A shock filter of a vibratory signal for damage detection

Bechir Badri 1; Marc Thomas 1 and Sadok Sassi2

Abstract- This paper describes a filter that is designed to track shocks in the time domain, and to isolate them from any other random or harmonics components. This innovative tool can be used in the time domain as a denoising filter to estimate the proportion of the total signal energy caused by the shocks and to quantify the severity of damage. It can also be applied in the frequency domain and will allow through envelope or time-frequency analysis to clearly identify the sources of the shocks even if they are from various origins.

Keywords—Bearing, Shock Filter, Signal Processing, Vibration, Time-frequency analysis, Envelop.

I. INTRODUCTION

Machines maintenance is conditioned to an adequate monitoring of potential failures. Machinery vibration consists essentially of three signal types: Periodic (unbalance, misalignment, blade pass), random (friction, noise, fluctuation, turbulence) and shocks (bearing faults, gear faults, etc.). The determination of each of these types of vibration constitutes in itself a powerful monitoring technique. One of the most involved mechanisms in rotating machines failures are the bearings. The recognition and classification of bearings defects by vibratory analysis remains a subject of great interest in the rotating machines, because the detection of the damage phenomena and its propagation still remain nebulous to date. Precedent works allowed for the development of a simulation software generating the vibratory response caused by defective bearings [1]. The numerical simulator has been used to generate a database covering a large range of defects configurations. A relevant review of vibration measurement methods for the detection of defects in rolling element bearings has been presented by Tandon and Choudhury [2]. The monitoring methods applied to bearings can be achieved in a number of ways [3]. Some of these methods are simple to use while others require sophisticated signal processing techniques. In fact, a large number of defects generate shocks that can be analyzed in either time domain: RMS, Peak, Crest Factor (CF), Kurtosis (Ku), Impulse Factor, Shape Factor, etc. [4], or in frequency domain: spectral analysis around bearing defect frequencies [5-7], frequency spectrum in the high frequency domain, Spike energy [8], enveloping [9], or time-frequency and wavelet analysis [10], etc.

The shocks are generally considered as abnormal phenomena in most rotating machinery and as reflecting the effect of defects for which the source must be identified. Usually shock phenomena can be identified by scalar time descriptors. RMS and Max-Peak values are quite adequate when the fault is quite developed and the signal-to-noise is high. Unfortunately, when the fault is small and the signal-to-noise ratio is weak, these two descriptors are not enough efficient alone. The increase in size defect is usually observed more readily by the Peak rather than by the RMS value. Because of this, the crest factor, which is defined by the ratio of the Peak to RMS value, is better adapted for monitoring the evolution of shock phenomena. This relationship between these two descriptors during the evolution of a fault is interesting, but it is easier to combine them in only one scalar descriptor such as the Crest Factor (CF) or the Kurtosis (Ku).

In this paper, a shock detector, based on the Julien Index [11-15] is described. The main goal of a shock filter is to examine the shock content into a signal. The method uses the time waveform and consists in recognizing the shock pattern of each defect, insulating it and treating it separately from the original signal. Thus, the effect of each defect in the vibratory signal is treated independently of the others and will make it possible to localize it. The shock descriptor also allows for counting the number of shocks per unit time, or better, for each cycle or revolution of the machine. This simple descriptor may be used by a non-specialist to monitor the number of shocks per revolution as the fault progresses. The shock detector allows not only for determining the number of shocks, but also their location and individual amplitudes. It is then possible to use the Fourier transform to determine the frequencies at which the shocks occur, similarly to an envelope analysis which would only react to shock signals, rather than to all the other manifestations of modulation phenomena.

II. PROCEDURE FOR SHOCK FILTERING

With excellent properties to detect shocks and fast computing time, Kurtosis has been found the best time descriptor for evaluating energy level of the three windows [4].

\[
Ku = \frac{1}{N} \sum_{k=1}^{N} (a_k - \bar{a})^4 \tag{1}
\]

\[
CF = \frac{a_{\text{peak-max}}}{a_{\text{RMS}}} \tag{2}
\]
At each sample (i) of the time signal, the Kurtosis of a window C centered on i (i-n; i+n) is computed and compared to the ones calculated on windows located to the left L (i-3n; i-n) and right R (i+n; i+3n) of the current sample (i). Figure 1 shows an example for a time sample centered at i = 15, and a window length of 2n+1 = 5; the central window is represented in orange and the windows to the right and left are in green.

Once the Kurtosis has been evaluated for each of the three windows, a classification and selection is conducted:

- If the energy of the central window is greater than the two others into the left and right window, we declare the presence of a shock and the peak amplitude of the signal at position (i) is assigned to the shock extractor.
- Otherwise, there is no shock and the shock extractor takes a null value.

Then, the scan continues and the current position value is incremented to i+1 (figure 1-b). The procedure continues until the value i= N_{max}-(3n+1) is reached, where N_{max} is the total number of samples in our signal, and n is very close to the half-length of the short time window.

The size of the windows (R, L and C) highly depends on the acquisition parameters, mainly the sampling frequency, as well as the nature of the impact. Ideally, the window will be the same as the length of the transient response to an impact [16]. If we consider that the transient response is stabilized at, a level close to 4% of the maximum amplitude, the length of the windows may be defined as:

$$T = \frac{1}{2\zeta f_n}$$

with $\zeta$, the damping rate and $f_n$, the dominant bearing resonance (Hz).

It is usual to consider a bearing damping rate of 5% and accordingly with the bearing size a dominant natural frequency between 3 and 5 kHz [9, 16]. We have tested the natural frequency of the bearing SKF 1210 at 4 kHz. This gives a T equal to 0.0025 s.

The length of the time window is:

$$T = 2n(\Delta t) = \frac{2n}{f_s}$$

where $\Delta t$ is the time increment and $f_s$, the sampling frequency.

This gives a number of samples equal to:

$$2n = \frac{f_s}{2\zeta f_n}$$

By considering a sampling frequency of 48 000 Hz, we obtain 2n = 120 samples.

A Hamming window is applied to each shock with a width equal to the shock length plus twice the short window length defined by the shock filter. The different steps of the signal processing are described in Fig. 2.
III. TIME ANALYSIS OF THE SHOCK SIGNAL

The method previously described was applied on two signals recorded on two defective rolling-element bearings turning at a speed of 1750 RPM, one with an inner race spall of 0.18 mm and another of 0.56 mm. The results are shown on Fig. 3 and 4, respectively.

Table 1: Computation of the shock/signal ratio

<table>
<thead>
<tr>
<th></th>
<th>Original (0.18 mm)</th>
<th>SF (0.18 mm)</th>
<th>Original (0.56 mm)</th>
<th>SF (0.56 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>1.51</td>
<td>1.51</td>
<td>2.87</td>
<td>2.87</td>
</tr>
<tr>
<td>RMS</td>
<td>0.33</td>
<td>0.21</td>
<td>0.46</td>
<td>0.38</td>
</tr>
<tr>
<td>CF</td>
<td>4.57</td>
<td>7.19</td>
<td>6.24</td>
<td>7.56</td>
</tr>
<tr>
<td>CFR</td>
<td><strong>63.6 %</strong></td>
<td><strong>82.6 %</strong></td>
<td></td>
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</tr>
</tbody>
</table>

By computing the ratio of Crest Factor (CF) of the original signal on the CF of the Shock filter (SF), it is then possible to determine the proportion (CFR) of shocks (%) present in the original signal. Table 1 shows a summary of the results. This new descriptor (CFR) gives thus an indication on the severity of damage.

IV. THE TIME-FREQUENCY ANALYSIS OF THE SHOCK SIGNAL

By applying a Short Time Frequency Transform (STFT) to the shock signal, it is then possible to determine the frequencies at which the shocks occur. This is particularly useful when the source of shocks must be identified since the STFT applied to the shock signal allows for determining which frequency range is excited by shocks.

Fig. 5 shows the Fourier transform of the signal processed on Fig. 4. The STFT analysis from the shock signal revealed to be clearer than those from the original signal (Fig. 6). As expected, the shock spectrum contains most of its energy in the high frequency range. The time-frequency analysis is thus very useful for identifying the natural frequencies excited by the transient shocks and the modulation frequencies cause by the defect.
The ENVELOP ANALYSIS OF THE SHOCK SIGNAL

The bearing frequencies that are excited by a defect are described accordingly with the bearing geometry [7]. At the second stage of degradation, these frequencies appear in modulation of the bearing natural frequency [6].

The Fundamental Train Frequency (FTF) reveals a problem on the bearing cage and appears usually in modulation of other bearing frequencies. It is close to 40% of the rotor angular speed. Eq. (8) is only true if the outer race is fixed.

\[
FTF = \frac{\omega}{2} \left(1 - \frac{Bd \cos \theta}{Pd}\right)
\]  

(8)

where Bd is the ball diameter; Pd, the diametral pitch; \(\theta\), the contact angle; and \(\omega\), the rotor angular speed.

The Ball Pass Frequency on Outer race (BPFO) and the Ball Pass Frequency on Inner race (BPFI) appears with their harmonics when a defect develops on outer or inner race respectively.

\[
BPFO = \frac{Nb}{2} \left(1 - \frac{Bd}{Pd} \cos \theta\right) \times \omega
\]  

(9)

\[
BPFI = \frac{Nb}{2} \left(1 + \frac{Bd}{Pd} \cos \theta\right) \times \omega
\]  

(10)

The Ball Spin Frequency (BSF) reveals a defect on the balls. A defect on balls will excite 2BSF, since it strikes the inner race and the outer race in the same revolution.

\[
BSF = \frac{Pd}{2Bd} \left(1 - \left(\frac{Bd}{Pd} \cos \theta\right)^2\right) \times \omega
\]  

These modulation frequencies can be easily identified from an envelope analysis or Hilbert transform [9]. The envelope analysis (also called amplitude demodulation) converts the modulation in amplitude or phase from a high frequency range to a low frequency range.

Fig. 7 shows an example of an envelope analysis performed on the shock signal of Fig.4 for a defect of 0.56 mm on the inner race.

The presence of the Ball Pass Frequency Inner race (BPFI) and one of its 2\textsuperscript{nd} harmonic in the shock spectrum indicate that the shocks are caused by a small defect on the inner race of the rolling-element bearing. The results obtained by this technique are less influenced by noise and interfering harmonics, which is very desirable when the signal-to-noise ratio is small.
the contribution of the shocks, after having removed all the
other components in the signal. A practical application is
presented in order to illustrate its use and efficiency in
diagnosis a defective rolling-element bearing. It is seen that
this new tool provides an estimate of the severity of damage
by comparing the shock signal from the original one.
Furthermore the STFT of the shock signal reveal the natural
frequencies of the system that are excited and an envelope
analysis around the natural frequency range reveal the
modulation frequencies that are characteristics of the source of
damage.

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