Fault Diagnosis of Rolling Bearings Based on Hilbert Resonance Demodulation Method

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Abstract. Rolling bearings play the role of transmitting power and bearing loads. In the event of failure, not only the failure modes are different, but also the vibration signal characteristics are different. Based on the analysis of the failure mechanism of rolling bearings, the application of Hilbert resonance demodulation method in the typical fault diagnosis of rolling bearings is verified by specific experiments, which provides an important reference for the accurate diagnosis of rolling bearing faults.

1. Introduction
Rolling bearings are important force-bearing parts in mechanical transmission, whose performance directly affects the normal operation of the mechanical transmission, and also affects the service life of the equipment and personal safety of the equipment’s operator. In order to ensure the normal operation of the rolling bearing and timely discover the potential failure of it, it is necessary to carry out the condition monitoring and fault diagnosis of the rolling bearing, in order to improve the efficiency of the equipment and avoid unnecessary accidents. At present, there are many diagnostic methods for rolling bearings, including vibration signal monitoring method, bearing lubrication condition monitoring and diagnosis method, oil analysis method, temperature analysis method, etc [1-2]. Among them, vibration signal monitoring method is one of the most mature and most effective monitoring methods. The method originally used for fault diagnosis of rolling bearings in the vibration signal monitoring method is the time domain analysis method, which uses the digital characteristics of the time domain signal, such as the crest factor and the kurtosis index, to make a diagnosis of the fault. However, the reliability of the time domain analysis method for the qualitative judgment of rolling bearings depends to a large extent on the selection of the judgment threshold, which has certain limitations. The spectrum analysis method derived from the time domain analysis method can accurately diagnose rolling bearing faults, and Hilbert resonance demodulation method is most effective [3-5].

2. Rolling bearing failure mechanism
The rolling bearing consists of an inner ring, an outer ring, a rolling element and a bearing cage. Under normal circumstances, the outer ring is installed in the bearing housing hole, and it does not rotate. The inner ring is mounted on the journal, the rolling element is the core component of the rolling bearing, and the cage is responsible for evenly arranging the rolling elements. Rolling bearing failures have many forms, mainly in the form of fatigue spalling, gluing, wear, corrosion, cracks, indentations
and bearing cage deformation. When the rolling bearing rotates, the damage of the part will cause periodic impact during the process of rolling contact, and then generate the pulse force with the same period, which will arouse the regular vibration of the rolling bearing and generate the characteristic frequency corresponding to a certain fault [6]. Through analyzing the signals and these characteristic frequencies can be gotten, the faults of the rolling bearings are found. The fault characteristic frequency of the rolling bearing can be calculated from the geometric dimensioning and rotational speed of the rolling bearing [7].

The formula for calculating the fault characteristic frequency of each component of the rolling bearing is given by:

Working axis frequency:

$$ f_0 = f = \frac{N}{60} \quad (1) $$

Inner ring fault frequency:

$$ f_{BPFI} = \frac{N}{2} \left( 1 + \frac{d}{D} \cos \theta \right) f_0 \quad (2) $$

Outer ring fault frequency:

$$ f_{BPFQ} = \frac{N}{2} \left( 1 - \frac{d}{D} \cos \theta \right) f_0 \quad (3) $$

Rolling element failure frequency:

$$ f_{BSF} = \frac{D}{2a} \left[ 1 - \left( \frac{d}{D} \cos \theta \right)^2 \right] f_0 \quad (4) $$

Cage failure frequency:

$$ f_{FTF} = \frac{1}{2} \left( 1 - \frac{d}{D} \cos \theta \right) f_0 \quad (5) $$

N—number of rolling elements; d—roller diameter; D—bearing pitch diameter; θ—contact angle

If there is some kind of failure with the rolling bearing, the vibration of the rolling bearing will inevitably be changed, and the vibration will be intensified, and there must be some kind of pulse caused by the fault in the vibration signal. The performance of the signal in the time domain is characteristic of some statistical parameters, such as peak and kurtosis. In the frequency domain, there are many high-frequency components appearing in the signal, and the energy distribution of the signal has been changed greatly. At the same time, there will be peaks in the bearing vibration signal that can reflect the fault characteristics. It should be noted that the peak in the vibration signal is not exactly equal to the theoretical calculation value, because the motion state of the rolling element cannot be ideal rolling, and in addition, the bearing inevitably has certain errors during the process of being manufactured and installed. Therefore, the value of the approximate fault characteristic frequency on the vibration signal spectrum can be used as the characteristic frequency for diagnosing the bearing condition.

3. Resonance demodulation technology

Resonance Demodulation Analysis, also known as Incipient Failure Detection, uses modulation techniques to modulate low-frequency signals into high-frequency resonant frequency region. It separates low-frequency shock signals from other energetic low-frequency signals, in order to make use of the fault information of the rolling bearing to diagnose the rolling bearing, whose sensitivity and reliability of the method are relatively high.

The early failure of the rolling bearing is very slight, and the impact of signal strength is very small. Therefore, the fault characteristics of the vibration signal are not obvious, and it is difficult to distinguish it through the general vibration analysis method. However, the resonance demodulation technology can effectively amplify and separate the fault signal, greatly improve the signal-to-noise ratio, and can easily diagnose the fault location. It can be seen that the resonance demodulation method can effectively diagnose the early failure of the rolling bearing, which is important for the on-site maintenance personnel to make plans for spare parts and avoid large shutdowns of the equipment [8].

The resonance demodulation technology can be implemented in two ways, hardware resonance
demodulation and software resonance demodulation. Hardware resonance demodulation is performed by hardware to realize electronic resonance, band pass filtering, envelope detection and other steps. After demodulating the low frequency fault signal, the data processing method is used to observe the envelope spectrum for fault diagnosis. The software resonance demodulation is used to first collect the vibration signal of the fault bearing by the traditional method, and then takes the steps of bandpass filtering, envelope detection, low-pass filtering, spectrum analysis, etc. through the signal processing method, and finally diagnose the fault according to the envelope spectrum curve [9]. The basic process is shown in Figure 1. The key to the software demodulation method is to envelope the acquired vibration signal by using the Hilbert transform. The Hilbert transform is the output after passing the signal through an all-pass filter of amplitude 1.

![Figure 1](image)

The implementation of hardware and software resonance demodulation is analyzed through the natural frequency of the sensor or rolling bearing. Therefore, the key to the fault diagnosis is to accurately select the center frequency and bandwidth of the bandpass filter to ensure that the filtered signal has sufficient fault information. The hardware resonance demodulation’s effect is better, but the cost is also higher and the implementation process is more complicated. In contrast, software resonance demodulation does not require additional cost and is easy to implement. As long as the vibration signal is correctly collected, good results can be obtained. This paper adopts software resonance demodulation method.

4. Experiment

The experiment was carried out on the rotating machinery vibration analysis and fault diagnosis experimental platform. The platform consists of variable speed drive motor, gear train, bearing, shaft and governor. The platform can perform a variety of fault simulations, including gear fault simulation, rolling bearing fault simulation, and shafting fault simulation.

The number of rolling bearings used in the experiment was 13 and the rolling element diameter was 7.5 mm and the pitch diameter was 39.5 mm. The inner ring is partially damaged, the outer ring is partially damaged, and the rolling element is partially damaged, which is our experiment choice, as is shown in Figure 2. The spindle is rotated at 1500r/min, and the vibration signal is collected by the acceleration sensor. The sampling frequency is 51200Hz, the resonance modulation frequency is 2000 Hz, the bandwidth is 4000 Hz, and the analysis frequency is 500 Hz. After calculating the working axis frequency $f_0 = 25$Hz, the inner ring fault frequency $f_{BPF1} = 193.375$Hz, the outer ring fault frequency $f_{BPF2} = 131.625$Hz, the rolling element fault frequency $f_{ETF} = 63.475$Hz, the cage fault frequency $f_{ETF} = 10.125$Hz.
4.1 Bearing normal operation status
The time domain characteristics of normal bearings are shown in Figure 3. The time domain waveform of the normal bearing vibration signal varies little, and there is no obvious periodic pulse component.

![Figure 3. The time domain characteristics of normal bearings](image)

4.2 Bearing inner ring fault diagnosis
The time domain characteristics of the inner ring fault of the rolling bearing are shown in the Figure 4. The time domain waveform of the inner ring fault bearing vibration signal exhibits a periodic pulse characteristic with the peak to peak value of 23.119 and a kurtosis of 6.861. It means that there is a fault in the bearing, and further perform resonance demodulation. As shown in the Figure 5, $f_{BPF1}$ and its harmonics can be clearly seen, and the bearing operating shaft frequency $f_0$ appears as a sideband spaced apart on both sides of $f_{BPF1}$ and its harmonics.

![Figure 4. The time domain characteristics of the inner ring fault](image)
4.3 Bearing outer ring fault diagnosis
The time-frequency domain characteristics of the outer ring fault of the rolling bearing are shown in Figure 6. The time domain waveform of the vibration signal of the outer ring fault bearing exhibits periodic pulse characteristics. The peak to peak has reached 27.523 and the kurtosis is 10.283. Explain that there is a fault in the bearing, and further perform resonance demodulation. As shown in the Figure 7, $f_{BPO}$ and its harmonics can be clearly seen. Since the relative positional relationship between the position of the damage and the load direction is not fixed, there is no amplitude modulation.

4.4 Bearing rolling element fault diagnosis

When the rolling element is damaged, impact vibration occurs when the defective parts pass through the inner ring or the outer ring raceway surface. The time-frequency domain characteristics of the rolling element fault bearing are shown in Figure 8. The time domain waveform of the rolling element fault vibration signal exhibits periodic pulse characteristics. The peak to peak reached 26.113 and the kurtosis was 10.626. It means that the bearing is faulty, and further perform resonance demodulation. As shown in the Figure 9, $f_{BSF}$ and its harmonics can be clearly seen, and the cage fault frequency $f_{FTF}$ appears, indicating that there are certain faults in the bearing cage.
Figure 8. The time domain characteristics of the rolling element failure

Figure 9. The resonance demodulation of the rolling element failure

5. Conclusion
Rolling bearings have different types of faults due to the factors, such as the load, and other factors, accompanied by corresponding vibration characteristics. Researches and explorations of these vibration characteristics are the prerequisite for accurate fault diagnosis of rolling bearings. Through the detailed analysis of the time domain and frequency domain signals of several typical faults such as inner ring, outer ring and rolling element of rolling bearing, the vibration signal characteristics and diagnosis basis of these typical faults are verified, and the Hilbert resonance demodulation method is further illustrated to be effective.

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