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Rolling element bearing fault diagnosis based on Over-Complete rational dilation wavelet transform and auto-correlation of analytic energy operator

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ABSTRACT

Local damage in rolling element bearings usually generates periodic impulses in vibration signals. The severity, repetition frequency and the fault excited resonance zone by these impulses are the key indicators for diagnosing bearing faults. In this paper, a methodology based on over complete rational dilation wavelet transform (ORDWT) is proposed, as it enjoys a good shift invariance. ORDWT offers flexibility in partitioning the frequency spectrum to generate a number of subbands (filters) with diverse bandwidths. The selection of the optimal filter that perfectly overlaps with the bearing fault excited resonance zone is based on the maximization of a proposed impulse detection measure "Temporal energy operated auto correlated kurtosis". The proposed indicator is robust and consistent in evaluating the impulsiveness of fault signals in presence of interfering vibration such as heavy background noise or sporadic shocks unrelated to the fault or normal operation. The structure of the proposed indicator enables it to be sensitive to fault severity. For enhanced fault classification, an autocorrelation of the energy time series of the signal filtered through the optimal subband is proposed. The application of the proposed methodology is validated on simulated and experimental data. The study shows that the performance of the proposed technique is more robust and consistent in comparison to the original fast kurtogram and wavelet kurtogram.

1. Introduction

Most of the modern world machines and equipments employed in various fields of industries consist of rotary components which are majorly supported on rolling element bearings. Over a period of time due to wear and tear faults may develop in bearings which may cause malfunctions, failure and may even lead to catastrophic failure of the machinery. Hence, it is necessary to detect bearing faults at an early stage. Bearing defect at an early stage implies a defect that has developed slowly due to wearing out of a component, which are represented by drift type changes [1].

Abbreviations: AC, autocorrelation coefficient; BDF, ball defect frequency; HFRT, high frequency resonance technique; EO, energy operator; FFT, fast Fourier transform; FK, fast kurtogram; IRDF, inner race defect frequency; MRFB, multi rate filter bank; ORDF, outer race defect frequency; ORDWT, over complete rational dilation wavelet transform; SNR, Signal to noise ratio; SK, spectral kurtosis; STFT, short time Fourier transform; TEO-AK, temporal energy operated auto correlated kurtosis; WK, wavelet kurtogram; WPD, wavelet packet decomposition.

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Nomenclature

A	amplitude of a signal
$A(t)$	instantaneous amplitude of a signal
$d_i(n)$	coefficients of ORDWT decomposition
d_o	magnitude of the impulse or amplitude level of defect
$d(t)$	impulse function
D_i	ith reconstructed ORDWT subband
E	energy of the system
$E(D_i)$	energy of the ith reconstructed ORDWT subband
f	frequency
f_{inner}	characteristic inner race defect frequency
f_{outer}	characteristic outer race defect frequency
f_{ball}	characteristic ball defect frequency
f_s	shaft rotational frequency
$G(\omega)$	high pass filter
$G_1(\omega)$	modified high pass filter
$h(t)$	harmonic interference signal
$H(\omega)$	low pass filter
$\overline{H}(\omega)$	modified low pass filter
k	stiffness of the system
m	mass of the system
$n(t)$	white gaussian noise
N_{ft}	probable data points gap between two consecutive fault impacts
p	controlling parameter of ORDWT
q	controlling parameter of ORDWT
$q_o(t)$	applied radial load on the shaft
$R_{xx}(\tau)$	autocorrelation of a signal
s	controlling parameter of ORDWT
T_d	reciprocal of corresponding bearing defect frequency
T_{do}	modified T_d to account for speed variation
$x(t)$	vibration signal in time domain
$\delta(t)$	dirac delta function
ε	load distribution factor
$\psi(\cdot)$	analytic energy operator
σ_n	noise variance level
$\theta_{\max}$	angle limiting the load zone

Different signal processing techniques have been extensively investigated by researchers in the past to carry out accurate fault diagnosis of rolling element bearings. Among them high frequency resonance technique (HFRT) has proved to be an effective and widely used tool to tackle this problem. HFRT filters out the bearing fault excited high-frequency resonance zone from the vibration signal; thereby minimizing the effects of noise and interfering signals from other machinery components. However, proper selection of central frequency and bandwidth of the bandpass filter poses to be a major challenge in the application of this method.

Spectral kurtosis (SK) has been recently proposed and successfully applied to the fault detection of rolling element bearing [2]. Antoni and Randall [3] investigated the mathematical insights of SK and developed a method for the detection of resonance zone in the frequency spectrum of the fault signal. The identified resonance band in which the signal is demodulated helps to extract the bearing characteristic defect frequencies. For determination of the optimal band pass filter parameters for signal demodulation, Antoni [4] proposed two methods based on: (1) short time Fourier transform (STFT) and (2) multi rate filter banks (MRFB). In STFT based method, a concept known as Kurtogram was introduced, which presents SK values in a 2D grid as a function of the central frequency and the bandwidth of the filtered signal. However, online practical implementation of this tool is computationally expensive, as a large number of window lengths need to be examined for its implementation. Hence, Antoni [4] proposed a Fast Kurtogram (FK) based on MRFBs, which investigated a few selected bandwidths to obtain the Kurtogram to reduce the enormous computation cost present in STFT based method. However, a few drawbacks hamper the performance of FK. Hence, improvements and advances in FK have attracted a great deal of attention recently.

Lei et al. [5] pointed out that the Kurtogram based on STFT or FIR filters, limit their performance in extracting transient characteristics from a noisy signal and hence used filters based on wavelet packet decomposition (WPD). Barszcz and Jabłoński [6] proposed a novel fault frequency band determination method called the Protrugram, which calculated