Coupling Singular Spectral and Envelope Analysis for Localised Bearing Defect Detection

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***Abstract*—In many industrial situations, bearing failure can lead to serious consequence on the overall process. A bearing's fault progressive character raises the question of finding the right moment to perform replacement at the cost of stopping the machine. The study done in this paper deals with mathematical modeling of the bearing's rolling element with a local defect on its fixed outer ring, based on a mass-spring-damper archetype system. A simulation of the vibratory behavior is performed, and its impact on ball-defect coincidences during shaft rotation under different working conditions is analyzed. The paper suggests applying advanced pre-processing techniques such as Singular Spectrum Analysis (SSA) and Envelope Analysis (EA) before extracting statistical indicators. Some well-known time-domain indicators such as the Root Mean Square (RMS), kurtosis, and Energy around Ball Pass Frequency Outer-ring (EBPFO) are used on the raw and processed signals to highlight the defect evolution. The results carried out show that, applying the EA with SSA on the raw time-series signal at the pre-processing level, before statistical analysis can significantly improve the detection, thus an excellent diagnosis to incipient defects in bearings.**

***Keywords*—Failure, Modelling, vibration analysis, Indicator, Detection, Diagnosis**

I. Introduction

The rolling bearing is one of the machine's elements present in most industrial plants, and its failure can lead to severe consequences in the production process [1]. Therefore, it is critical to monitor the defect from the very beginning of its occurrence [2]. The vibration analysis technique has already been used in several research projects. It is suitable for continuous or intermittent monitoring of machine state, and defects detection [1]–[3]. Indeed, vibrations extracted from machines present complex frequency spectra, with peaks correlated with particular physical phenomena [5]. Mathematically, vibration can be modeled by a periodic signal characteristic of faulty element [6]. However, most defected bearing signals are masked by noise because of their lower energy and require specific vibration analysis techniques like the one developed in this paper. The singular spectrum analysis (SSA) is a time series analysis technique based on decomposing the original signal into independent ones, the sum of which gives the starting signal. These independent components are reconstructed to distinguish the trending component, the oscillatory content, and the noise, respectively [2]. On the other hand, envelope analysis (EA) demodulates the system's resonant response, followed by frequency shifting and low-pass filtering in the time domain. This produces an analytical signal from which the envelope spectrum is obtained. Results from work done by Siegel D et al.2012 [7], show that the technique is widely used to detect periodic shocks, such as flaking defects in bearings. Moreover, evidence suggests that these techniques are well suited when the fault generates impulsive signals.

Numerical analysis is another helpful approach in the simulation of the vibratory response of the bearings to excitation produced by the defects [8]. The approach makes it possible to test the rings' analytical models formulated using the Lagrange equations, thanks to the vibratory signals resulting from the bearing defects [9]. Jing et al. used the numerical method and proposed a dynamic simulation combining the piecewise function and the Hertzian deformation on the edge of the localized defect. This gives an impulse closer to the reality of the ball-ring contact under different defect sizes, instead of a simple rectangular, or half-sinusoidal type function [10]. Patil et al., used a mathematical model of a bearing with a defect on a ring considered a sinusoidal half-wave. It is a mass-spring-damper system that allows the simulation and prediction of vibratory behavior and spectral components [11]. Feiyun et al. investigated a local fault model on the outer ring, which produces successive pulses that can excite resonances in the machine bearing [12].

Combining the ideas of Jing, Patil, and Feiyun et al., this paper suggests applying the coupling of mentioned advanced pre-processing techniques, SSA and EA, on a simulated vibratory response of a bearing with a local fault. The fault is located on the non rotating bearing outer ring. The SSA signal is obtained using a 300 points sliding window with a reconstruction based on the 200 last eigen components.

II. Simulation Setup

Fig.1 shows a descriptive diagram of the used case. Different parameters which influence the vibratory response were explored. The SKF 6206 bearing was used, with the following characteristics: number of rolling elements $z = 8$, contact angle $\alpha = 0$; rolling element diameter $d = 9.525$ mm; pitch diameter $D_m = 46.482$ mm. The simulation is done with MATLAB R2017a environment on a windows 64bits PC.

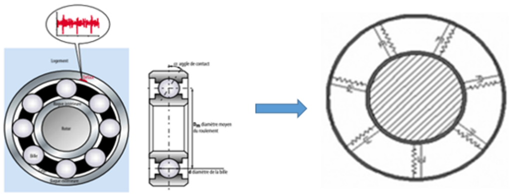

Fig. 1. Descriptive diagram of a ball bearing with defect (left) and its physical model according to Patil et al (right) [11]

Data for a nominal working are given in the table I.

TABLE I
IDEAL OPERATING CONDITIONS PARAMETERS

Test Number	Damping factor	Speed [rpm]	Load [kN]	Defect size : Ld
Experiment 1	0,0047	1200	20,3	0

III. METHODS

This paper applies SSA in combination with EA to simulated signals. The simulation model makes use of the mathematical formulation of Hertzian force theory. This force acting between rings and rolling elements is expressed as a non-linear function of the radial deflection (δ_r) , which intensity is given by the Eq.1.

$$F_z = k\delta_r^n \tag{1}$$

The none linearity factor n between load and deflection, whose value is 3/2 for ball bearing according to reference [12] and, k is the loading factor.

Considering successive passage of the balls on the defect, the influence of the defect size (L_d) on the radial deflection and a probable centrifugal force with parabolic distribution q_θ [5], [6], [10], [12], the excitation source of the structure due to presence of defect is finally written as :

$$F^*_{(t)} = q_\theta k.(C_r + Ld.sin\theta_i)^n.\sum_{m=-\infty}^{+\infty}\delta\left(t - \frac{m}{f_{BPFO}}\right) \tag{2}$$

where

$$q_\theta = \begin{cases} q_0\left[1 - \frac{1}{2\epsilon}(1 - cos\theta)\right]^n \\ 0;\ \text{elsewhere} \end{cases}$$

$q_0 = \frac{5.F_r}{Z.cos\alpha}$ is the maximum load, and ϵ is a function of the radial ring shift and the radial clearance.

The dynamic response of the system to the repetitive excitation is given, in the frequency domain by the product of the input excitation with the frequency response of the structure:

$$S_{(f)} = H_{(f)}.F_{(f)} \tag{3}$$

The following mathematical expression can be written after development :

$$\begin{aligned} S_{(f)} = q_0 k(C_r + L_d.sin\theta_i)^n.H_{(t)}SHA_{fBPFO}(f) \\ +\frac{\gamma}{2}SHA_{fBPFO}\{f - (m.f_{BPFO} - f_r)\} \\ +\frac{\gamma}{2}SHA_{fBPFO}\{f - (u.f_{BPFO} + f_r)\} \end{aligned} \tag{4}$$

where C_r is the radical clearance, SHA the Dirac comb function, f_{BPFO} the ball pass frequency of outer ring and f_r the rotation frequency.

This study uses well-known time-domain scalar features such as the kurtosis which allows to capture the impulsive nature of a signal [3], [13], [14] and the RMS which gives an indication on the global energy content of the signal [15]. We use also E_{bpfo}, a feature built in frequency domain based on energy around the fault frequency peak. SSA and EA are used as powerful processing techniques before feature extraction even from signals masked by noises. The following features have been extracted:

- K1 and K4, the kurtosis of raw and SSA signals respectively, whose variation was below 4%
- K2 and K3, the kurtosis of squared envelope of raw and SSA signals, respectively whose variation was beyonds 20%
- E_{BPFO1} and E_{BPFO2}, frequency domain feature from SE of both raw and SSA signal
- and RMS1 and RMS2 indicate the root mean square values of raw and SSA signals.

IV. RESULTS AND DISCUSSION

Figure 2 shows the raw signal of a healthy bearing as well as its frequency spectrum.

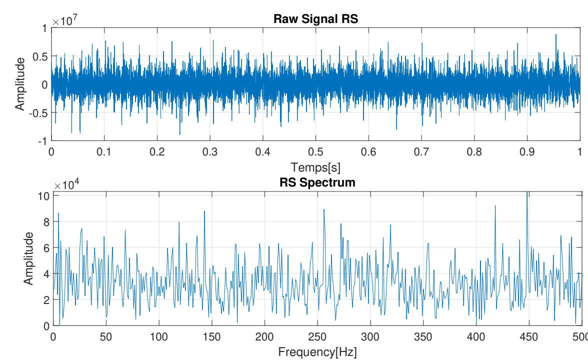

Fig. 2. Signal generated by basic test

From the following healthy bearing signals , one can notice the increase of vibratory amplitude in the spectrum of both SE and SSA faulty bearing . Furthermore, envelope analysis allows to highlight chocks periodicity of drowned in noise signals.(add fig of faulty bearing)

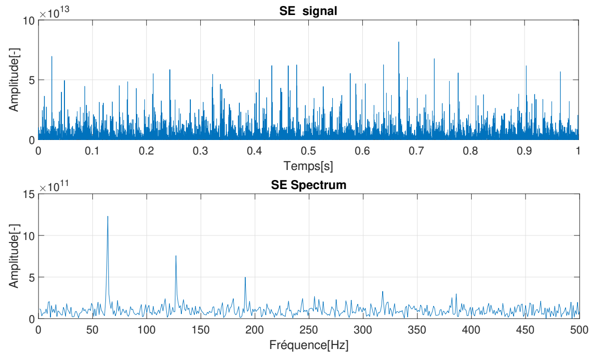

Fig. 3. Healthy SE signal and its spectrum

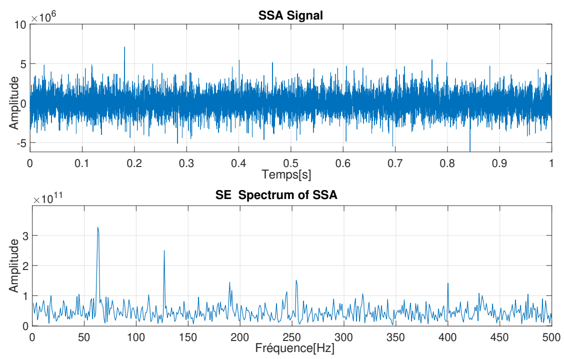

Fig. 4. Healthy SSA signal and its SE spectrum

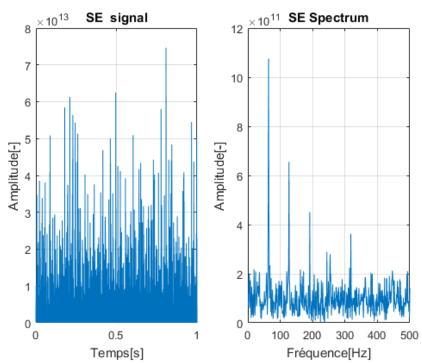

Fig. 5. Faulty SE bearing signal and its spectrum

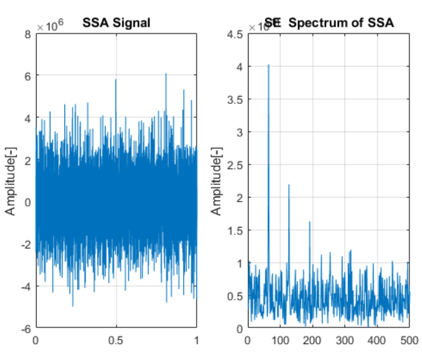

Fig. 6. Faulty SSA signal and its SE spectrum

In the following, we discuss the effect induced on the fault features by the speed, the load, the fault size and the damping factor.

A. Effect of defect size

Figure 7(a) and 7(b) show the variation of Kurtosis (for k1 - k4 , and k2 - k3 respectively) in function of defect size. These variations are evaluated with respect to the baseline test with a defect $L_d = 0$. The increase in the size of the defect is reflected in the variation of the kurtosis which increases in a sawtooth pattern, the defect character is more pronounced after envelope analysis (k2) than after singular spectral analysis (k3). The same behavior has been noticed for RMS and E_{bpfo} feature even though this is not reported in this paper.

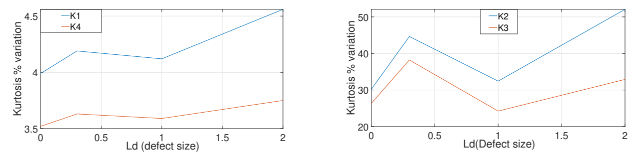

Fig. 7. Evolutions of Kurtosis with respect to the defect size for raw and SSA signals (left), SE and SE of SSA signals (right) .

B. Effect of speed

At very low speed (400 rpm) the defect detection is not optimal through impulsive indicators due to the low energy that the contact of the rolling element with the defect generates. As the speed increases, the detectability improves. However, above a certain speed, the detection becomes difficult because the impulse caused by the impact does not have time to be absorbed before the next impact occurs. This results in a reduction in the impulsiveness of the signal. The described phenomena can be observed on figure 8.

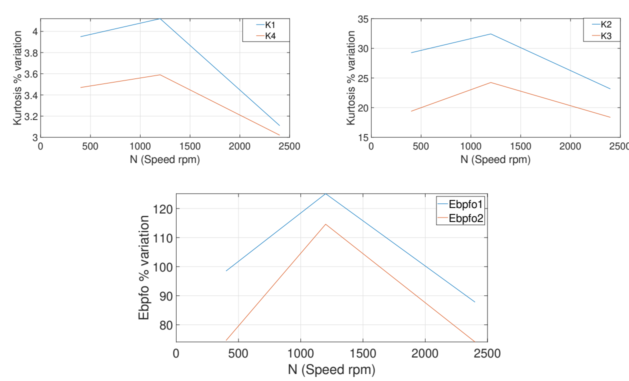

Fig. 8. Evolutions of Kurtosis and E_{bpfo} with respect to speed

C. Effect of radial load

In general, the features that capture the signal impulsiveness (kurtosis and Ebpfo) show a decreasing trend with increasing load. Indeed, when the rolling element is forced into contact with the outer ring by the radial force, the intensity of the shock is reduced.

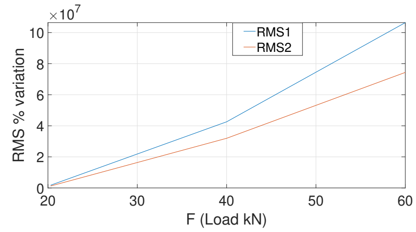

Fig. 9. Evolution of RMS with respect to the radial load

The RMS captures the overall energy in the signal, which naturally increases with load, especially at rotation frequency. This is presented in Fig. 9 for both for raw and SSA signal. Kurtosis of SSA signal and E_{bpfo} of SE on the other hand, present an increasing profile until L_d reaches level 1, but with an opposite effect of the load (Fig. 10).

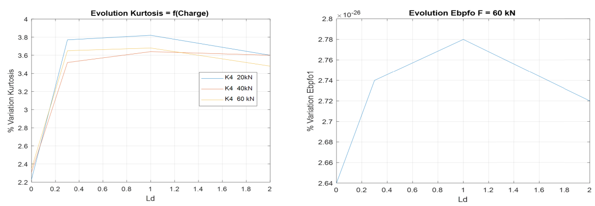

Fig. 10. Evolution of K4 and E_{BPFO1} with respect to the radial load

D. Effect of damping

Concerning the influence of the damping (represented by the time constant), two zones can be observed for the kurtosis: the one with very low time constant (less than 0.0047) and the one with high values. Low values of the time constant correspond to high damping. The kurtosis shows the expected behaviour because the higher the damping, the more separated the pulses appear. This is reflected in the kurtosis value (Fig. 11).

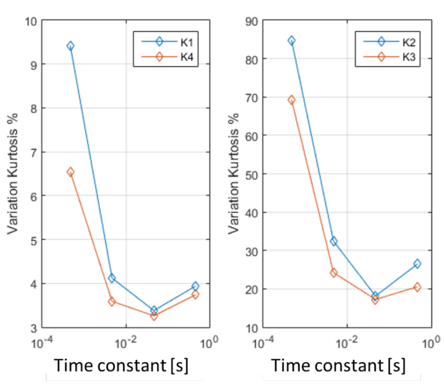

Fig. 11. Effect of damping on kurtosis.

V. Conclusion

This paper deals with bearing fault diagnosis based on modeling of outer ring localized defects and simulation of its vibratory behavior through different scenarios. The goal consisted in studying the use of coupling SSA and squared envelope by analysing the behavior of some fault features. It was noticed that kurtosis presents a good trend on the evolution of the defect for the raw signal and after applying singular spectrum and envelope analysis for a maximum speed value equals to 1200 rpm, when compared with the energy around the BPFO indicator. On the other hand, the RMS shows good sensitivity to the increasing load. Furthermore, the envelope analysis technique helped highlight the periodic shocks due to weak defects masked by noise. However, the hypothesis that the coupling SSA technique and envelope analysis could improve the detectability of incipient bearing faults was demonstrated to be possible only if one chooses a specific range of speed, not over the nominal working condition.

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