Fault Diagnosis for Centre Wear Fault of Roll Grinder Based on a Resonance Demodulation Scheme

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Abstract. Roll grinder is one of the important parts in the rolling machinery, and the grinding precision of roll surface has direct influence on the surface quality of steel strip. However, during the grinding process, the centre bears the gravity of the roll and alternating stress. Therefore, wear or spalling faults are easily observed on the centre, which will lead to an anomalous vibration of the roll grinder. In this study, a resonance demodulation scheme is proposed to detect the centre wear fault of roll grinder. Firstly, fast kurtogram method is employed to help select the sub-band filter parameters for optimal resonance demodulation. Further, the envelope spectrum are derived based on the filtered signal. Finally, two health indicators are designed to conduct the fault diagnosis for centre wear fault. The proposed scheme is assessed by analysing experimental data from a roll grinder of twenty-high rolling mill. The results show that the proposed scheme can effectively detect the centre wear fault of the roll grinder.

Keywords: fault diagnosis; wear; roll grinder; demodulation

1. Introduction

As one of the most important parts in rolling equipment, roll grinder is utilized to improve or modify the surface quality of the working roll which is used in rolling mill. However, the roll grinder usually contains multiple components, which means multiple vibration sources. Besides, it is difficult for the roll grinder to stay at a stable grinding process. Therefore, some undesirable chatter marks can be found on the roll surface, as shown in Fig. 1, which may have a direct effect on the surface quality of the steel strip [1, 2]. In roll grinder machine, the centre bears the gravity of the roll and alternating stress during grinding process. Therefore, wear or spalling fault is easily observed, which may lead to an unstable vibration and generate chatter marks on the roll surface.

Envelope analysis (*EA*) is widely used in the fault diagnosis of rotating machinery, i.e. bearings and gearboxes [3]. For instance, Yang presented a hybrid method which employed *EA* and empirical mode decomposition to detect different fault patterns of bearings [4]. Krishnappa discussed the development of several parameters based on amplitude and phase modulation method, and showed their applications in the fault diagnosis of helicopter transmissions [5]. Figlus proposed a method based on envelope spectrum for fault diagnosis of gearbox with tooth chipping and wear faults [6]. However, most times it requires the users should have a rich knowledge of the vibration signal and engineering experiences to determine the filter parameters by using the traditional *EA* demodulation method. Therefore, some scholars tried to select the parameters automatically by the application of fast kurtogram based on the principle of maximum kurtosis. This method can yield a sub-band in which the signal should be demodulated [7, 8]. Therefore, based on these techniques it is possible to detect the fault characteristic frequencies in envelope spectrum.

The rest of the paper is organized as follows. Section 2 describes the methodology structure of envelope analysis with fast kurtogram and the computing process of the proposed two health indicators. Section 3 presents the experiment system of the roll grinder. Then the effectiveness of the proposed method is validated in section 4. Conclusions are drawn in section 5.
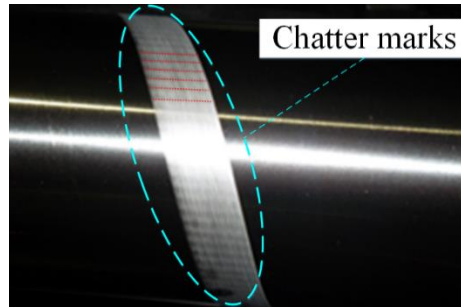

Fig. 1. Chatter marks on the roll surface

2. Methodology

2.1. A Review of the fast kurtogram

In fault diagnosis of rotating machinery, different sub-band signals carry different amount of fault-related components. Therefore, it is of significance to find the most fault-related sub-band signal for analysis. Firstly introduced by J. Antoni in Ref. [7, 8], fast kurtogram is an advanced technique based on spectral kurtosis (*SK*) that can indicate the presence of series of transients and their locations in the frequency domain through the estimation of kurtosis of each sub-band signal. The calculation of the fast kurtogram is shown in Fig. 2. Firstly signal x is decomposed into k levels through filter banks. In each level C_k^i means the ith (i=0, 1,$\cdots$, 2k-1) sub-band signal in k level and $C_0 \equiv x$ is the original signal. Then the kurtogram is estimated by computing the kurtosis of all sequences, which can be obtained by

$$K_k^i = \frac{\left\langle \left| C_k^i(n) \right|^4 \right\rangle}{\left\langle \left| C_k^i(n) \right|^2 \right\rangle^2} - 2 \tag{1}$$
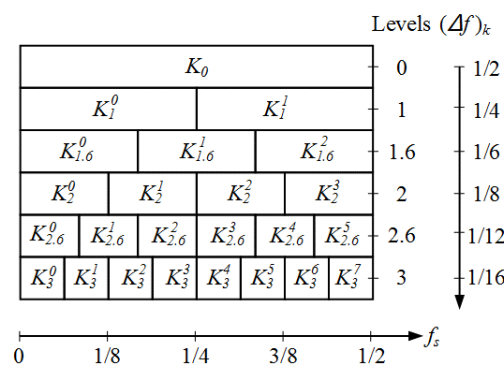

Fig. 2. Paving of the (frequency/frequency resolution) plane in the case of the 1/3-binary tree kurtogram estimator [7]

2.2. Envelope analysis (EA)

When roll fault occurs, impulsive shocks are modulated by high frequencies, i.e. resonance frequencies. This will lead to complex sidebands in frequency spectra, which increases the difficulty of fault detection. *EA* is one of the most effective demodulation techniques to detect these impulses by

removing the carrier signal. In order to derive the envelope spectrum of the time domain signal $x(t)$, Hilbert transformation is performed as

$$\hat{x}(t) = -\frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{x(t-\tau)}{\tau} d\tau \tag{2}$$

Then the analytic signal $x_a(t)$ is obtained as

$$x_a(t) = x(t) + j\hat{x}(t), \quad j = \sqrt{-1} \tag{3}$$

The envelope signal is derived by computing the magnitude of $x_a(t)$. After that the envelope spectrum can be obtained by performing fast Fourier transformation to the envelope signal.

2.3. Two health indicators

There mainly exist two problems for the detection of wear fault characteristics in the grinding process. One is the time-varying working conditions, i.e. rotating speed and grinding force. Another is that the wear fault signals are contaminated by noise as well as normal grinding signals. Therefore, traditional dimensional indicators may suffer degradation in finding the wear fault in grinding machine, i.e. root mean square (*RMS*), skewness etc. Aiming to overcome these problems, two dimensionless health indicators based on envelope spectrum are proposed: envelope spectrum kurtosis (*ESK*) and envelope spectrum entropy (*ESE*). When there is a local wear fault, some corresponding fault frequency components will be found in envelope spectrum. And the *ESK* and the *ESE* are sensitive to the change of the envelope spectrum structure. Thus they are expected to increase and decrease respectively no matter how the working conditions will be. The *ESK* and *ESE* can be obtained by

$$ESK = \frac{\sum_{m=1}^{M}(S(m)-\bar{S})^4}{M\left(\sum_{m=1}^{M}(S(m)-\bar{S})^2\right)^2} \tag{4}$$

$$ESE = -\sum_{m=1}^{M} P(m)\log_2 P(m) \tag{5}$$

where $S(m)$ is the envelope spectrum for $m=1, 2, \ldots, M$. M is the number of spectrum components. $\bar{S}$ is the mean value of $S(m)$ and $P(m) = S(m)^2 / \sum_{m=1}^{M} S(m)^2$.

2.4. Signal processing procedure

The flow chart of the fault diagnosis model is shown in Fig.3, which mainly consists of 3 stages. First of all the raw data is analysed via fast kurtogram and the most fault-related sub-band is selected. Secondly, based on the Hilbert transform and FFT the envelope spectrum of the filtered signal are obtained. Finally two health indicators: *ESK* and *ESE* are proposed for fault diagnosis of the roll grinder.
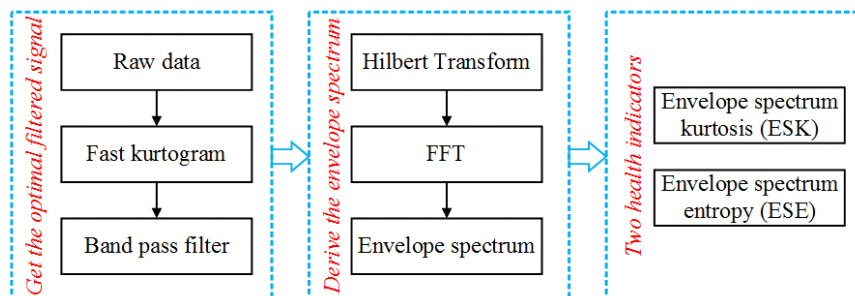

Fig. 3. Flow chart of the fault diagnosis model

3. Experiment

The experimental system consists of two parts: test bench of the roll grinder and the measurement setup, as shown in Fig. 4. The test bench is composed of headstock, tailstock, head centre, tail centre, roll, grinder, support plates and support board. It is noted that the support board will carry the roll to move around in the grinding process, and spalling fault is seeded on the tail centre. Three experiments are conducted to acquire the vibration data in normal condition and centre wear condition respectively. The grinding parameters are listed in table 1, where "*N*" and "*W*" denote normal condition and centre wear condition respectively. For the measurement setup, a PCB ICP (Integrated Circuit Piezoelectric) accelerometer is mounted on the tail centre to acquire vibration signal. NI 9234 is selected for data acquisition. The sampling frequency is chosen as 10k Hz and the signal length is 40 seconds.
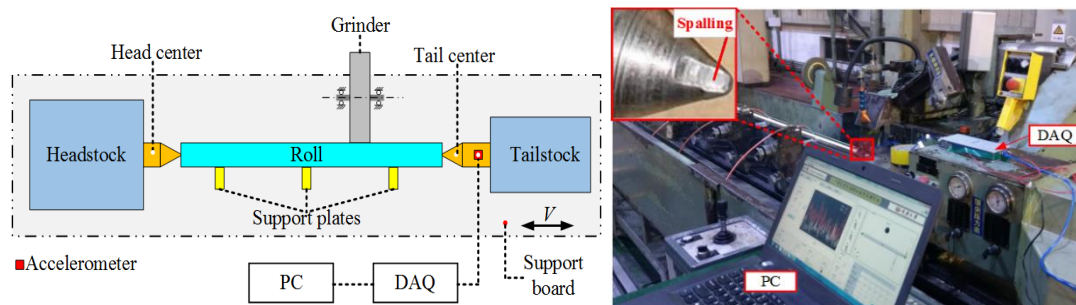

Fig. 4. Experimental system of the roll grinder.

Table 1. Grinding parameters of the 3 experiments

	Grinder speed (m/s)	Roll speed (rpm)	Support board speed (mm/min)	Grinder diameter (mm)	Roll diameter (mm)
Experiment 1	19	100	1000	394.5 (*N*) 450.9 (*W*)	59.22 (*N*) 59.87 (*W*)
Experiment 2	19	100	1000		
Experiment 3	19	110	650 (*N*)/750 (*W*)		

4. Results and discussions

In order to verify the effectiveness of the proposed method, all the datasets of the three experiments are analysed. Figure 5 shows an example of the (a) time domain signal and (b) spectrum in normal and tail centre spalling situation. In Fig. 5 (a), it can be observed that some impulsive components occur, and the time interval between two impulses is equal to the rotating period of the roll. Meanwhile, there are some differences between the normal situation and the seeded centre spalling situation as shown in Fig. 5 (b). Figure 6 shows the fast kurtogram and the envelope spectrum of the example signal. The most fault-related sub-band is selected according to kurtogram with the parameters (frequency centre=1718.75 Hz, bandwidth=312.5 Hz) as marked in Fig. 6 (a). The rotating frequency of the roll and its harmonics "f_r", "$2f_r$" and "$3f_r$" are obvious in the seeded centre spalling situation, which yield higher values than the normal situation, as shown in Fig. 6 (b).
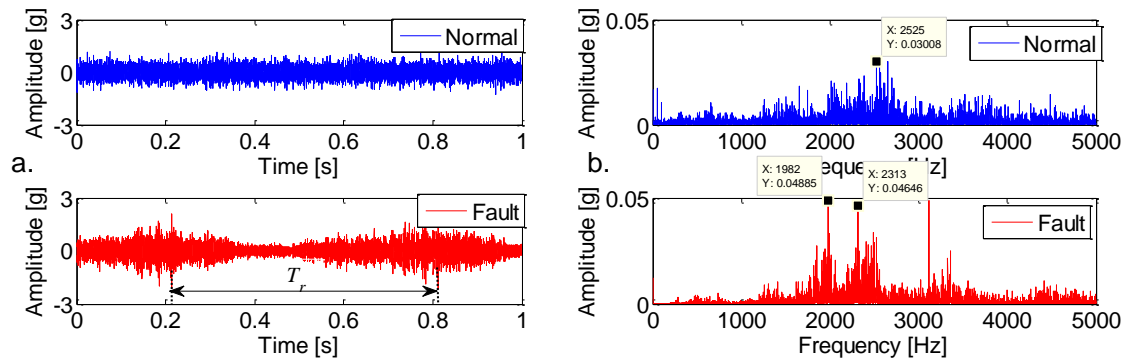
Fig. 5. An example of the (a) time domain signal and (b) spectrum in normal and tail centre spalling situation
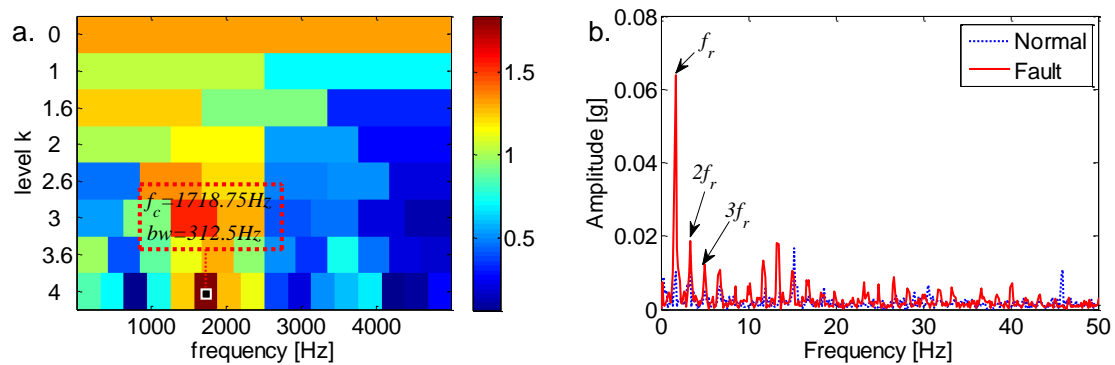

Fig. 6. (a) Fast kurtogram and (b) envelope spectrum of the example signal

Figure 7 to Fig. 9 illustrate two health indicators' plots of the three experiments. The x axis is the feature number and y axis is the amplitude. The dataset in each experiment is divided into 8 segments uniformly. It can be observed that the *ESK* of the vibration signal in seeded centre spalling situation always yields higher value than normal situation, as shown in Fig. 7 (a), Fig. 8 (a) and Fig. 9 (a), while the *ESE* of the vibration signal in seeded centre spalling situation always yields lower value than normal situation, as shown in Fig. 7 (b), Fig. 8 (b) and Fig. 9 (b). Conclusions can be drawn that the *ESK* and *ESE* could be good indicators for the roll grinder with centre spalling fault. Figure 10 shows the scatter plot of the normalized *ESK* and normalized *ESE* of all 3 Experiments. The normal samples are located at the left-up of the scatter plot with a relatively concentrated group, while the seeded centre spalling samples are located at the right-bottom of the scatter plot. Among them 5 samples are near to the normal group and others have a concentrated group.
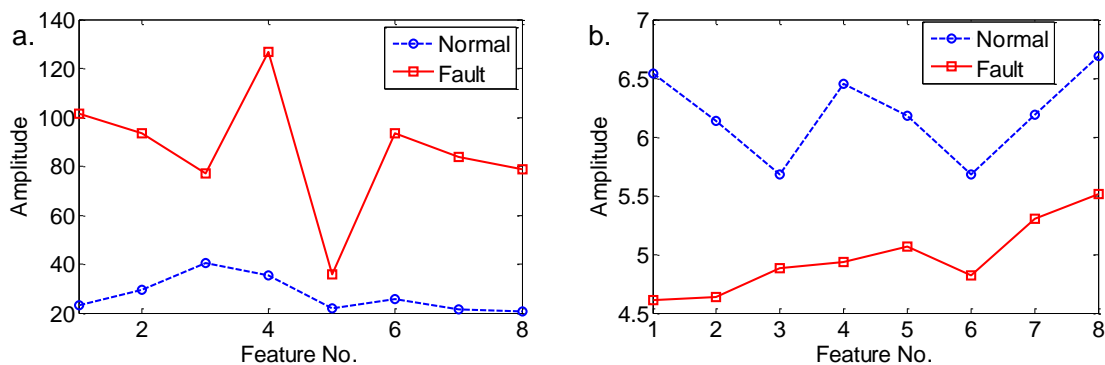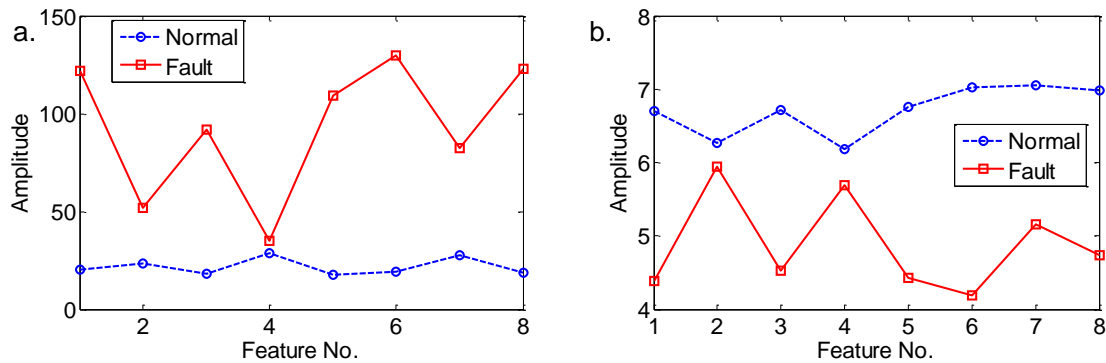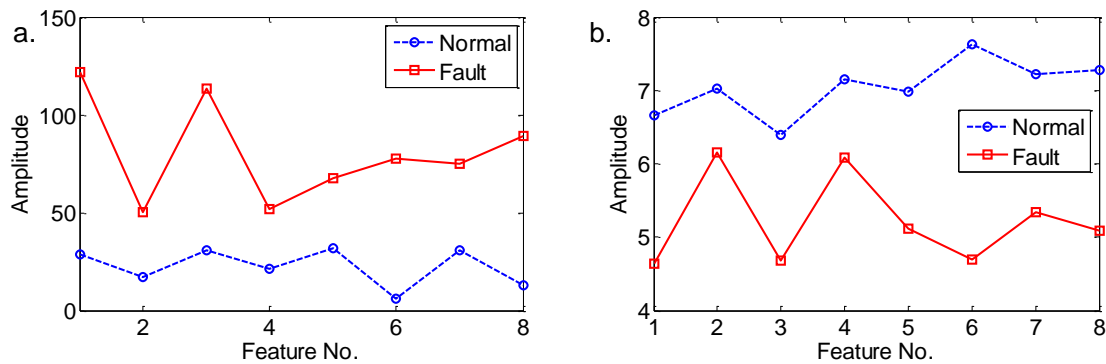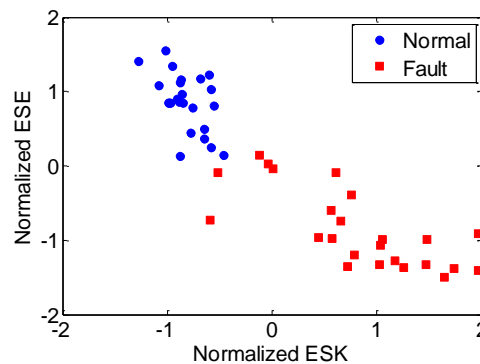

Fig. 7. (a) The *ESK* plot and (b) the *ESE* plot of Experiment 1

Fig. 8. (a) The *ESK* plot and (b) the *ESE* plot of Experiment 2

Fig. 9. (a) The *ESK* plot and (b) the *ESE* plot of Experiment 3

Fig. 10. Scatter plot of the normalized *ESK* and normalized *ESE* of all 3 Experiments

5. Conclusions

In this paper, two health indicators are proposed based on the envelope spectrum to detect the centre spalling fault of roll grinder. Firstly the optimal sub-band signal that contains more fault-related components are selected through fast kurtogram method. Then based on Hilbert transformation, envelope spectrum of the filtered signal is obtained. Finally two dimensionless health indicators are designed based on envelope spectrum to detect the centre spalling fault. It can be summarized from the results that the two health indicators can successfully distinguish the centre spalling situation from normal situation in all 3 experiments, and the scatter plot of all 3 experiments yields a good cluster performance.

Acknowledgement

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