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FAULT DETECTION OF ROLLING BEARINGS USING AN ENSEMBLE AVERAGE AUTOCORRELATION BASED STOCHASTIC SUBSPACE IDENTIFICATION

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Rolling bearings are the crucial parts of rotating machines. The detection and diagnoses of their defects at early stages are significant for ensuring safety and efficient operations. Usually, the vibration feature associated with bearing faults are submerged by the heavy background noise and nonstationary impacts. To enhance detection performance, this paper proposes a novel method developed based on ensemble average autocorrelation and stochastic subspace identification (SSI) techniques. It establishes the theoretical basis of the method based on the general characteristics of bearing vibration signals under faults. Then it examines the robustness of techniques under different level noise, which leads to an optimal selection of centre frequencies that have high signal to noise ratio and thereby high accuracy of envelope analysis for fault diagnosis. Both simulation and experimental results show that the proposed method is able to extract bearing fault signatures at very low signal to noise ratio (<-20dB) and consequently produces accurate detection.

Keywords: fault detection, bearings, SSI, autocorrelation, envelope

1. Introduction

Rolling elements bearings are the most essential parts of the machinery in the modern industrial society. Condition monitoring of the bearings plays an important role in terms of the safety and efficiency of the machines. Vibration, highly correlated with the dynamics of the bearings, is widely used to detect and diagnose the faults. However, one of the challenging problems is that the features are submerged by the heavy noise caused by the parts of the machines and the ambient environment. Hence, many researchers have paid great attention to developing high efficient time and frequency domain methods to detect and diagnose bearing faults. Darlow [1] introduced the techniques of envelope analysis, the original name of which is high frequency resonance techniques. The first step of an envelope analysis is to determine the high resonance frequency. However, the early defect information is not obvious and it is very difficult to select the optimal bands, in which the fault information is much clearer. Since Antoni [2] studied spectral kurtosis (SK) thoroughly, fast kurtogram [3] based on short-time fast Fourier transform (STFT) and wavelet transform (WT) has been explored by many researchers[4], [5]. Tian [6], Rehab [7] et al presented a novel method named modulation signal bispectrum (MSB) with high performance of robustness to detect the bearing faults even though the signal-to-noise ratio (SNR) is very low.

However, only several methods focus on the determination of the optimal narrow bands. System identification techniques has been employed to thoroughly understand the dynamics of bearings. Based on the understanding of the outputs and inputs, the determination of the proper frequency bands is the identification of the natural frequencies. In this paper, a novel method, ensemble aver-

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age autocorrelation based stochastic subspace identification (SSI) was developed to automatically select the optimal frequency sub-bands according to the characteristics of modulation signals and detect the bearing faults based on the outstanding features of autocorrelation functions.

2. The Method to Determine Optimal Bands and Extract Faults

Envelope analysis is the popular method in fault detection and diagnostics filed and vibration is the commonly used signal to monitor the bearings. Usually the vibration feature, associated with bearing faults, are submerged by the heavy background noise and nonstationary impacts. Hence, envelope analysis in the whole frequency band is difficult to detect the local defects. However, in some specific bands the fault features are clear and the determination of the optimal narrowband becomes the prior challenge [4]. A novel method, ensemble average autocorrelation[8]–[10] based stochastic subspace identification[11]–[14] (EAAC-SSI), is introduced and examined. The main steps of the method are shown in Figure 1.

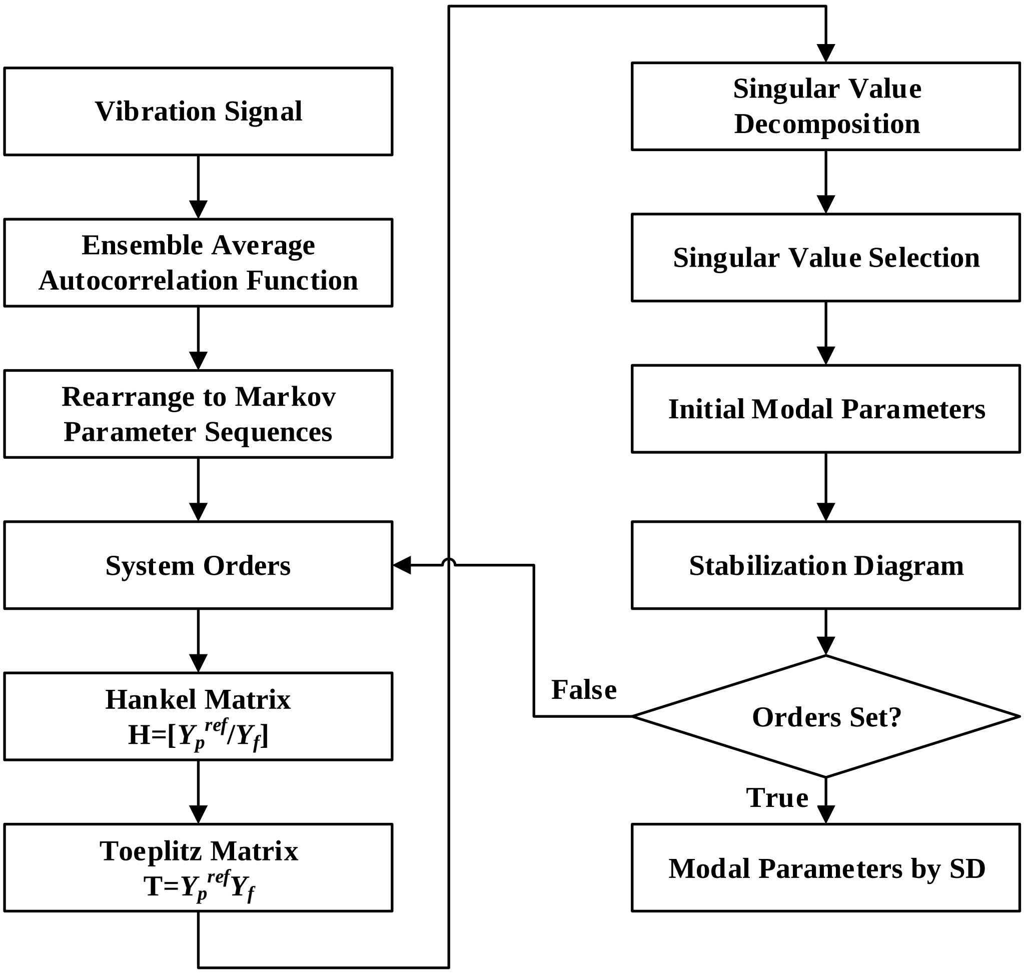


Figure 1 Flow chart of EAAC-SSI

The resonant frequency of a fault bearing vibration signal is the centre frequency of the optimal bands. Since optimal bands are determined, the ensemble average autocorrelation envelope is further used to extract the fault signatures.

3. Simulation Study

3.1 Bearing Signal Simulation

A defective bearing signal is a typically amplitude modulation signal [15]. The vibration signal of a bearing system with a local fault consists of periodical impulses, system resonance and noise. Hence, it can be expressed as

$$x(t)=x_f(t)\cdot x_{bs}(t)+n(t) \tag{1}$$

Where, $x_f(t)$ is the periodical impulses induced by the local defect, which occurs periodically corresponding to the shaft rotation; $x_{bs}(t)$ is the bearing resonant behaviour; $n(t)$ is the inevitable noise which results from the working environments and the data acquisition system.

The parameters of the simulated noise-free signal were set up to fixed values shown in Table **1** to assess the performance of the proposed method.

Table 1 Parameters of the simulated signals

Parameters	**Value**
Sampling Frequency F_s	25600 Hz
Fault Frequency f_f	52.1 Hz
Resonance Frequency f_{bs}	5000 Hz
Rotating Frequency f_r	12 Hz

What is more, to evaluate the influence of the Gaussian noise, signal-to-noise ratio (SNR) is used to restrict the noise, which is defined as

$$SNR=20\log_{10}\left(\frac{P_s}{P_n}\right) \tag{2}$$

Where: P_s and P_n are the power of the noise free signal and the white noise respectively.

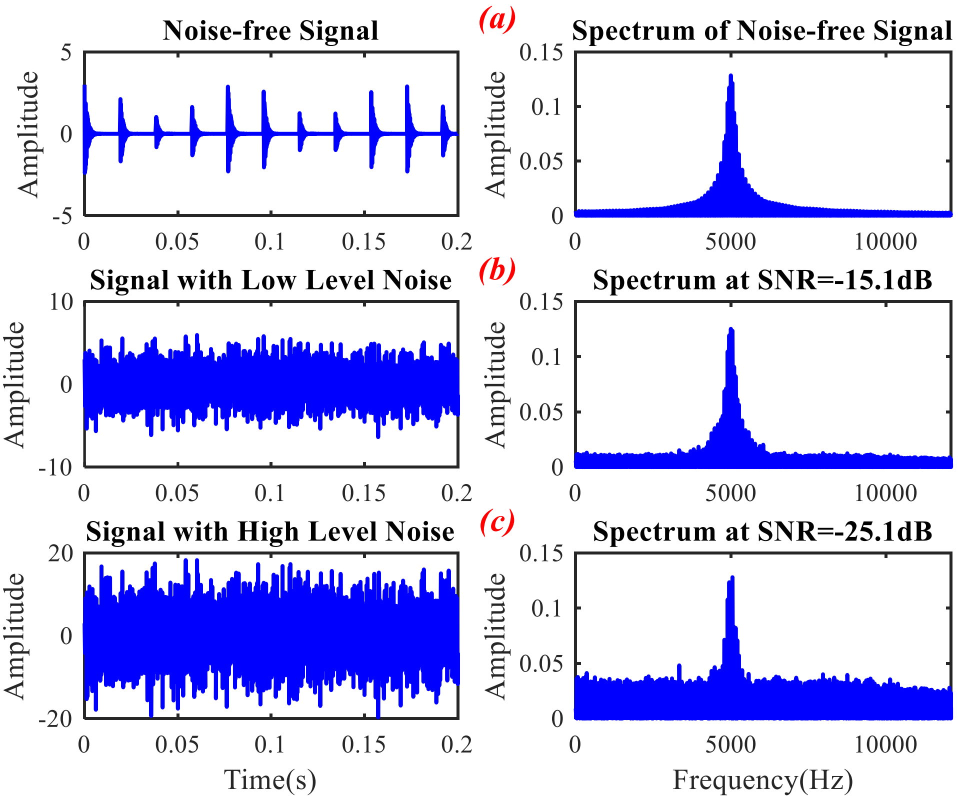


Figure 2 Simulated signals and corresponding spectrum

Figure 2 shows the time waveform of the simulated signals and their corresponding spectrum. Figure 2 *(a)* illustrates the simulated rolling element bearing vibration without noise and its amplitude spectrum. Figure 2 *(b)* presents the signal with low level Gaussian noise. As the SNR is not very low, the high resonant frequency is still clear in the spectrum. Figure 2 *(c)* demonstrates that the high level noise was added to the time waveform. The impulses are submerged by the noise, moreover, most of the harmonics are disappeared in the frequency domain.

3.2 Fault Detection of Simulated Signals

The bearing vibration with a local defect is simulated and the proposed method is used to extract the fault features.

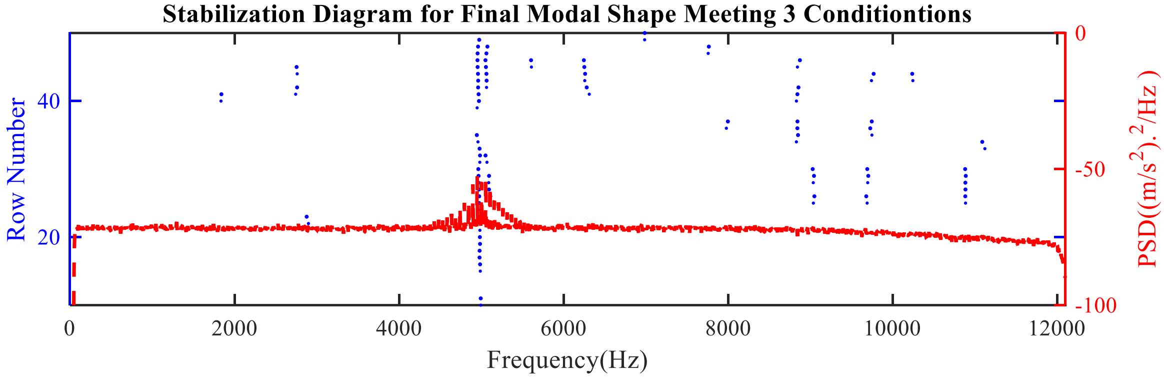


Figure 3 Stabilization diagram for simulated signal at SNR -15dB

As illustrated in Figure 3, the resonant frequency can be determined by the stabilization diagram. The blue points are the modes to meet three conditions, which are the modal frequency stability, modal shape stability and damping ratio stability and the red lines are the power spectrum density. The left y axis on the figure is the row number while the right y axis is the power spectrum density (PSD) and the x axis is the frequency. In this method, three criteria are implemented by the initial threshold value of the variation. According to SD, the optimal band focused on 5058.9 Hz is selected.

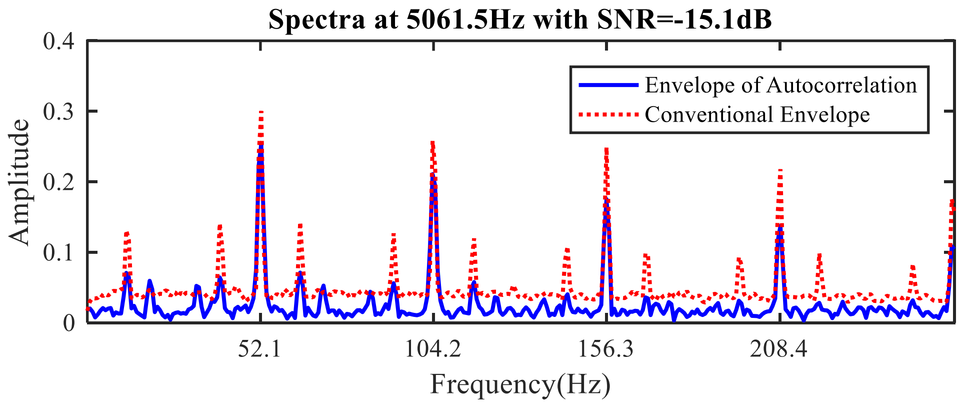


Figure 4 Envelope analysis results of two methods

Figure 4 demonstrates that the fault frequency 52.1Hz and its harmonics are obvious. However, the baseline of the conventional envelope is higher than the novel method, which means envelope autocorrelation performs better in denoising.

In order to examine the performance of the novel method, a lower SNR waveform is simulated and the following figures are the corresponding results.

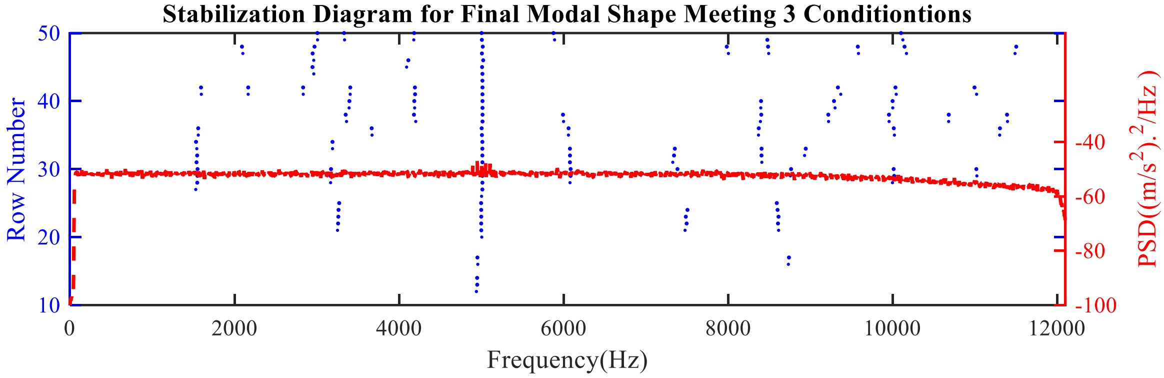


Figure 5 Stabilization diagram for simulated signal at SNR -25dB

As the signal consists of more Gaussian noise, the distribution of the system poles is more disordered in Figure 5 and the resonant frequency 5012.7 Hz is determined based on SD.

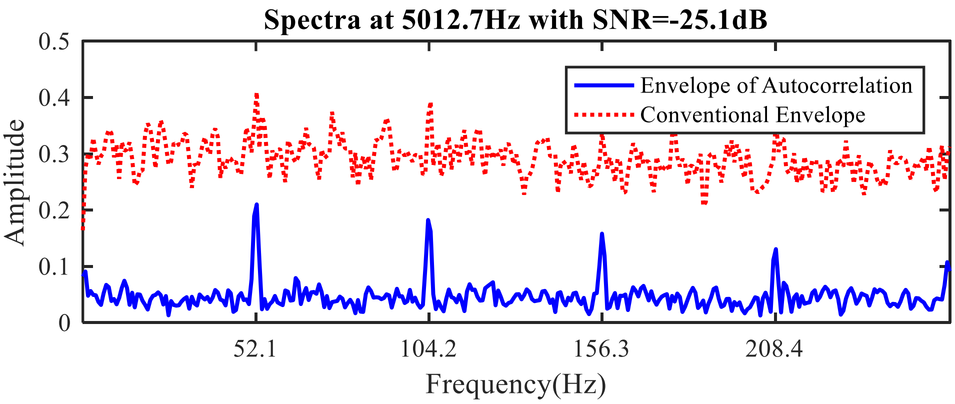


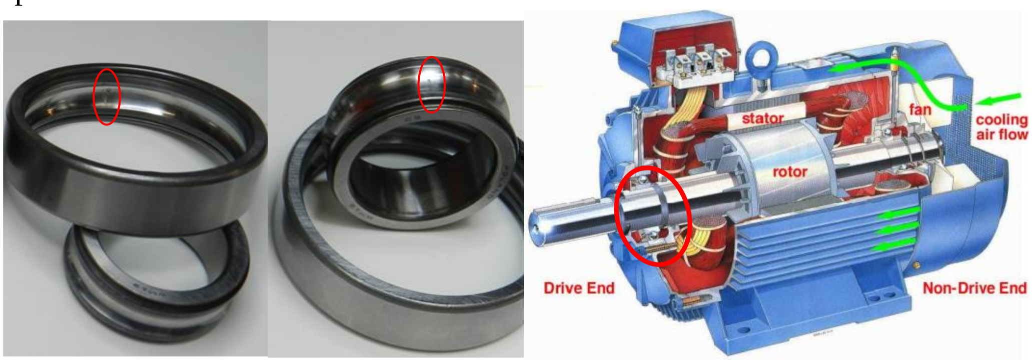
Figure 6 Envelope analysis results of two methods

Considering the increase of the additive noise, the envelope autocorrelation method is more robust than the conventional envelope analysis. As presented in Figure 6, the proposed method is able to detect the fault signature while the conventional envelope analysis is unreliable.

4. Experimental Evaluation

4.1 Experimental Setup

To explore the application of EAAC-SSI, experiments of motor bearings were investigated. The monitoring of electric motor driver has always been of interest because of their popularity and importance as prime moves. The experimental motor bearing is shown in Figure 7 and motor vibration is usually expected to have lower noise and a narrow bandwidth.



(a)Outer Race *(b)Inner Race*

Figure 7 Faulty ball bearings

As shown in the Figure 7, the faulty bearing circled by the red ellipse is at the drive end of the motor. The specification of the faulty bearings is shown in Table 2.

Table 2 Specification of bearings

Rolling Ball Bearing	Value
Number of Balls	9
Ball Diameter	9.53 mm
Pitch Circle Diameter	46.4 mm
Contact Angle	0

The tests are scheduled to proceed in one speed (1450rpm) versus 100% torque loads for every fault bearing. Besides, the test loop repeated three times to decrease the measurement error. The theoretical frequencies of inner race fault and outer race fault are 128.9Hz and 86.4Hz respectively.

4.2 Fault Detection and Discussion

Since the vibrations data sets were acquired, the proposed method is examined by the experimental signals. Figure 8 shows that the results of two methods to highlight the fault signature of the outer race fault. The optimal band centred with 1466Hz are determined automatically by SSI and based on the narrowband, two methods are able to extract the faults of bearings.

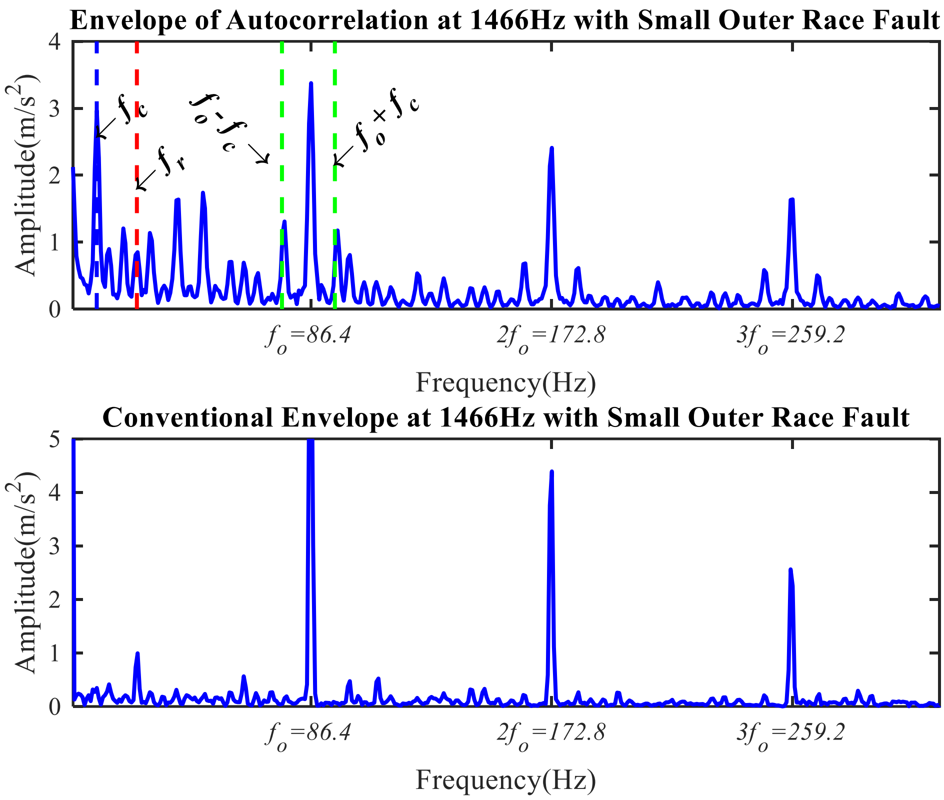


Figure 8 Outer race fault detection results of two methods

Practically, sizes of bearing faults are difficult to control manually, hence it is almost impossible to obtain the aimed vibration signals. In the experiments, the faults of bearings are small but the fault features are still apparent. As presented in Figure 8, the dashed lines with different colours are theoretical values of the bearing fault frequencies so that the differences of two methods are obvious. However, the conventional method only shows the fault information and the shaft rotating frequency, while the envelope of autocorrelation tells the detailed information including the shaft rotating frequency, the cage frequency, the fault frequency and their corresponding harmonics.

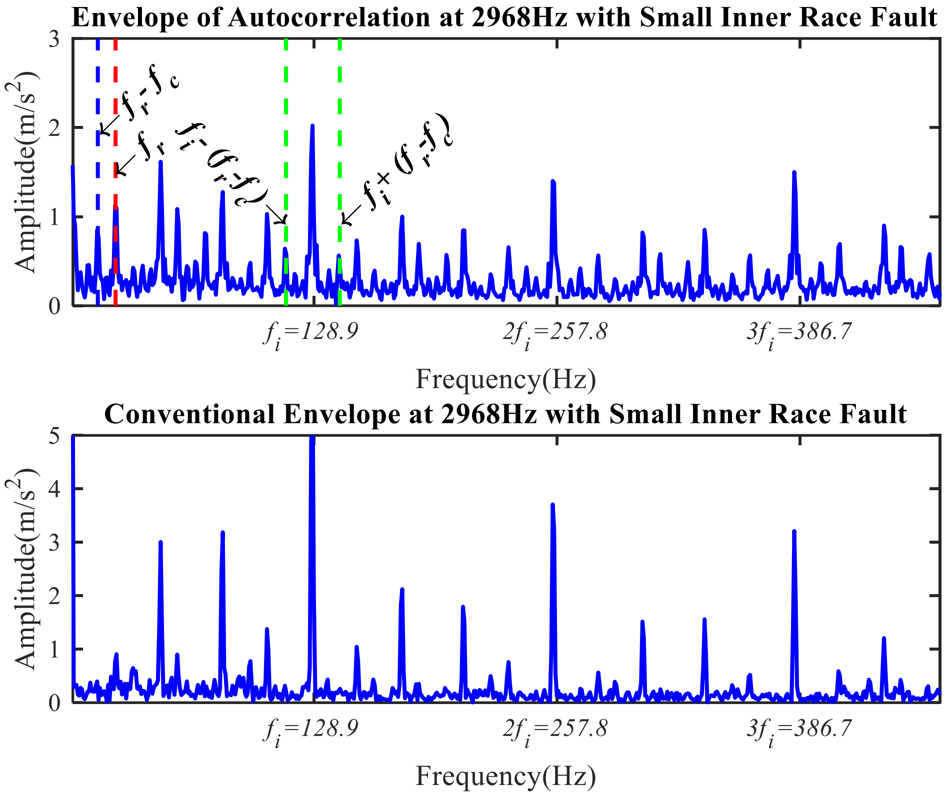


Figure 9 Inner race fault detection results of two methods

Generally, the inner race fault signal is rich of modulation effect. As illustrated in the last graph, Figure 9 also demonstrates that the envelope of autocorrelation gives more details of the vibration behaviours of the ball bearing with a local defect on the inner race. As the experimental bearings are dismantled to make a fault, the cage does not work well since reassembly. The novel method can reveal the flaw of cages while the conventional envelope gives none sense.

5. Conclusion

Ensemble average autocorrelation based SSI is effective in supressing white noise and highlighting the periodic components of signals. In this paper, the novel method is able to determine the optimal band automatically and detect different bearing faults accurately. In the simulation study, the proposed method can extract the fault information even though the signal to noise ratio lowers to -25dB while the conventional envelope analysis becomes unreliable owing to the effect of high random noise. Furthermore, according to the experimental investigation, the envelope analysis can detect the main faults of bearings but it cannot monitor problems of the cages. The envelope of autocorrelation is more sensitive to the early bearing faults and it discovers the potential problems of cages. To sum up, the method introduced in the paper performs well in denoising and detecting bearing faults and it is more robust and more reliable than the conventional envelope.

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