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ROLLER ELEMENT BEARING FAULT DETECTION AND DIAGNOSIS BASED ON AN OPTIMISED ENVELOPE ANALYSIS

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ABSTRACT

The rolling element bearing is a key part in many mechanical facilities and the diagnosis of its faults is very important in the field of machinery health monitoring for safe and efficient operations. Currently, envelope analysis is widely used to obtain the bearing defect harmonics from the envelope signal spectrum for the detection and diagnosis and has shown good results in identifying incipient faults occurring on the different parts of a bearing. However, a critical step in implementing envelope analysis is to determine a frequency band that contains faulty bearing signal component with highest signal to noise. Conventionally, the choice of the band is made by manual spectrum comparison via identifying the resonance frequency where the largest change occurred. This paper presents a spectral kurtosis (SK) based method to determine optimum envelope analysis parameters including the filtering band and centre frequency through a short time Fourier transform (STFT). The results show that the maximum amplitude of the kurtogram provides the optimal parameters for band pass filter which allows both small outer race fault and large inner race fault to be determined from optimised envelope spectrum.

Keywords: Bearing faults, Envelope analysis, Spectral kurtosis, Kurtogram.

INTRODUCTION

Rolling element bearings are at the heart of almost every rotating machine. Therefore, they have received a lot of attention in the field of vibration analysis as they represent a common source of faults, which can be detected at early stage to avoid the machine catastrophic failure, financial cost and personal injuries [1, 2].

For rolling element bearings, an impulse is generated when the defect rolling elements make a contact with another surface. This impulse has an extremely short duration compared to the interval between the pulses. The energy from the defect pulse will be distributed at a very low level over a wide range of frequencies. It is this wide distribution of energy that makes bearing defects so difficult to detect by conventional spectrum analysis when they are in the presence of vibrations from bearing and other machine components. The impact usually excites a resonance in the system at a much higher frequency than the vibration generated by the other components [1-4].

Vibration based envelope analysis is considered as the most common method for monitoring bearing faults. However, this technique involves complicated operations such as fast Fourier transforms and digital filter. The successful implementation of the envelope analysis is depending on proper selection of the central frequency and window length of the band pass filter [2]. Ho et al. [1] describes two methods of performing the envelope analysis digitally using Hilbert technique and band pass rectification.

The conventional band pass filter parameters proposed by McFadden et al. [2] where centre frequency should be selected to match with the structure resonance frequency. The bandwidth should be at least double the highest characteristic defect frequency to ensure that the filter will pass the carrier frequency and at least one pair of modulation sidebands.

The filtered signal is then processed by an envelope analysis, which consists of a half wave or full wave rectification followed by peak hold (smoothing circuits) to recover the approximate envelope signal [1, 3, 4].

Sawalhi et al. [4] as well as Yu et al. [5] mentioned the limitation of envelope analysis where the central frequency (structural resonance) and the bandwidth of the filter are based on the existence of historical data and on the experience of the user. Recently, researchers have employed time-frequency analysis combined with the use of different statistical criteria in order to automate the envelope analysis.

Spectral kurtosis represents an effective and important tool in this regard as it builds on locating the bands with high amount of impulsive. SK is potentially useful for determining the frequency bands dominated by the bearing fault signals, usually containing resonance frequencies excited by the faults. This information is required in order to choose the optimum frequency band to perform envelope analysis [4, 6].

SK provides a means of determining which frequency bands contain a signal of maximum impulsively, it was first used in the 1980s based on short time Fourier transform (STFT) and give a measure of the signal impulsiveness as function of frequency [7]. The application of SK to rolling element bearings and gear surveillance has been studied through the use of simulated and actual signals [8, 9].
Antoni et al. [9, 10] proposed a definition and an application of STFT based spectral kurtosis for non-stationary processes. The selection of the best window for the STFT analysis and thus optimising the STFT based SK has been achieved by the use of the Kurtogram [9].

THE CHARACTERISATION OF ROLLING BEARING SIGNALS

The key to fault diagnosis of a rolling element bearing is to capture the special symptoms arising from their faults. Moreover, measured signal $y(t)$ is a mixture of fault signal $x(t)$ and some strong additive noise $n(t)$:

$$y(t) = x(t) + n(t) \tag{1}$$

Incipient bearing faults produce a series of repetitive short transient forces, which in turn excite structural resonances. Hence, Antoni et al. [9] generalized the reasonable model for $x(t)$ as:

$$x(t) = \sum_k X_k\, h(t - \tau_k) \tag{2}$$

In equation (2), $h(t)$ is the impulse response resulting from a signal impact. $\{X_k\}$ and $\{\tau_k\}$, $k \in Z$ are sequences of random variables, which account for possibly random amplitude and random occurrence of the impact, respectively [10]. The amplitudes $\{X_k\}$ are always non-negative because the pulse only generated by positive force between components. The occurrences $\{\tau_k\}$ is caused by the random slips of the rolling elements, and the amplitudes $\{X_k\}$ indicate the time varying amplitude modulation of the impacts [6].

SPECTRAL KURTOSIS AND KURTOGRAM

The global kurtosis is a statistic parameter that quantifies the deviation of the probability density function of the historical trend of a random variable $x(t)$ from the Gaussian distribution.

$$kurt\, x(t) = \frac{\langle (x(t) - \mu)^4 \rangle}{\delta^4} - 3 \tag{3}$$

where, μ and δ are the mean and standard deviation of the signal $x(t)$ respectively.
The main idea is that the random mechanical noise follows a Gaussian distribution, that is the kurtosis of the signal is almost equal 3.0, while the presence of impact hidden in the vibration signal, change the value of kurtosis to higher values than 3.0 [11].
Antoni et al. [9] defined SK as the kurtosis computed at the output of a perfect filter bank at each frequency and then formulized the spectral kurtosis of the signal (1) as.

$$K_Y(f) = \frac{K_X(f)}{[1 + \rho(f)]^2} \tag{5}$$

where $K_X(f) > 0$ is the SK of the signal (2) and $\rho(f)$ is the noise to signal ratio. $\rho(f) = S_N(f)/S_X(f)$ where $S_N(f)$ and $S_X(f)$ donates the power spectral density of the noise and fault signal respectively.
Immovillli et al. [12] mentioned that, the values of SK are strongly dependent on the choice of the frequency resolution. For any non-stationary signal, the SK is a function that depends on frequency and frequency resolution.
Antoni et al. [9] proposed a kurtogram for selecting filtering bandwidth. It is a two dimensional representation of the signal kurtosis respective to FFT window length and frequency. The maximum of the kurtogram then can be based on to determine the central frequency and optimal bandwidth (1/window length). With sampled signal available kurtogram can be calculated by STFT with different window lengths.
Antoni [10] formalised definition of the spectral kurtosis for non-stationary signals as fourth order of time/frequency envelope of $H(t, f)$ as:

$$K_X(f, n) = \frac{\langle |X(t,f)_n|^4 \rangle}{\langle |X(t,f)_n|^2 \rangle^2} - 2 \tag{4}$$

The constant 2 (instead of 3 as in the classical kurtosis) is used to enforce $K_X(f) = 0$ in the case $X(t, f)$ is complex Gaussian. $X(t, f)_n$ is computed by TFT, n donates the window length of STFT which will be referred as N_w

TEST RIG FACILITY AND FAULT SIMULATION

The bearing vibration data was acquired from a research bearing test rig shown in Figure (1). It consists of a 3-phase electric indication motor combined with dynamic brake. The motor is connected

to the brake through 3 shafts that are connected by two pairs of matched flexible couplings. These 3 shafts are held in two bearing housings.
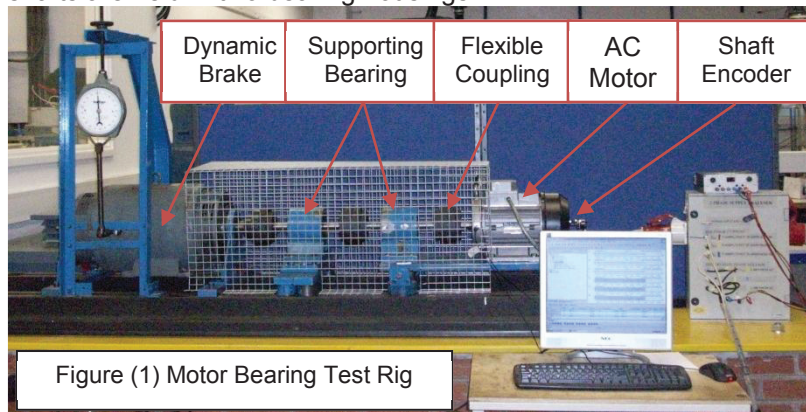

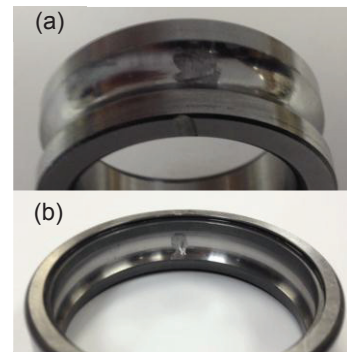Figure (1) Motor Bearing Test Rig

Figure (2): (a) Inner Race Fault
(b) Outer Race Fault

The vibration accelerometer CA-YD-181D is an IEPE transducer with frequency range 1~10000 Hz and voltage sensitivity 1.04 mv/ms^2 is mounted in the rear of the motor casing in vertical direction to collect the roller bearing vibration data. Motor bearings type (6206 ZZ) deep groove ball bearing was used in this experiment and its geometric dimensions are listed in Table (1).

Table (1) Geometric Dimensions of Deep Grove Ball Bearing

Bearing Elements	Measurement
Ball Diameter	9.53 mm
Number of Rollers	9
Contact Angle	0º
Pitch Circle Diameter	46.4 mm

The bearing faults characteristic frequencies can be determined based on equation (4) and (5) [13],

$$Ball\ Pass\ Frequency\ Inner\ Race\ (BPFI) = \frac{n\,f_r}{2}\left(1 + \frac{d}{D}\cos a\right) \qquad (4)$$

$$Ball\ Pass\ Frequency\ Outer\ Race\ (BPFO) = \frac{nf_r}{2}\left(1 - \frac{d}{D}\cos a\right) \qquad (5)$$

where, f_r is shaft rotational frequency in rad/s or Hz. d indicates ball diameter in mm. D denotes pitch circle diameter in mm. α is contact load angle from the radial plane in degrees. n is number of ball.

In this study, healthy and two faulty bearings ((a) inner race fault and (b) small outer race fault) were tested under full constant speed and four different torque loads (0%, 25%, 50%, and 75%). Each test acquired data at twenty seconds record and sampling rate of 96 kHz.

RESULTS AND DISCUSSION

Figures (3a) and (3b) show waveform of raw vibration signals from healthy and inner race fault or outer race fault bearing at four different torque loads. It can be seen that there are some impulses in fault signals compared with baseline signals. The impulses of inner race fault signals are more obvious than out race signals. But it is difficult to determine the impulse periods because of high level background noise.
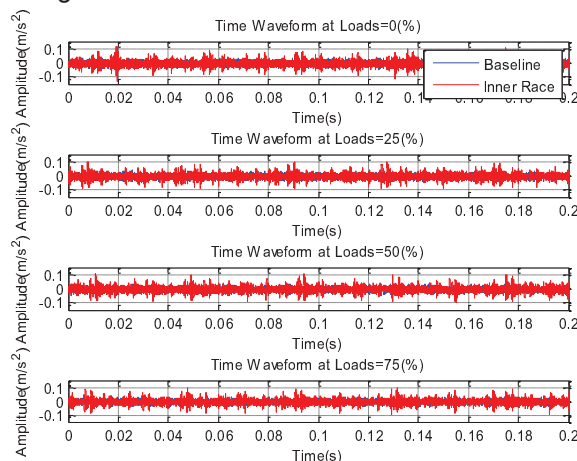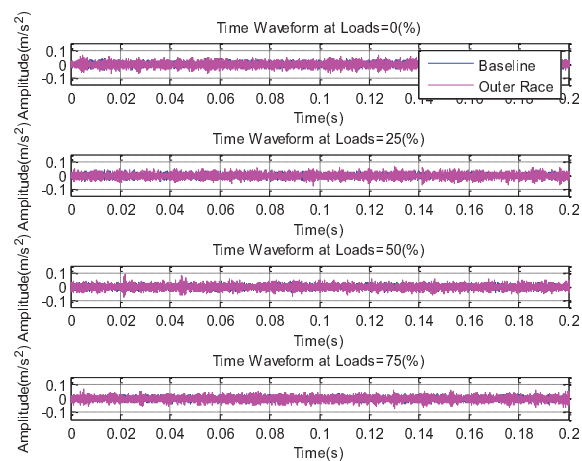

Figure (3a) Inner Race Row Signal

Figure (3b) Outer Race Row Signal

The repetitive impacts at intervals corresponding to the time interval between the rolling elements passing the point on the inner race or outer race where the faults are located. Time domain feature extraction can be done by determining statistical parameters, which provides information about overall level and the "spikiness" of the signal associated with the defect bearing.

The interaction of defects in rolling element bearings produces pulses of very short duration whenever the defect strikes the inner race or outer race of the bearing. These pulses excite the natural frequencies of bearing elements and housing structures, resulting in an increase in the vibrational energy at these high frequencies.
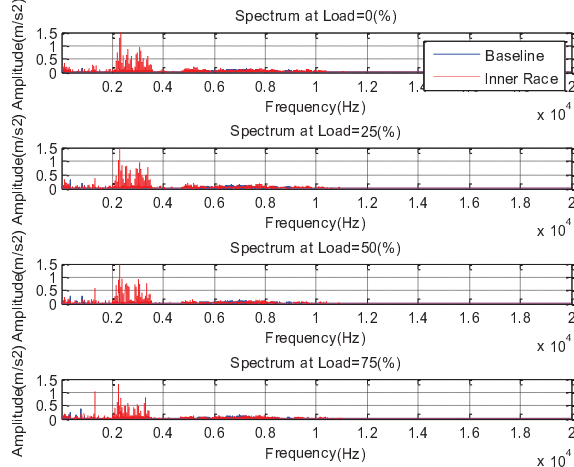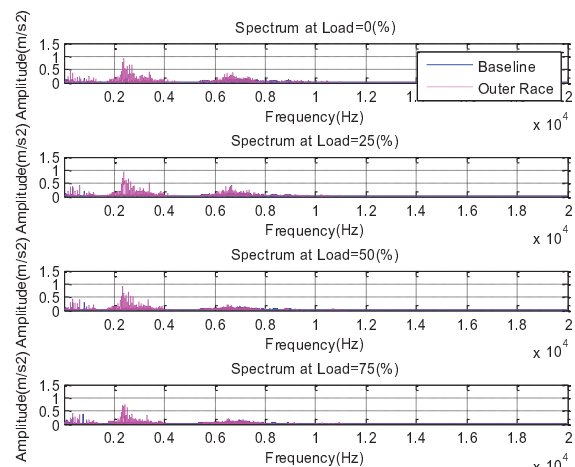

Figure (4a) Inner Race Spectrum   Figure (4b) Outer Race Spectrum

Figure (4a) and (4b) show the vibration spectra of inner race fault and outer race fault respectively in comparing with that of baseline case which has no fault induced to. The dominant peaks in the spectrum can be easily identified by the difference between the baseline and faulty spectra. The shaft rotational frequency and high order harmonics as well as system resonances can be easily identified but the characteristic fault frequencies and its harmonics are not obvious in the spectrum.

In addition, the torque load impact is inversely proportional to the speed makes slightly decrease to the shaft frequency which affects the bearing elements fault frequencies as shown in table (2).

Table (2) Bearing Faults Characteristic Frequency

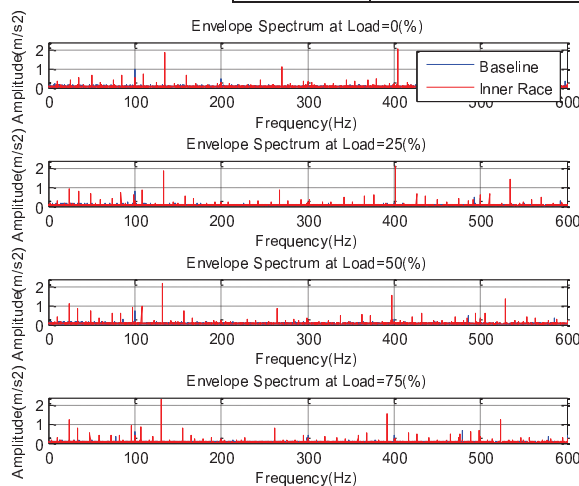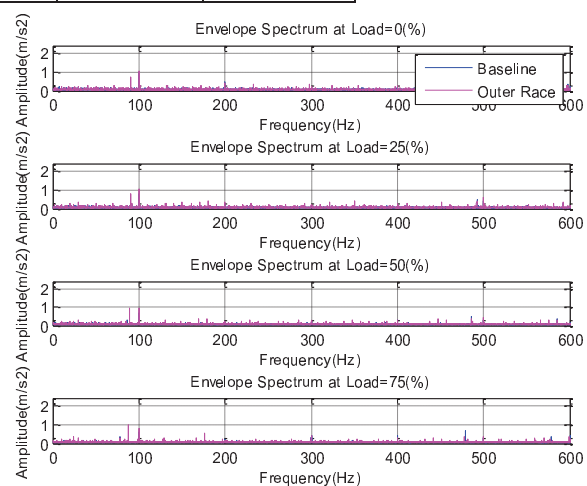| Load (%)	Shaft Frequency (Hz)	BPFI (Hz)	BPFO(Hz)
0	24.9362	135.2601	89.1657
25	24.7353	134.1703	88.4474
50	24.5034	132.9125	87.6181
75	24.2394	131.4805	86.6741

Figure (5a) Inner Race Envelope Spectrum   Figure (5b) Outer Race Envelope Spectrum

The envelope spectrum has been applied to remove the resonance frequency by using band pass filter (designed based on raw data spectrum) followed by fast Fourier transformation.

Figure (5a) and (5b) show the envelope spectrum of inner race fault and small outer race fault referring to baseline. There is clear indication of the presence for inner race fault. Furthermore, the

fault characteristic frequencies clearly indicated as well as the pair of modulation sidebands for the inner race, but there are some unwanted frequencies caused by noise appear on the spectrum. But the fault characteristic frequencies of the small outer race are not clearly obvious.

Kurtogram has been used in order to design the band bass filter, so as to maximize the kurtosis the filtered signal. Here, optimised frequency and the window length can be obtained by maximizing the STFT based SK. Figure (6a) illustrates the kurtogram of inner race fault. The maximum kurtogram is achieved at central frequency 31.69 KHz and window length 105. Hence, the optimal normalized bandwidth is 1/ window length = 1/105 = 0.00952. Moreover, Figure (6b) displays the kurtogram of small outer race fault where maximum kurtogram is obtained at central frequency 26.25KHz and window length 35, so optimal normalized bandwidth is = 1/35 = 0.028571.
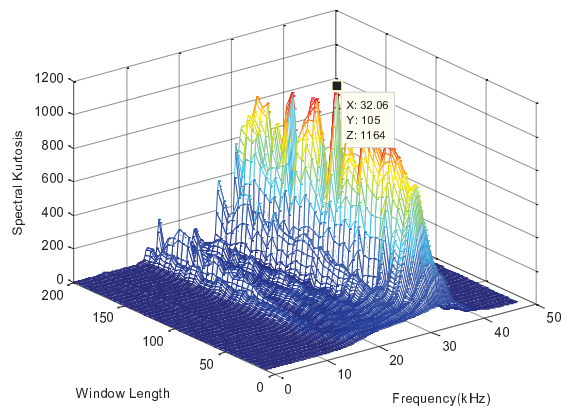

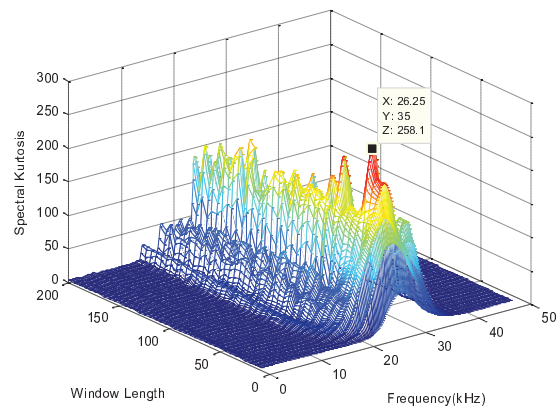Figure (6a) Inner Race Kurtogram   Figure (6b) Outer Race Kurtogram

The optimised envelope analysis based on kurtogram parameters has been applied to remove the resonance frequency by using optimal band pass filter parameters followed by fast Fourier transformation. The filter designed with the optimal central frequency and bandwidth corresponding to maximum kurtogram to improve the signal to noise ratio.
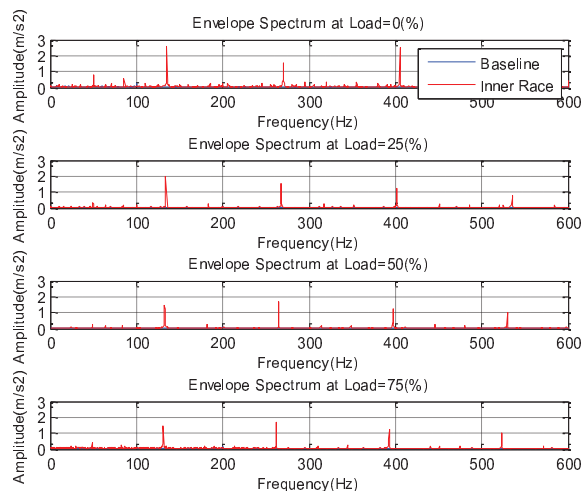

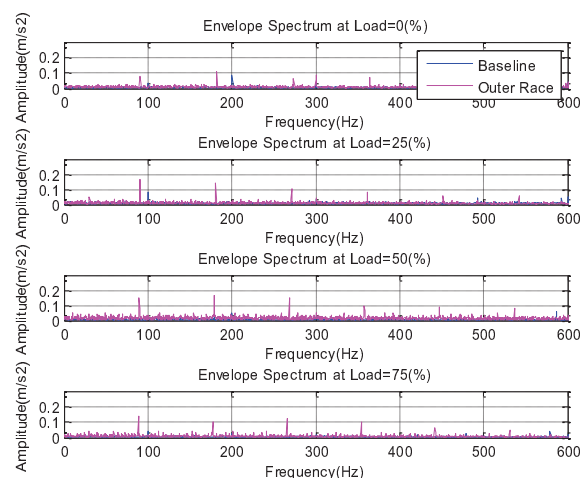
Figure (7a) Inner Race Envelope Spectrum   Figure (7b) Outer Race Envelope Spectrum

Figure (7a) gives out the envelope spectrum of the baseline and inner race fault. The characteristic fault frequencies and their harmonics are clearly visible. The envelope spectrums of the baselines are very flat with no clear spectral lines to be seen. Similar results are obtained for the small outer race fault as presented in Figure (7b). However, the amplitudes of fault frequency and its harmonics are small compared with inner race fault. From Figure (7a) and (7b), the fault frequency amplitudes of inner race are significant higher than outer race which indicates that the inner race fault is larger. This is consistent with experiment bearing conditions. Therefore, we can draw a conclusion that the optimised envelope analysis method can be implemented on ball element bearing inner race and outer race fault detection and severity diagnosis.

CONCLUSION

In this paper, an optimised envelope analysis method is studied for roller element bearing fault detection and diagnosis. The parameters of band pass filters are optimised by spectral kurtosis

because it is an effective technique to enhance impulse components. It is evaluated using data sets with different faults from bearing test rig in lab. The results show that the optimised envelope analysis method is effective for ball element bearing inner race and outer race fault detection and their fault severity diagnosis.

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