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TRENDING ANALYSIS OF DEFECTIVE ROLLING ELEMENT BEARINGS USING A MORPHOLOGICAL INDEX

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Abstract

Alternatively to the traditional time domain indices, such as the root mean square, the crest factor, the kurtosis, the impulse factor and the shape factor, a morphological index for processing vibration signals has been proposed, addressing the issues of how to quantify the shape and the size of the signals directly in the time domain.

The morphological closing using a flat structuring element, results to the extraction of a series of impulses corresponding to the impact series, produced by a defective bearing. This series can offer a better visual inspection of the impulsive signal and contain sufficient quantitative information about the repetition period and the intensity of the impacts. Based on this extracted impulse series, the morphological index can be used as a measure of the development of the defect.

In this paper, the sensitivity of the morphological index is first assessed and compared to the previous traditional time domain indices, using simulated signals that correspond to bearing faults. The morphological index presents a more uniform and reliable behaviour in the cases of different excited natural frequencies, increase of the additive noise level and different propagation media. This fact is then further verified in a case from an industrial installation, presenting fault trending analysis of bearings under an inner race defect.

INTRODUCTION

Rolling element bearing vibration measurement is one of the major condition monitoring tools in regular use. Vibration based condition monitoring of rolling element bearings is typically based on trends of several indices, such as the root mean square of the signal, the crest factor, the kurtosis, the shape factor and the impulse factor, resulting from measurements obtained at regular intervals, and theoretically on the same point and direction under the same operating conditions of the machine. However, although the overall condition of the machine may remain the same during the measurements, several conditions may vary from measurement to measurement, such as environmental noise level, rotational speed, signal propagation path to the transmitter, or other changes resulting internally in the machine, not necessarily related to the evolution of the defect of the bearing. Consequently, the indices used for fault trending should be insensitive to such effects.

Pachaud et al. [4] examined the sensitivity of the kurtosis and the crest factor, using a model of a linear mechanical system of one degree of freedom with viscous damping. As they have shown, the kurtosis is extremely sensitive to the noise and to the variations of the rotational speed of the shaft and that the crest factor has limited success for the detection of localized defects.

The shape factor and the impulse factor are alternative fault indicators. According to [5], when the presence of the defect is more pronounced, the impulse factor becomes a very sensitive indicator. However, the shape factor always remains insensitive to the extent of the damage. The sensitivity of these factors decreases with the size and the number of the localized defects.

Alternatively to the traditional time domain indices, which are based on the quantitative processing of the signal, morphological processing has been proposed for envelope extraction in signals resulting from defective rolling element bearings [3] leading to the definition of a morphological index. Morphological operators [2] are used to modify the geometric characteristics of the signals directly in the time domain, in order to extract the useful information contained in the signal.

The aim of this paper is to assess the performance of the proposed morphological index [3], comparing its sensitivity and fault trending capability to the five above mentioned traditional time indices, when a number of parameters is varied.

DEFINITION OF THE MORPHOLOGICAL INDEX (MI)

Morphological operators are indices that are sensitive to the geometric characteristics of the signals and they are a result of morphological signal processing [2]. The fundamental concept of morphological signal processing is the modification of the shape of the signal through its interaction with another object, called the structuring element. The basic morphological operations of set erosion, dilation, opening and closing are related to Minkowski set operations and are used to construct morphological filters. The proposed morphological index is produced by applying the closing process to a signal produced by a defective rolling element bearing, using a flat structuring element [3]. For a signal $f(k)$, defined over a domain D_f, and for a function $g(u)$, called the structuring element, which is of length L and defined over a domain D_g, the closing of the signal $f(k)$ by the element $g(u)$ is defined as:

$$cl(k) = (f \bullet g)(k) = er(dil(k)) \tag{1}$$

The flat (zero) structuring elements are selected because they present the simplest structuring element with a straightforward application, since the only parameter which must be selected for their application, is their corresponding length *L*. Additionally, morphological operations using flat structuring elements with a length in the range of 60%-70% of the impulse repetition period seem to be quite appropriate for the detection of peaks of impulsive type vibration signals.

After the closing operation, a local maxima algorithm is further implemented, in order to evaluate the impulsive information contained in the closing. According to this algorithm, an impulse series *p(i)* can be obtained by retaining only the local maxima of a closing *s(i)*, located at the time instants *i* which satisfy:

$$\begin{cases} p(i) = f(i) & , \text{if } \ f(i) > f(i-1) \wedge f(i) > f(i+1) \wedge f(i) > tr \\ p(i) = 0 & , \text{otherwise} \end{cases} \tag{2}$$

where t_r is a threshold value, used to suppress low amplitude peaks, which are typically attributed to noise effects. The optimal range for the threshold value is typically between 25 to 35% of the maximum impulse amplitude. A threshold value equal to 33% of the maximum impulse amplitude is further chosen in this paper.

The morphological index *MI* is then expressed as the *RMS* value of the impulses detected by the closing operation and characterizes the amount of energy involved in the pulse series caused exclusively by the bearing defect.

Figure 1 presents a characteristic example of the application of the morphological operator in reconstructing the impulse sequence.

SENSITIVITY ANALYSIS

The ideal performance of an index capable to predict and to monitor the evolution of a bearing defect should be characterized by the minimum possible sensitivity to a number of parameters, like environmental noise level changes, different signal transmission paths, fluctuations of the rotating speed, or other changes internally in the machine, not related to the evolution of the defect of the bearing. The impact of these parameters is quantitatively reflected in the model used in equation (3) [1]:

$$d(t)=\begin{cases} \sum_{k=0}^{N}[q(t)A_k d(t-kT_d) \otimes \sum_{i=1}^{M} B_i e^{-t/m_i} \sin(2pf_{0i}t)] + n(t), & \textit{for inner race defect} \\ \\ \sum_{k=0}^{N}[A_k d(t-kT_d) \otimes \sum_{i=1}^{M} B_i e^{-t/m_i} \sin(2pf_{0i}t)] + n(t), & \textit{for outer race defect} \end{cases} \tag{3}$$

where the symbol $\otimes$ denotes convolution, n(t) is an additive background noise, which takes into account the effects of other vibration sources of the system and the external environment, f_{oi} is the excited natural frequencies, Q_i is the quality factors and T_d is the impulse period depending on the type of the defect.

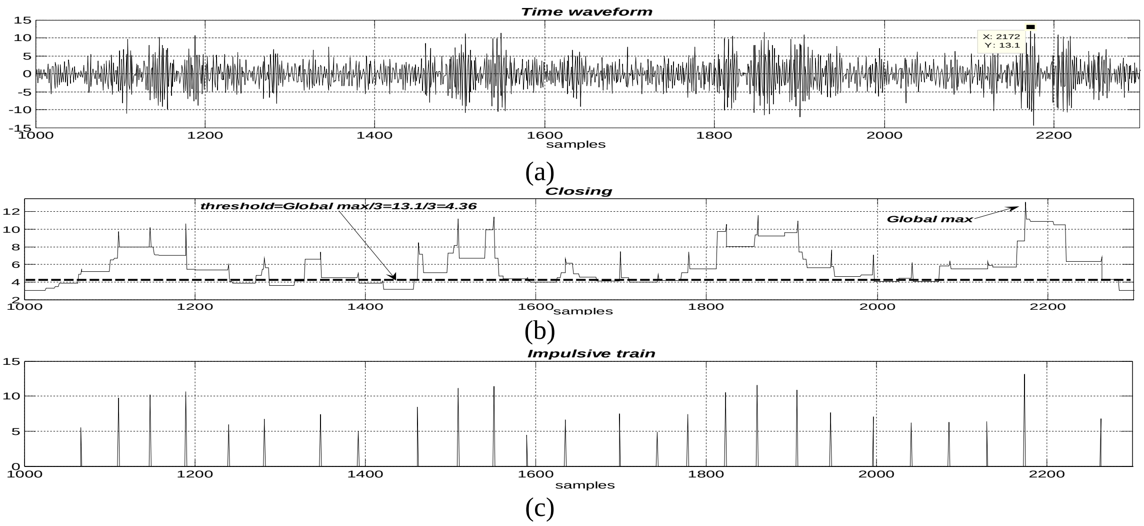


Figure 1 - (a) a characteristic vibration signal measured on a bearing with inner race defect, (b) the application of the closing operation to the signal and (c) the resulting impulse sequence.

Initially, the indices are tested for their sensitivity in the environmental noise and the excited resonances for the case of bearing with an outer race defect. Figure 2 presents some characteristic results for a BPFO frequency equal to 50 Hz, and quality factor Q equal to 12.5. The signal to noise ratio SNR fluctuates form 100 to 0%, and the excited natural frequency f_o varies from 1000 to 5000 Hz.

Figure 2(a) indicates the performance of the morphological index. The increase of the environmental noise does not influence this index for any natural frequency above 1500 Hz. The curves for almost all the natural frequencies appearing in the figure 2(a) fluctuate between a narrow zone. The reduction of SNR from 60% to 10% affects to a minimum degree the sensitivity of this operator for medium and low resonances. The almost constant behaviour of the Morphological Index is due to the closing process, which tends to isolate the random components.

Figure 2(b) shows the corresponding evolution of the RMS of the signal. It is observed that the RMS value is sensitive to the growth of the noise level and increases with the reduction of SNR for any natural frequency. This increment is more intense for medium and low resonances. As also shown in figures 2(c), 2(e) and 2(f), the increase of the additive noise level contributes in the drastic reduction of the kurtosis, the shape factor and the impulse factor, respectively. The smaller becomes the natural frequency, the higher is the estimated value of these time-domain indices. When the ratio of signal-noise SNR is decreased below 80%, the shape operators converge abruptly and uniformly. This implies that noise can render these time-domain indices practically inactive. The increase of the environmental noise leads to a random fluctuation of the crest factor curve [figure 2(d)]. Additionally, the estimated values of the crest factor are affected by the value of the excited natural frequency. Thus, for a shift of the resonance band not related to the evolution of a bearing wear, which may result between successive measurements, the crest factor will falsely alert for the deterioration of the wear or will become ambiguous. Hence, the Morphological Index constitutes the most insensitive index with respect to variations of the additive noise level and the value of the excited natural frequency. This result is further verified for all the other values of the BPFO tested. It should be noted that the variation of this parameter also reflects corresponding changes of the rotation speed, since these two parameters are proportional.

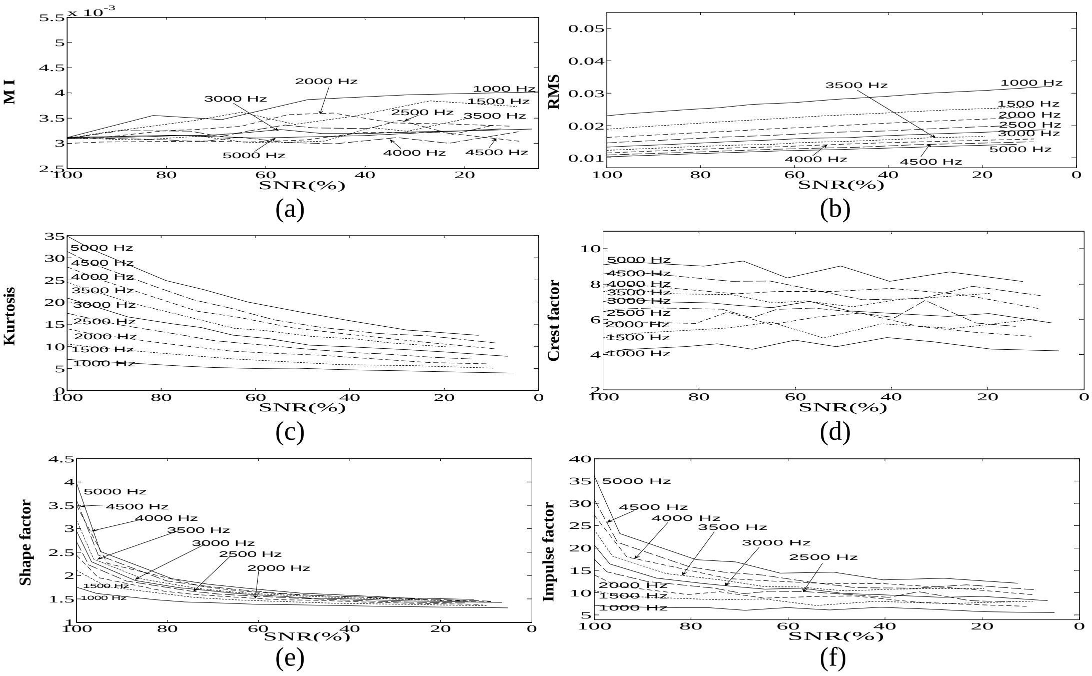


Figure 2 - Performance of the time-domain indices in the case of an outer race defect with respect to variations of the added noise and the excited natural frequency. (a) morphological index, (b) RMS, (c) kurtosis, (d) crest factor (e) shape factor and (f) impulse factor.

Following a similar process, the sensitivity of the six indices is examined in the cases of different propagation media, as this effect is mainly reflected to variations of the quality factor Q. Figure 3 presents such a typical analysis for a defect frequency BPFO equal to 125 Hz and an excited natural frequency f_o equal to 3000 Hz. The signal to noise SNR varies form 100 to 0%, and the quality factor Q varies from 4 to 14.

The morphological index presents an almost constant response under the variations of the quality factor [figure 2(a)], while the crest factor presents an increased sensitivity, as illustrated in figure 2(d), where the crest factor values present a number of maxima and minima, leading to indeterminate results. Figure 2(b) shows the evolution of the RMS with respect to variations of the SNR and the quality factor. The results for kurtosis shape factor and impulse factor are presented in figures 2(c), 2(e) and 2(f), respectively. The growth of the environmental noise in the signal leads to an abrupt convergence of the curves, verifying the poor performance of these methods in noisy environments.

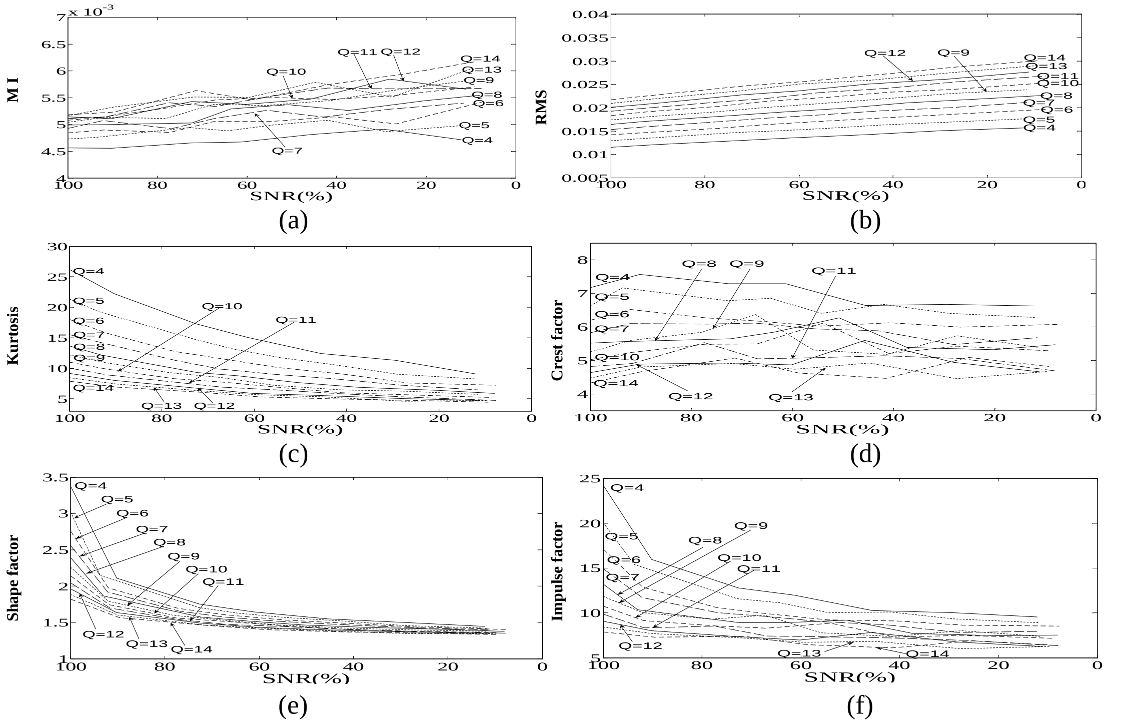
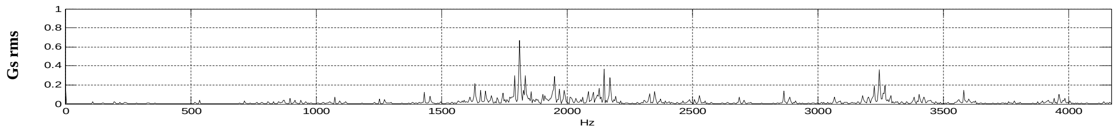


Figure 3 - Performance of the time-domain indices in the case of an outer race defect with respect to variations of the added noise and the quality factor. (a) morphological index, (b) RMS, (c) kurtosis, (d) crest factor (e) shape factor and (f) impulse factor.

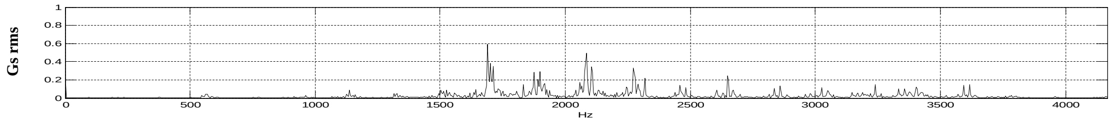
APPLICATION IN INDUSTRIAL VIBRATION MEASUREMENTS

The measurements in this industrial application were conducted on a rolling element bearing of a pump, presenting an inner race fault. The shaft rotation speed during the measurements was around 1,320 rpm (22 Hz). The bearing monitored is type 22205 EK, with a BPFI frequency equal to 8.32 times the shaft rotation speed, leading to a theoretical estimation of the expected BPFI frequency around 183 Hz. Each signal is 2,048 samples long and recorded with a sampling rate of 8.33 KHz. Each measurement was recorded with a time interval about 40 days from the next one. The frequency analysis of the measured signals is shown in figure 4.

The analysis of the spectra of the measurements (figure 4) confirms the growth of an inner race fault. In this case, BPFI and 1xRPM sideband frequencies are developed around the excited structural resonances. The frequency band in the range form approximately 1,500 to 2,500 Hz is excited during the first three measurements. As the defect proceeds, it begins to excite the natural frequency band from 2,500 to 4,000 Hz.



(a)



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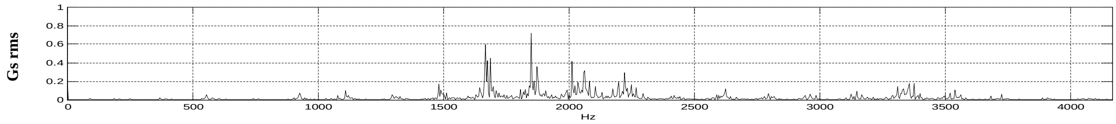
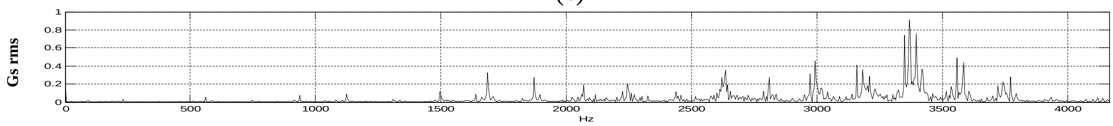
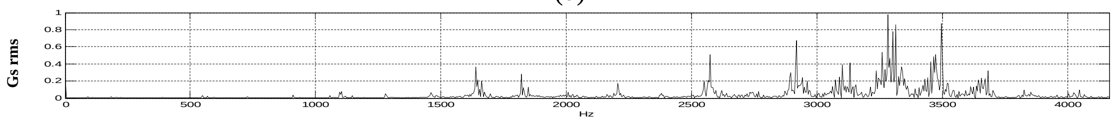


(c)



(d)



(e)

Figure 4 - Frequency analysis of the measurements.

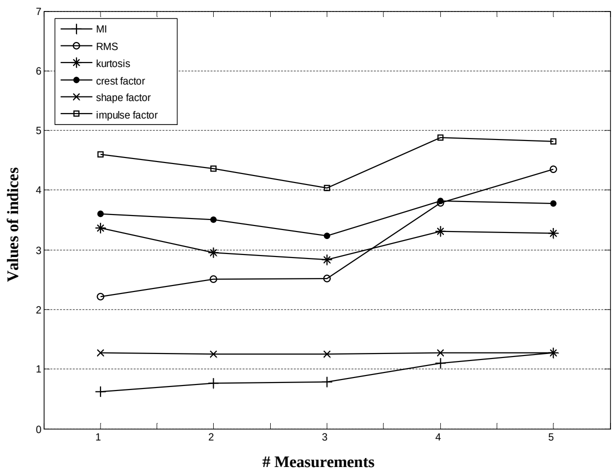


Figure 5 - Trending of the crest factor, kurtosis, RMS, shape factor, impulse factor and the morphological index for the vibration measurements.

Then, the crest factor, the kurtosis, the RMS, the shape factor, the impulse factor and the morphological index of the measured signals are estimated. Figure 5 presents the evolution of these six indices over time. A drastic degradation of the kurtosis, the impulse factor and the crest factor performance is observed, as they fail to follow the deterioration of the bearing fault. Their curves slope down at the first three measurements. Afterwards, their values increase temporally and finally decrease again. The curve of the shape factor is observed to be constant around a value of 1.4 for all the measurements. Thus, this indicator cannot monitor the evolution of the bearing defect. The RMS indicator achieves to follow the evolution of the bearing wear. However, the use of this index involves a risk due to the fact that its value can change significantly by the modification of a parameter which is not related with the deterioration of the bearing fault.

Finally, the morphological index achieves to follow the evolution of the bearing wear. It is noted that the morphological index is not affected by the shift of the band of the structural resonances, which is excited by the impacts with respect to the position of the fault. Thus, this test case proves that the morphological index is an effective and reliable index in fault trending.

CONCLUSIONS

The morphological closing using a flat structuring element, contrary to the five traditional time domain indices considered, presents a more uniform and reliable behaviour in the cases of different excited natural frequencies, growth of the additive noise level, different propagation media and varying defect frequencies.

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