kurtosis and, to a lesser degree, the Impulse Factor and the Crest factor are three particularly well adapted time scalar indicators for detecting the appearance of initial flaking. However after

the defect has reached a maximum, the evolution of these indicators becomes decreasing monotonous functions of the deterioration; furthermore, if a trend analysis is not conducted, they are difficult to use as surveillance indicators without being associated to the evolution of the RMS value of the amplitude of the signal. Unfortunately, these scalar indicators decrease with the number of defects and with the rotational speed, and they are unable to detect failures resulting from widespread damage. They reveal fault propagation, but do not predict when the fault will become excessive.

To provide more useful information to maintenance teams, two new time domain scalar indicators have been designed. The first parameter is known as TALAF, and enables a description of the evolution of the damage by combining data from Kurtosis and RMS values. It presents the damage in four stages: the first zone designated as *Stage I damage* corresponds to the initiation of the defect; the second and third designated as *Stage II damage* and *Stage III damage* respectively, correspond to the progression of the defect, and finally, the fourth one, designated as *Stage IV damage*, corresponds to the catastrophic failure of the bearing. Whenever the defect size is located in zone IV, failure is imminent, and a shutdown of the production line should urgently be anticipated for shortly thereafter. Consequently, it is recommended to perform maintenance only after Stage 3. This stage is identified by a null slope of TALAF, while stage 4 is marked by a high increase of the TALAF slope.

The second new parameter called *THIKAT*, expressed in terms of several parameters (Ku, RMS, CF, Peak), illustrates the confidence in using the defective bearing. Whenever the curve slope is positive, it is still possible to use the bearing. However, when the slope becomes negative, an imminent catastrophic failure must be anticipated. Thikat will give an alarm at the end of stage 3. It is a better predictor of the severity than Kurtosis that would give a too earlier alarm at the end of the stage two of degradation. Furthermore, Thikat is more sensitive to the number (or spreading) of defects and to the rotational speed of rotor.

8. ACKNOWLEDGEMENTS

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