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ARTICLE

ROLLING ELEMENT BEARING SPALL DETECTION AND DIAGNOSIS USING A SIMPLIFIED APPROACH

Nader Sawalhi*

Department of Mechanical Engineering, Prince Mohammad Bin Fahd University, SAUDI ARABIA

ABSTRACT

In recent years a number of advanced algorithms and techniques for diagnosing localized faults in rolling element bearings have been developed. These proposed algorithms and techniques are, in general, highly mathematically based and require a signal processing expert to understand the steps involved in this processing. In this paper a simple and effective surveillance and diagnosis means for detecting a defective component in a rolling element bearing from the measured vibration signal is presented. The approach is based on applying a smoothening filter to the absolute values of a first or higher derivative of the vibration signal before transforming it to the frequency domain to inspect its content. This gives a very useful first measure for detecting localized faults in rolling element bearings, without much complexity. This paper serves the purpose of presenting the algorithm and more work is being undertaken to expand the number of tested signals and compare it with highly developed algorithms in complex situations.

KEY WORDS
Bearings, Diagnosis, Spalls, Simplified Approach

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***Corresponding Author**
Email: nsawalhi@pmu.edu.sa
Tel.: +966 13849 9795
Fax: +966 13 896 4566

INTRODUCTION

Rolling element bearings (REBs) are main components in almost all rotary machines. Monitoring their health and preventing their failure is crucial for machines reliability and safety. REBs fail in a number of modes such as excessive loading, brinelling, overheating, lubricant failure, contamination, fatigue, etc. Fatigue failure results in spalls (pitting) which starts as localized faults and extends to become a distributed fault. When measuring the vibration signal from a defective bearing using an accelerometer, the signal contains a series of pseudo periodic (second order cyclostationary) bursts, which tend to excite natural frequencies of the structure [1]. The bursts are spaced at the frequency at which the ball passes over the defect (ball pass frequency: inner race, outer race or ball). Bearing fault bursts are normally weak, in particular for incipient faults, and are masked in the low frequency region by the presence of deterministic components and noise from other components in the system such as gears, blades, unbalance, misalignment, electrical noise, etc. Experimental ball pass frequencies are 1-2 % in deviation from the theoretical calculated frequencies due to the slippage of the rolling elements as a result of the variation of the load angle [2]. Slippage in rolling element bearings causes a fluctuation (smearing) in the defect frequencies and the direct detection using frequency analysis (raw Spectrum of the measured vibration signal) becomes difficult. For this a technique known as envelope analysis [2 and 3] is used for fault diagnosis. Envelope analysis is the basis of fault diagnosis in rolling element bearings. It was first introduced in 1974 by Mechanical Technology Inc. [3]. This technique was originally known as "*the high frequency resonance technique*" (HFRT), and is now denoted by other names such as "*amplitude demodulation*", "*demodulated resonance analysis*", "*narrow band envelope analysis*" or only as "*envelope analysis*".

Localized defect in a rolling element bearing will result in an impulse response each it is in contact (under load) with another surface. These impulses will have an extremely short duration compared to the interval between them, and so their energy will be distributed across a very wide frequency range. The result is that various resonances of the bearing and the surrounding structure will be excited by the impacts. The essence of the HFRT is to perform an amplitude demodulation over an excited band and to calculate the frequency of the enveloped demodulated signal. This used to be carried out classically using an analogue circuit to band-pass filter the analogue vibration signal around a structural resonance (defined by spectrum comparisons) and then to use full or half wave rectification followed by a smoothing circuit to recover the approximate envelope signal. Recently [2] a digital approach for envelope analysis using the Hilbert transform has been proposed by Ho and Randall. In order to improve the detectability of bearing faults, signal pre-processing is usually carried out to separate the bearing signal from other deterministic components, which mask the bearing effect. The separation is possible by a number of algorithms such as angular resampling and synchronous average, discrete random separation (DRS), Autoregressive models, etc. [4]). To select the best band for amplitude, the power spectrum density of the defective signal is usually compared with the healthy signal and the band of the highest dB difference is selected as the optimum band. In the recent advances in bearing diagnosis, a number of auto-band selection methods have been proposed. Among these are the Kurtogram [5] and the Protrugram [6]. A comprehensive tutorial on a number of the start of art technique has been published recently by Antoni and Randall [1].

In this paper, a simple, effective and easy to use envelop analysis is proposed to enable detecting the presence of spalls in bearing and diagnose the source of these faults. The proposed algorithm is tested on a signal from a defective inner race bearing measured from a single stage gearbox. The paper is organized as follows. After this interlocutory section, the processing algorithm is presented in the next section. This is followed by the results section and conclusions. It is worth mentioning here that this paper introduces the basics of the algorithm and shows its successes on one case. Further work will be carried out to set criteria

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selection, expand the testing base with more complex signal and compare the results of this algorithm to established well accepted algorithms.

PROCESSING ALGORITHM

The proposed algorithm encompasses three main operations to obtain an envelope spectrum for bearing diagnosis. The processing flow is presented in [Fig. 1]. The first step of processing involves *whitening the signal using signal differencing* (signal differentiation). The second step is done simple by *taking the absolute value of the differentiated signal and smoothen it* using a smoothing filter. The third step is done by *performing a Fast Fourier transform* (FFT) to obtain the spectrum.

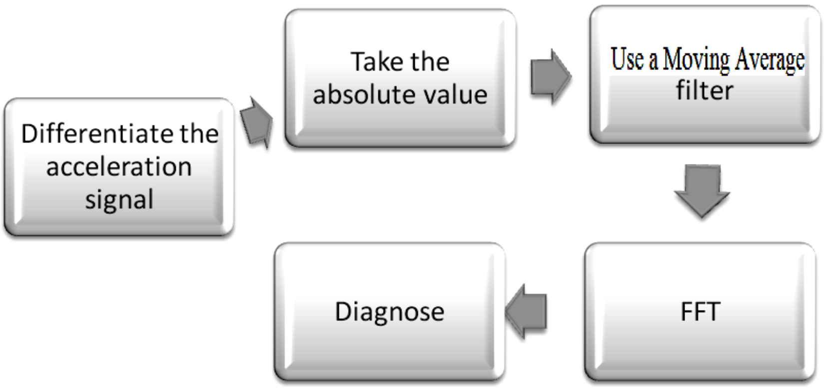

Fig. 1: Schematic presentation of the steps of the proposed simple envelope analysis.

In this proposed simple the band-pass filter around the structural resonance is replaced by differentiating the signal, which acts as a high pass filter. The full/half wave rectification is the process of taking the absolute values of the differenced signal. The smoothing circuit is replaced by a moving average filter, which acts as a low pass filter. The proposed procedure is quite simple, quick and easy to use. It utilizes basic functions and requires minimal parameters. [Fig. 1] shows a schematic presentation of the steps of the proposed simple envelope analysis.

Signal differencing

For a digitized signal, differencing (differentiation) refers simply to the process of taking the difference between two consecutive samples. In ref [7], it is shown that for a time series of length n: $x_1, x_2, x_1, x_2, \ldots\ldots x_n$

First differencing (∇) as can be seen from (1), leads to a series of length n-1 such that:

$$\nabla x_i = x_i - x_{i-1} \cdots i = 2:n \tag{1}$$

First-differencing has the effect of removing the linear trend from the series and thus reduces the correlation between the samples.

Signal differencing can then be thought of as a “high-pass filtering" for the time series; as it passes and enhances the high frequency variations and attenuates those low-frequencies. In ref [8][14], the first differencing has been recognized as the residual of an Autoregressive (AR) process of an order 1 (AR (1). Sawalhi and Randall [9] showed that signal differencing and in particular the 4th derivative was found to give the highest kurtosis and clarity of detecting impulses. Bozchalooi and Liang [10] give a very detailed analysis and description to the enhancement of the signal to interference ratio (SIR) that can be obtained by the successive differentiations of the vibration signal in the case of detecting faults in rolling element bearings. They proposed a differentiation method to enhance the fault delectability. It is reported that the iterative application of a differentiation step can enhance the relative strength of the impulsive faulty bearing signal component with respect to the vibration interferences. This has the effect of preserving the effectiveness of amplitude demodulation and hence leads to more accurate fault detection. As a means to decide on the number of optimum number of differentiations, the percentage of kurtosis increase between one differentiation process and the other can be used as a guide; as the ultimate aim is to enhance the impulsiveness of the signal and to enhance the detection ability of impacts in the high frequency region.

Moving average smoothening filter

As the importance of detecting the faulty component in a bearing resides in finding the periodicity/frequency of the impulses, rather than the impulse high frequency content, it is recommended to low pass filter the enveloped signal (absolute value of the high pass filtered signal, which was found by the differencing method). This can be achieved simply through a smoothing (Moving average filter). A moving average (MA) filter [11][13] in the simplest means implies replacing of each sample in the time domain by an average value of *M samples*. As the length of the filter (*M*) increases, the signal becomes smoother and the sharp events are reduced. Thus, it is usually considered as a good filter in the time domain, but not in the frequency domain. Smoothing is the opposite of the differencing/whitening process; as it removes the high frequency content of the signal rather than the low frequency variation. Smoothing can be achieved by setting a moving average window of a certain length (*M samples*), where the values of the new series represent the averaging of the *M* samples. In the simplest case (samples), this process gives a series (2):

$$Y(i) = \frac{1}{M} \sum_{j=0}^{M-1} x[i+j] \quad (2)$$

where:

x :Absolute values of differenced signal
Y: Smoothened signal
M: Filter length

The order of the smoothing process can be guided by the average length (duration) of the enveloped impulses, which can be examined visually to make this decision. This is discussed in the experimental results to set an example.

RESULTS

The vibration signal collected from a single stage gearbox (spur gear) [12] with a defective (seeded fault) inner race bearing has been used to illustrate the effectiveness of the processing algorithm discussed in the previous section. The gearbox was run at 10 Hz and under a torque of 50 Nm. An accelerometer was placed on the top of a defective bearing and vibration signal was collected at a sampling rate of 48 kHz. The theoretical ball pass frequency of the inner race (BPFI) was estimated at 71.2 Hz. The raw time domain signal and its frequency content (resolution of 5.86 Hz/line) are presented in [Fig. 2].

The third and twentieth derivatives are plotted in [Fig. 3(b)] and [Fig. 3(c)] respectively and compared to the raw signal [Fig. 3(a)]. The fault impacts can be seen clearly in the differentiated signals. No further advantage was recorded when using the higher order.

In [Fig. 4(a)], the absolute value of the third derivative is plotted. The Moving average filter used to smoothen the envelope signal was based on 100 samples (i.e. half the duration of the impulse response), The result of smoothening the envelope is plotted in [Fig. 4(b)] where the low pass effect can be seen clearly Finally the spectrum (envelope spectrum) of the signal presented in [Fig. 4(b)] was obtained and is presented in [Fig .5]. The envelope spectrum shows the harmonics of 71.04 Hz, which is the ball, pass frequency of the inner race (BPFI). The modulation by the shaft speed is not clear, which may be the case when the load on the bearing is small.

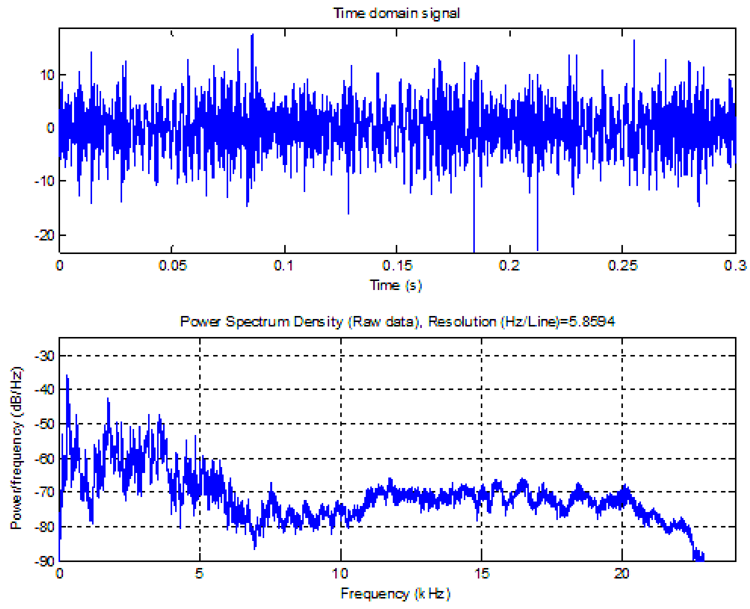

Fig. 2: Top: Raw time domain signal (0.3 seconds, which correspond to 3 shaft rotations). Bottom: Power Spectrum density.

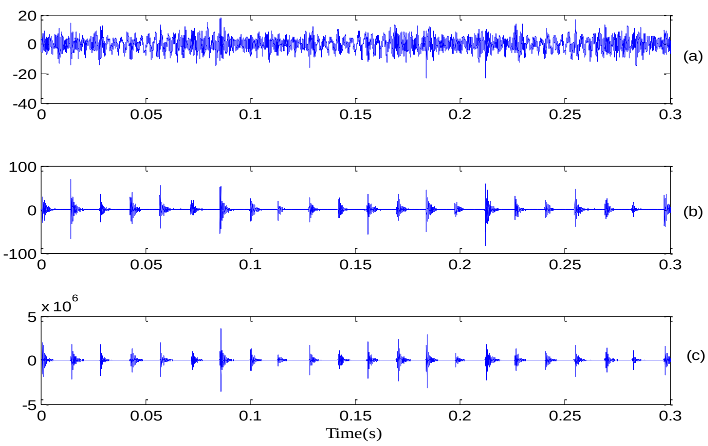

Fig. 3: (a) Raw signal (b) Third differentiation (c) twentieth differentiation.

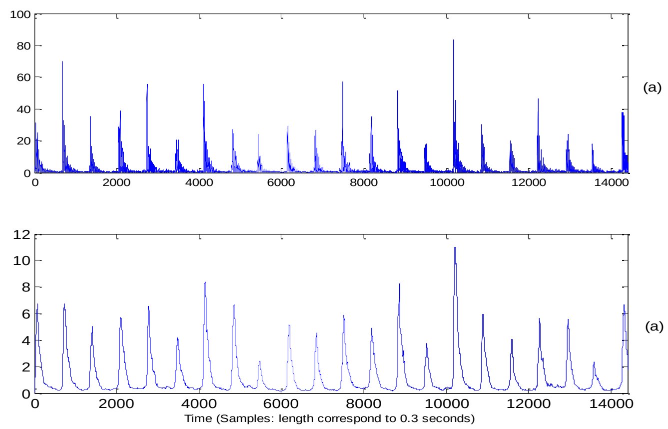

Fig. 4: Top: Enveloped (Absolute value) of signal 6.b. Bottom: after using a median filter of order 100.

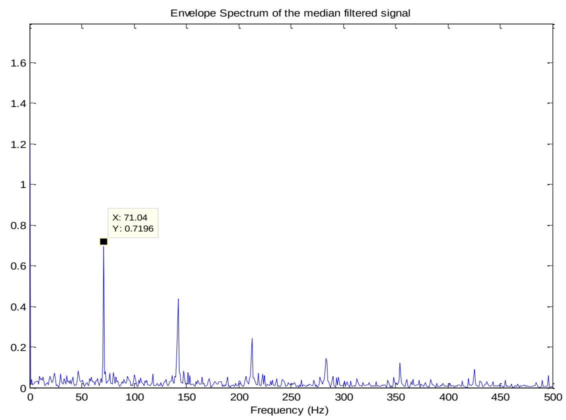

Fig. 5: Envelope spectrum.

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CONCLUSION

This paper discusses the use of signal differencing and Moving average filtration as a simple means of obtaining the envelope spectrum for the purpose of detecting and diagnosing the presence of a localized fault in rolling element bearings. It has been shown, using an example from a faulty bearing of a single stage gearbox, that this method is quite simple to use and requires a minimal intervention from the analyst. This paper serves the purpose of presenting the algorithm and more work is being undertaken to expand the number of tested signals and compare it with highly developed algorithms in complex situations.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this paper.

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