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The Autogram: An effective approach for selecting the optimal demodulation band in rolling element bearings diagnosis

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ABSTRACT

Envelope analysis is one of the most advantageous methods for rolling element bearing diagnostics but finding a suitable frequency band for demodulation has been a substantial challenge for a long time. Introduction of the Spectral Kurtosis (SK) and Kurtogram mostly solved this problem but in situations where signal to noise ratio is very low or in presence of non-Gaussian noise these methods will fail. This major drawback may noticeably decrease their effectiveness and goal of this paper is to overcome this problem. Vibration signals from rolling element bearings exhibit high levels of second-order cyclostationarity, especially in the presence of localized faults. The autocovariance function of a 2nd order cyclostationary signal is periodic and the proposed method, named Autogram, takes advantage of this property to enhance the conventional Kurtogram. The method computes the kurtosis of the unbiased Autocorrelation (AC) of the squared envelope of the demodulated signal, rather than the kurtosis of the filtered time signal. Moreover, to take advantage of unique features of the lower and upper portions of the AC, two modified forms of kurtosis are introduced and the resulting colormaps are called Upper and Lower Autogram. In addition, a thresholding method is also proposed to enhance the quality of the frequency spectrum analysis. A new indicator, Combined Squared Envelope Spectrum, is employed to consider all the frequency bands with valuable diagnostic information and to improve the fault detectability of the Autogram. The proposed method is tested on experimental data and compared with literature results so to assess its performances in rolling element bearing diagnostics.

1. Introduction

Rolling Element Bearings (REBs) are one of the most used elements in rotating machinery and their failure is the most important cause of machinery breakdowns [1]. Thus, correctly detecting and diagnosing bearing faults at stages prior to their complete failure is of vital importance. It avoids potential catastrophic damage not only to the apparatus but also to the personnel.

As a localized defect develops, either on an inner race, an outer race or a roller part of a bearing, an impact is generated each time the defect is engaged. Consequently, the bearing and the machine structure are excited, in particular at their resonance frequencies [2]. The corresponding vibration signal will comprise all the harmonics of this impact, which repeats almost periodically at a rate dependent on bearing geometry. Investigation of the generated vibrations is indispensable to detect the faults and many methods have been developed to extract the bearing characteristic frequencies from the

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Nomenclature

AC	unbiased Autocorrelation
BPFI	Ballpass Frequency Inner Race
BPFO	Ballpass Frequency Outer Race
BSF	Ball Spin Frequency
CMS	Cyclic Modulation Spectrum
CPU	Central Processing Unit
CSA	Cyclic Spectral Analysis
CSES	Combined Squared Envelope Spectrum
CWRU	Case Western Reserve University
EES	Enhanced Envelope Spectrum
FF	Fundamental Frequency
FK	Fast Kurtogram
FP	Fundamental Period
GCD	Greatest Common Divisor
LCM	Least Common Multiple
MODWPT	Maximal Overlap Discrete Wavelet Packet Transform
REB	Rolling Element Bearing
SC	Spectral Correlation
SES	Squared Envelope Spectrum
SK	Spectral Kurtosis
SNR	Signal to Noise Ratio
STFT	Short-Time Fourier Transform
WPT	Wavelet Packet Transform

measured vibrations. Among them, envelope analysis [2,3], also called high frequency resonance technique, has been used successfully for a long time: a signal is first bandpass filtered in the excited structural resonance frequency band, and then the spectrum of the envelope signal -which contains the desired diagnostic frequencies- is formed. The main challenge has always been finding the most suitable frequency band for demodulation.

Spectral Kurtosis (SK) has been a significant step to unravel this problem. It is a method which effectively detects the sequence of impulses in a signal and can be used to determine the proper demodulation frequency band in which a signal has the maximum impulsivity.

Antoni proposed two methods to calculate the SK, one based on Short-Time Fourier Transform (STFT) [4] and another one based on filter banks [5]. In the STFT based SK, the aim is to find the central frequency f and the window length N_w which maximize the value of the SK over all possible choices. A colured 2D map called Kurtogram displays the values of SK for each couple f and N_w. Antoni [5] also developed the Fast Kurtogram (FK), which is based on the multirate filter-bank structure (MFB) to overcome the rigorous but long computation of full Kurtogram. The method is numerically very efficient and suitable for industrial applications, giving almost the same result as the other one. The improved Kurtogram was further proposed by Lei et al. [6] in which the Wavelet Packet Transform (WPT) is adopted to exploit its good capacity in detection of transients from a noisy signal.

Barszcz and Jablonski [7] argue that, when a signal contains relatively strong non-Gaussian noise such as large impulses, the temporal based kurtosis indicator of Kurtogram would fail as the value of kurtosis, in general, decreases when the transients repetition rate increases. To overcome this drawback, they consequently propose Protrugram, where the kurtosis of the envelope spectrum is displayed, instead of kurtosis of the filtered time signal. However, their proposed method uses a fix demodulation bandwidth and therefore, unlike SK, is not blind and prior knowledge about the defect frequencies is needed. Enhanced Kurtogram was proposed by Wang et al. [8] in which, similar to Protrugram, kurtosis of envelope spectrum of the filtered signal is employed as an indication of faults presence. Nonetheless, both Protrugram and Enhanced Kurtogram may fail when defect frequencies are not dominant in the spectrum in comparison to discrete components generated by other sources such as shaft frequency. To capture the signature of repetitive transients in both time and frequency domains, Antoni [9] proposed the infogram which combines the concepts of the Kurtogram and Protrugram. In this case, kurtosis is replaced by negentropy, time and frequency domains infograms share the same units and are therefore additive. A review and compendium of more research on the SK theories can be found in Ref. [10].

Cyclic Spectral Analysis (CSA) provides a different family of REBs diagnosis techniques which represent a signal in a bi-spectral map, with carrier and modulation frequencies. It has been brought to the field of diagnostics of mechanical systems by Antoni [11,12] but it did not get the attention it deserves due to, presumably, its advanced theory and high computational cost. Spectral Correlation (SC) [12] and Cyclic Modulation Spectrum (CMS) [13] are two key approaches for CSA. The latter was introduced as a computationally efficient alternative to SC but this advantage is lessened by its inferior statistical properties. The link between SC and CMS, i.e. the estimation of SC by using CMS algorithm, was presented by Ref. [14].