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FAULT DIAGNOSIS METHOD BASED ON PRECISE FREQUENCY DOMAIN INTEGRAL AND VIBRATION SEVERITY

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Abstract. *Aiming at the features of vibration signal, a fault diagnosis method based on precise frequency domain integral (PFDI) and vibration severity (VS) was proposed. With this method, the hidden feature components in vibration signal were accurately extracted. Meanwhile, the interferences of ineffective signals such as trend item and noise were commendably overcome. And the desired vibration velocity signal was precisely obtained. Moreover, the type and severity of faults were identified through further spectrum analysis and VS comparison. The reliability and effectiveness of the method were testified by the measured data analysis. Results indicate that the method can accurately confirm fault type and severity.*
Keywords: Fault diagnosis, Precise frequency domain integral, Vibration severity, Rotating machinery, Feature extraction

1. Introduction.

In most instances, mechanical vibration tends to damage equipment operation, which leads to poor performance and even severe accident. On the other hand, vibration signal contains rich information which reflects health condition. Thus vibration signal can be used for condition monitoring and fault diagnosis, which provides reference for making a reasonable maintaining plan to reduce fault [1,2]. However, the evaluation criteria of condition monitoring and fault diagnosis have not been perfected, so it's necessary to refer to the current criteria. Among them, the vibration severity (VS) criterion specified in the international standard ISO2372 is generally applied due to its versatility [3]. Moreover, researches show that VS possesses strong practicability in comprehensively reflecting the vibration state of machine, which can be used to effectively evaluate the operation quality of machinery [4].

Recently, the vibration acceleration is generally used as a parameter directly measured in the field of condition monitoring and fault diagnosis [5]. However, vibration velocity is essential in calculating VS. And the frequency component of signal is not always consistent with the specified range defined in VS. Thus, in computing VS, it is inevitable to implement signal conversion via integral and band-pass filter. Fortunately, the fast Fourier transform (FFT) shows the unique advantages in time-frequency domain transformation. So, it can be used as a favorable method [6]. At present, the traditional frequency domain integral based on FFT is comparatively mature in theory. However, due to the influences of noise and low-frequency trend, the integral accuracy still needs further improvement in application [7,8]. In order to solve this problem, a precise frequency domain integral (PFDI) was proposed in our previous research [9]. Results indicate that the interference problem of ineffective signal is well solved, and the low-frequency error is effectively overcome. However, some related application studies were not presented in our previous work.

In this paper, we focus on the features of vibration signal, and further perform an extension to our previous work [9] by merging PFDI and VS. Furthermore, the merged method is employed to an application study on fault diagnosis of rotating machinery. This method takes full advantages of PFDI and VS in feature extraction. With this method, the useful fault information can be accurately extracted from the complex vibration signal. And the fault type and severity can be effectively identified. The principle of the proposed method is introduced in Section 2. Moreover, some experimental data analyses are presented in Section 3. Finally, conclusions are provided in Section 4.

2. **Algorithm Implementation.** For faulty rotating machinery, the effective components of signals mainly consist of rotational frequency (RF) and fault characteristic frequency (FCF) and its high-order harmonic. In the signal spectrum, the feature frequencies where spectrum peaks appear are commonly used to estimate fault type. This means that, in the vibration analysis, we can pay attention to limited components such as RF, FCF and its high-order harmonic. And other components can be seen as undesired signal to be removed [8,10].

Based on the aforementioned analysis and previous research, this paper proposes a fault diagnosis method based on PFDI and VS. The main idea of the method is mainly to consider the effective vibration components that reflect signal features. Firstly, the feature information of original signal is extracted. Then, the desired velocity signal is acquired by PFDI. Furthermore, the type and severity of faults are identified by further spectrum analysis and VS comparison. The process of the proposed method is displayed in Figure 1.

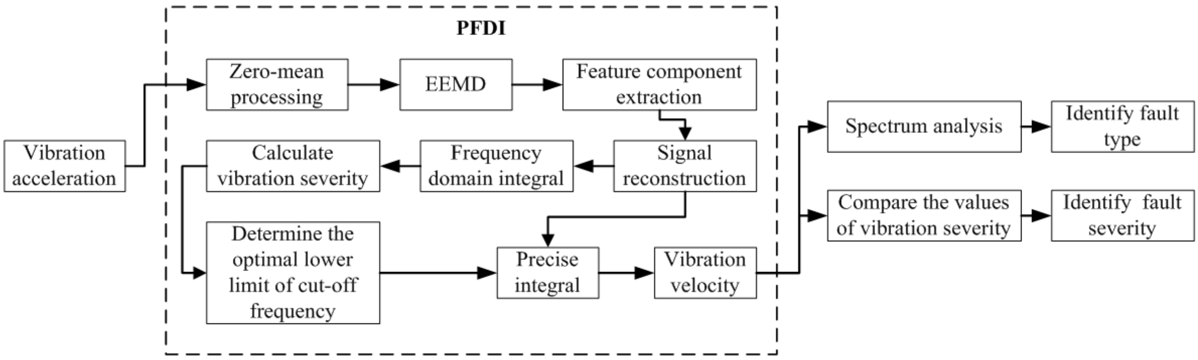

Figure 1. Algorithm process

(1) Precise frequency domain integral (PFDI)

The original vibration acceleration signal is firstly processed by means of PFDI. The detailed steps of PFDI have been described in our previous research article [9].

(2) Spectrum analysis

Perform spectrum analysis to the vibration velocity signal obtained from step (1). Then, the different fault types can be identified.

(3) Compare the values of vibration severity

The vibration severity of the velocity signal obtained from step (1) is calculated. As for discrete signal, it can be expressed by

$$VS = \sqrt{\frac{1}{N}\sum_{n=1}^{N} v^2(n)} \tag{1}$$

where N is the number of sampling points, and v is the vibration velocity of object.

Moreover, the fault severity can be accurately identified through further VS comparison.

3. **Experiment Data Analysis.** In order to further validate the effectiveness of the proposed method, the rolling bearing commonly used in rotating machinery is taken as study object. And the practicability is further verified via analyzing the measured signals. The experiment data are measured from the fault test bench in Case Western Reserve University [11]. The type of the test bearing is 6025-2RS JEM SKF. Its parameters are: pitch diameter is 39.04 mm, ball diameter is 7.94 mm, number of balls is 9, and pressure angle is 0°.

The fault feature frequency of the bearing outer race is [10]

$$f_o = \frac{z}{2}\left(1 - \frac{d_0}{D}\cos\alpha\right) f_r \tag{2}$$

The fault feature frequency of the bearing inner race is

$$f_i = \frac{z}{2}\left(1 + \frac{d_0}{D}\cos\alpha\right) f_r \tag{3}$$

where d_0 is ball diameter, D is pitch diameter of the bearing raceway, z is the number of balls, α is pressure angle, and f_r is shaft rotational frequency.

3.1. **Data analysis of different fault types.** This section mainly takes the fault data of drive end bearings as samples. The diameter of the damage points is 0.1788 mm and the depth is 0.2794 mm. According to the relevant parameters in Equations (2) and (3), when rotational speed is 1797 r/min, the rotational frequency is about 30 Hz and the fault feature frequencies of the outer and inner races are about 107 Hz and 162 Hz.

The time-domain waveforms of the acceleration signals are presented in Figure 2. It is hard to recognize the pulse component associated with the faults from Figure 2 because the signals are mixed with intense noise. The common solution is to convert the preprocessing signals into frequency domain and determine the fault types through identifying the fault frequency. In order to further compare the effectiveness, the original signals are preprocessed with widely used wavelet de-nosing method. The amplitude spectra of

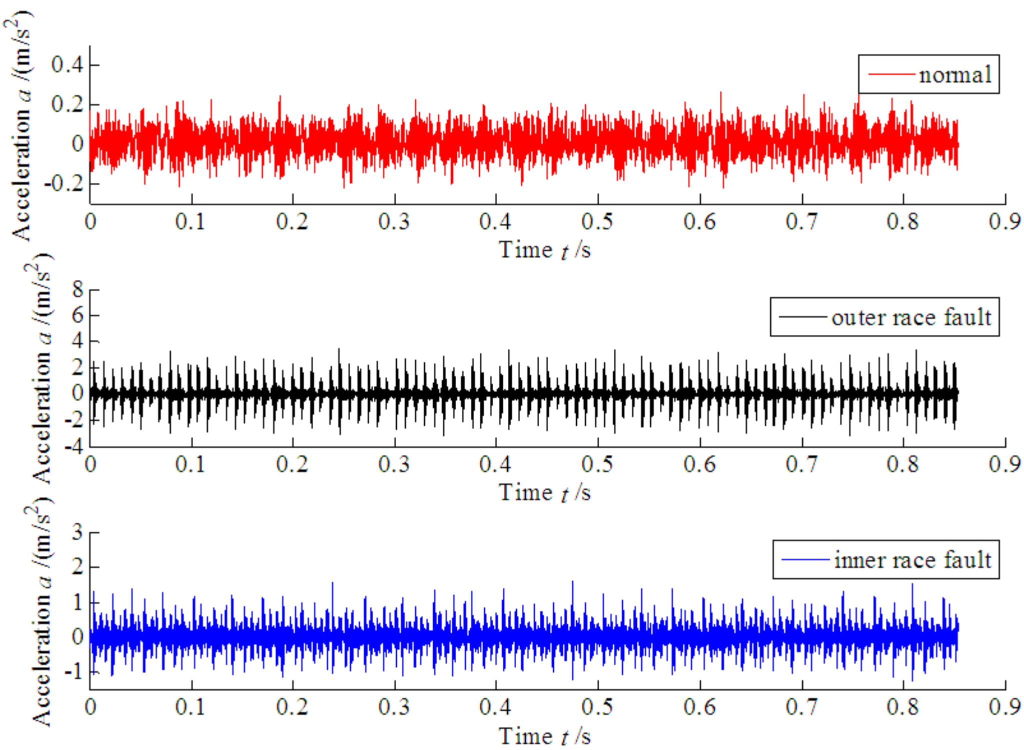

Figure 2. Time domain waveforms of the original acceleration signals

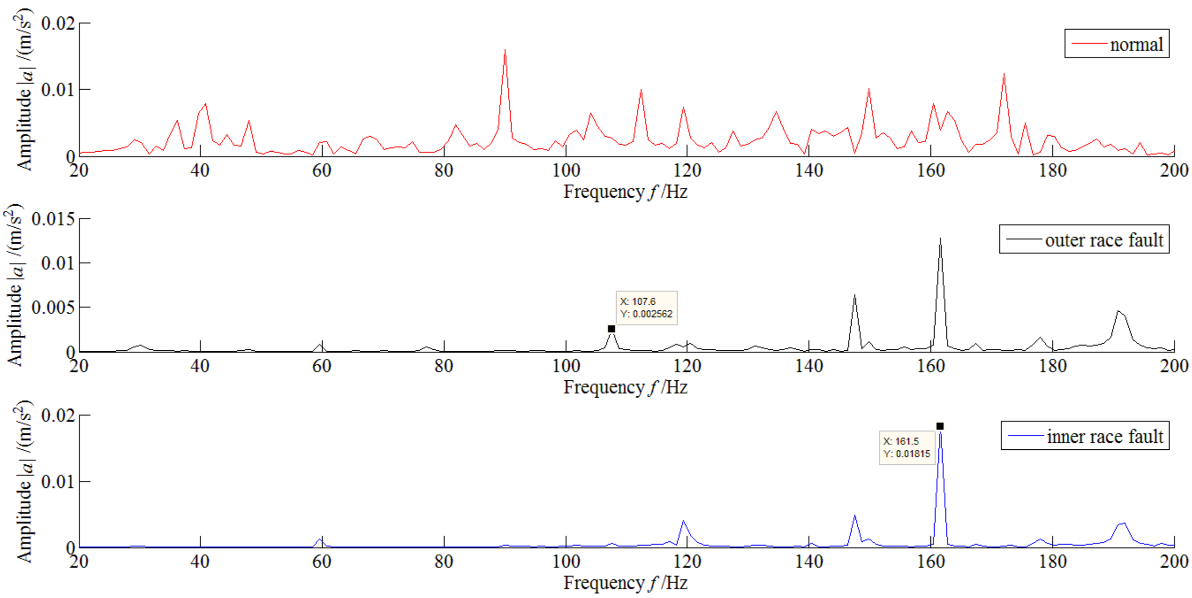

Figure 3. Amplitude spectra of the acceleration signals after wavelet de-noising

the acceleration signals after wavelet de-noising are represented in Figure 3. In order to exactly identify fault, the band 20 $\sim$ 200 Hz is selected as a key analysis section. The range can completely contain all feature frequencies, such as 30 Hz, 107 Hz, and 162 Hz [10].

In Figure 3, for normal signal, some peaks occur at the shaft fundamental frequency 30 Hz and its high-order harmonic. When it comes to outer race fault, the peak occurs at the fault feature frequency 107 Hz. And for inner race fault, it occurs at 162 Hz. It indicates that the signals after wavelet de-noising effectively include fault information. The fault types can be visually determined from the amplitude spectra. However, it also demonstrated that the noise is too intense to be fully eliminated, which leads to some clutter waves to appear in the spectrum of normal signal. Moreover, the feature frequencies at 30 Hz and its high-order harmonic are almost drowned in the amplitude spectra of the outer and inner race fault signals.

Now, the acceleration signals are performed by the proposed method. Then the same as the aforementioned discussion, we analyze the results in frequency domain. The amplitude spectra of the obtained vibration velocity signals are depicted in Figure 4.

Figure 4 shows that clutter waves in the amplitude spectra of the normal signal are effectively restrained, which is better than the results after wavelet de-noising process. Moreover, the background noise of the fault signals is also effectively restrained, and the feature frequencies at 30 Hz and its high-order harmonic are commendably presented. And the fault types can be effectively confirmed because the frequencies which reflect fault feature are clearly revealed. The results indicate that the vibration velocity obtained by the proposed method effectively includes the useful fault information. And the hidden feature information is accurately extracted from the complex vibration signal.

3.2. **Data analysis of the same fault type at different severity.** To test whether the proposed method is effective to fault data of different severity, this section takes the fault data of inner race as samples. The diameters of the damage points are 0.3556 mm (fault degree 1), 0.5334 mm (fault degree 2) and 0.7112 mm (fault degree 3). The depth of the damage points is 0.2794 mm.

Figure 5 shows the time-domain waveforms of the vibration acceleration signals measured in the three fault degrees. With the proposed method, the vibration acceleration

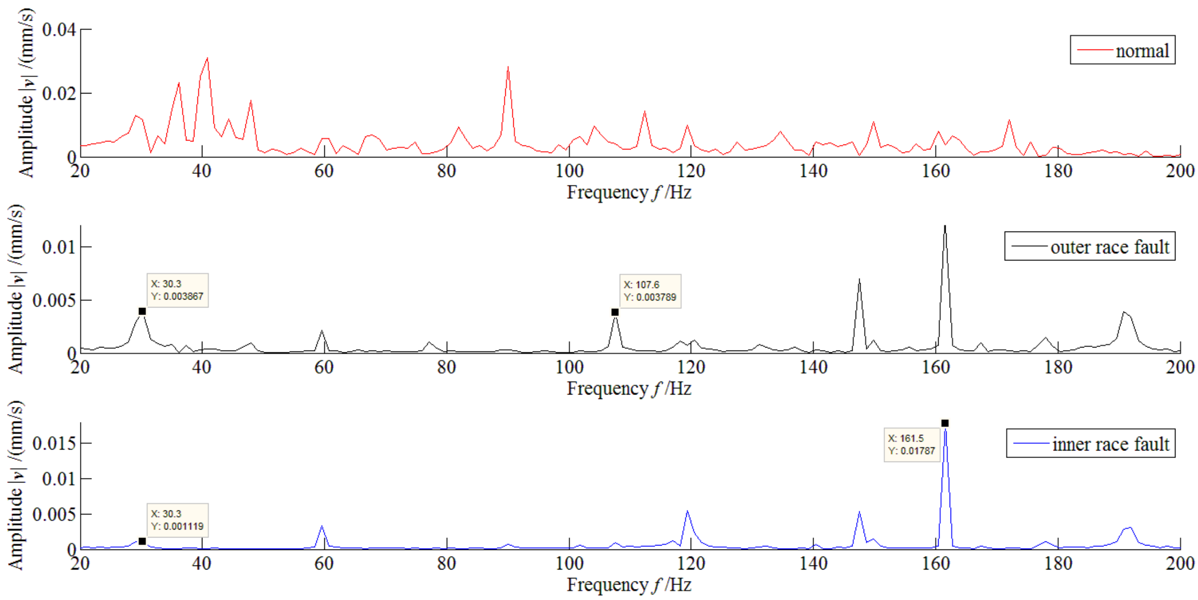

FIGURE 4. Amplitude spectra of the velocity signals

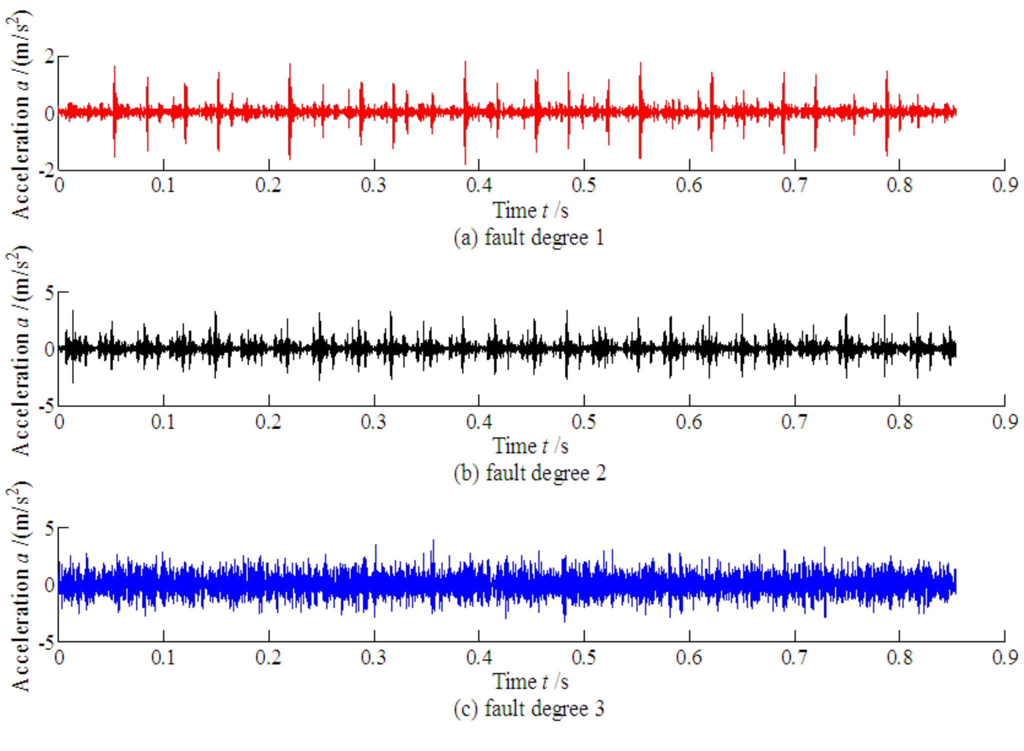

FIGURE 5. Time domain waveforms of acceleration signals at different fault degrees

TABLE 1. Values of vibration severity

fault severity	degree 1	degree 2	degree 3
vibration severity (mm/s)	0.0177	0.0399	0.0847

signals are performed and the amplitude spectra of the obtained vibration velocity are displayed in Figure 6. The VS values are depicted in Table 1.

Figure 6 shows that the fundamental frequency of the rotation shaft and the fault feature frequencies are commendably presented, so it can be precisely confirmed that they belong to inner race fault. Moreover, Table 1 shows that the values of VS increase

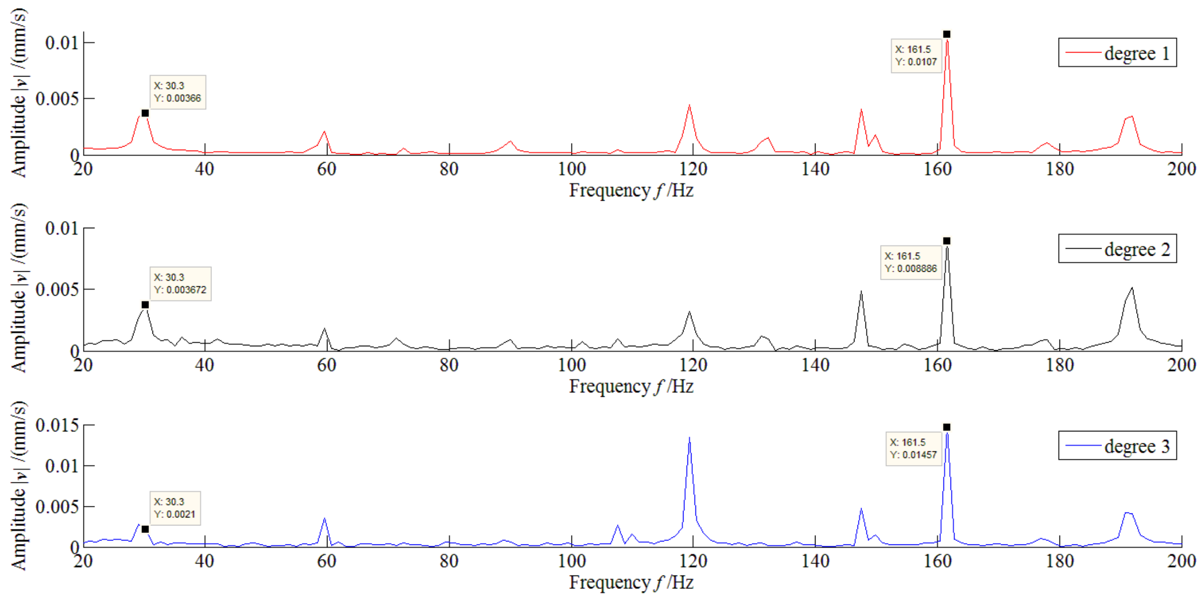

FIGURE 6. Amplitude spectra of ve locity signals at different fault degrees

obviously with the increasing fault degrees. The results indicate that the useful fault information is accurately extracted from the complex vibration signal through the proposed method. And the fault severity can be effectively determined.

4. **Conclusions.** This paper proposes a novel fault diagnosis method for rotating machinery based on PFDI and VS. The reliability and effectiveness of the method are testified by the analysis of measured data. Results indicate that the method can accurately confirm the fault type and severity. This study can provide an important basis for the future application research on condition monitoring and fault diagnosis of machinery equipment.

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