Bearing Defect Recognition Based on Optimal Impulse Response Wavelet Denoising Technique

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Abstract. A rolling bearing defect detection and recognition technique based on optimal impulse response continuous wavelet transform (IRCWT) de-noising technique is proposed. In the proposed technique, the IRCWT is used as a tool for local time and frequency characteristics analysis, and the spectral kurtosis (SK) is used as the impulse index to extract transient pulse components from the processed rolling defect vibration data. Firstly, the IRCWT is used to process the sampling vibration data. And then SK is calculated to choose the best signal band-pass band from the time frequency analysis of vibration data, in order to restrain the interference noise and highlight the transient shock feature. Finally, the envelope spectrum is computed and the rolling bearing defect feature is extracted. The rolling element bearing defect recognition results show that the proposed approach can effectively detect the transient characteristics and distinguish the rolling element bearing localized defect.

1. Introduction

As a general machine element, rolling bearing is widely utilized in rotating machine. Monitoring the health status of rolling bearing parts has merits in the fields of safe operation and maintenance. At present, a great deal of approaches based on vibration data processing technique have been exploited for fault detection and recognition of rotating machinery. These approaches include fast Fourier transform (FFT), power spectrum, envelope spectrum, cepstrum, short time Fourier transform, wavelet transform (WT), Hilbert-Huang transform (HHT) and so on, which have been shown to be especially efficacious in rolling element bearing defect recognition [1,2]. Among these methods, resonance demodulation technique is one of the most effective used approaches for bearing defect detection and recognition. However, in the traditional resonance demodulation approach, the selection of the parameters of the band-pass filter is often decided by the experience and historical data of the operator. Before getting the best parameters of band-pass filter, it needs many attempts to adapt to the changes in rolling element bearing defect diagnosis, thus it is unable to adapt to the changes in the bearing fault diagnosis [3].

WT is one of the most commonly applied time-frequency analysis approach, which is a more effective multi resolution technique both in time domain and frequency domain, so it has been become a powerful method to pick up transient characteristics of un-stationary vibration data generated by defect rolling bearings [4]. However, in order to pick up the defect features of vibration data more effectively, it is essential to choose suitable mother wavelet functions. When the shape of wavelet is close to the vibration signal to be analyzed, the effect of time-frequency analysis is better. On the
contrary, when the shape of wavelet is very different from the vibration signal to be analyzed, it is difficult to achieve the ideal analysis effect. Therefore, how to choose a suitable mother wavelet function is very critical.

In order that improving the reliability and accuracy of bearing fault characteristics extraction, based on continuous impulse response wavelet transform and spectral kurtosis technology, an improved resonance demodulation method is put forward. Impulse response wavelet (IRW) is a real, double damped sinusoidal signal, which can be represented as the impulse response of a unimodular system similar to the common signal characteristics in defect diagnosis and monitoring tasks. Firstly, a great number of wavelet coefficients are got by using the continuous impulse response wavelet transform, which represent the distance between the signal and the specific mother wavelet. Then, the SK is used to choose the best band-pass filter frequency band, so as to suppress the noise and highlight the transient shock feature of bearing fault. Finally, the envelope spectrum of the optimal band-pass filter band signal is calculated, and the bearing fault detection and identification are carried out by using the envelope analysis technique. The rolling bearing defect detection results confirm that the wavelet denoising technology based on the optimal continuous impulse response can effectively suppress the noise, highlight the feature of rolling element bearing defect, accurately diagnose the rolling bearing fault, and enhance the reliability and accuracy of bearing defect recognition.

2. The theory of optimal impulse response wavelet filtering approach

2.1. Impulse response wavelet transform

The continuous IRW is a real mother wavelet, which is a double damped sinusoidal wavelet, which can be shown bellow:

\[
\varphi(t) = Ae^{-\frac{\xi}{\sqrt{1-\xi^2}}} \sin(\omega_c t)
\]

\[\text{(1)}\]

\[\text{Figure 1. The IRW and its spectrum}\]

In Equation (1), \(A\) is an arbitrary scale parameter, represents the wavelet amplitude, \(\xi\) is the parameter that dominates the attenuation speed of the sinusoidal envelopment in time domain, so as to
adjust the damping factor of the settlement of the impulse response wavelet. It is also corresponding to the frequency band of IRW in frequency domain. The circular frequency $\omega_c$ dominates the quantity of wavelet vibration in time domain, which is corresponding to the central frequency of impulse response wavelet in frequency domain. On the basis of the realistic vibration system characteristics of the bearing fault test system, selecting appropriate vibration signal frequency band and constantly changing the scale of continuous impulse response wavelet transform can effectively pick up the transient impact features of the rolling bearing defect vibration signal [5]. Figure 1 exhibits the time domain waveform and its spectrum of continuous impulsive response wavelet. As the impulse response wavelet has more similar transient pulse shape characteristics, it is very suitable to extract the transient characteristics of bearing defect vibration data.

2.2. Spectral kurtosis
SK is mainly utilized to calculate the spectral kurtosis value of the vibration data time-frequency representation. According to the magnitude of the spectral kurtosis value, the vibration magnitude of the impulse shock transient feature in the original vibration signal is determined. The larger the kurtosis value is, the more severe the transient impact feature is in the vibration data. Otherwise, the transient impact in the signal is not obvious. This method effectively solves the problem that Fourier transform can’t detect and extract the transient impact feature in the original vibration signal.

The spectral kurtosis represents the peak value of the probability density function of time-frequency distribution, which is formulated as the normalized fourth-order cumulative quantity:

$$SK_x(f) = \frac{S_{4x}(f)}{S_{2x}^2(f)} - 2$$

(2)

Where $S_{4x}(f)$ is the fourth-order cumulative quantity of the spectral density of vibration signal $x(t)$ and $S_{2x}(f)$ is the second-order cumulative quantity.

When the original vibration signal $x(t)$ contains noise, the spectral kurtosis can be calculated by the following formula:

$$SK_x(f) = \frac{K_x(f)}{[1 + \xi(f)]^2}$$

(3)

Where $SK_x(f)$ is SK of original vibration data $x(t)$ without noise and $\xi(f)$ is the count backwards of signal to noise ratio.

The magnitude of the spectral kurtosis reflects the intensity of the transient impact phenomenon of the original vibration signal. It is related to the resonance frequency band of the selected bearing fault vibration signal. The premise of accurate bearing defect characteristics extraction and recognition is to search the frequency band center and its bandwidth where the maximum value of the spectral kurtosis lies.

3. Bearing damage detection based on optimal impulse response wavelet transform
The experimental ball bearing is only utilized to research one kind of localized surface defect: bearing inner ring or outer ring fault. The tested rolling element bearing is used discharge device to machine a slot on the inner or outer ring. Then the localized fault is a machine formed on the inner or outer ring. The defect was 1 mm deep and 1.5 mm wide. The gearbox is driven by three-phase alternating current motor. The input spindle speed is 1500 r/min, in other words, $f_r$ is 25Hz. The bearing model is deep groove ball bearing 6208. The number of balls is 10 and the contact angle $\alpha = 0^\circ$. The bearing pitch diameter D is 97.5mm and the ball diameter d is 55/3 mm. The bearing defect feature frequencies of inner ring and outer ring are computed according to Eq. (4) and Eq. (5), respectively [5].
\[ f_{\text{inner}} = \frac{z}{2} \left( 1 + \frac{d}{D} \cos \alpha \right) f_r \]  
\[ f_{\text{outer}} = \frac{z}{2} \left( 1 - \frac{d}{D} \cos \alpha \right) f_r \]

According to Eq. (4) and Eq. (5), as well as the geometric and kinematic parameters of rolling bearing, the defect feature frequencies of bearing inner ring fault and bearing outer ring fault are calculated. The rolling bearing defect characteristic frequencies of inner ring and outer ring are 148.5 Hz and 101.5 Hz.

![Figure 2. Vibration data with inner ring defect](image1)

![Figure 3. FFT with inner ring defect](image2)

![Figure 4. Envelope spectrum](image3)

![Figure 5. Amplitude map](image4)

![Figure 6. Phase map](image5)

![Figure 7. Spectral kurtosis](image6)
The sampled bearing inner ring defect vibration data is displayed in Figure 2 and the FFT is showed Figure 3. Figure 4 is the traditional envelope spectrum. In Figure 3 and Figure 4, there is no significant spectral peak near the rolling element bearing defect feature frequency $f_{inner}$ and its high-frequency harmonics. Therefore, the classical Fourier analysis and envelope spectrum analysis can not accurately extract the transient impact characteristics of bearing fault in noise environment, so it is difficult to effectively diagnose bearing localized fault.

![Figure 8. The optimal kurtosis filtered signal](image1)

![Figure 9. Envelope spectrum](image2)

Figure 5 and Figure 6 show the magnitude and phase wavelets plot of continuous impulse response wavelet transform. The peak degree of wavelet spectrum of impulse response is defined as the peak degree of magnitude on each wavelet scale, as shown in Figure 7. For the sake of illustrating the
validity of the proposed technique compared with the traditional envelope spectrum. Figure 8 shows the optimal kurtosis filtered signal with wavelet scales of 0.5 and Figure 9 is its envelope spectrum. In Figure 9, we can clearly see the characteristic frequency and higher harmonic of bearing inner ring fault, which shows that the proposed approach of spectral kurtosis de-noising and envelope spectrum technique based on continuous impulse response wavelet transform can effectively extract bearing defect feature.

4. Conclusions
Envelope spectrum analysis based on resonance demodulation technology is one of the most popular utilized methods for bearing defect diagnosis. However, the most difficult problem of resonance demodulation technology is how to choose the best demodulation frequency band. The commonly used method to choose the best solution of frequency modulation band is to use band-pass filtering technology. The bandwidth and central frequency of band-pass filter usually need to be tested according to the experience of fault diagnosis experts or multiple times. As a result, the self adaptability is poor. In order to effectively extract the transient characteristics of bearing fault hidden in the noisy vibration signal, a bearing defect detection method based on the optimal IRW de-noising technology and envelope analysis technique is proposed. This technique has obvious advantages in extracting the transient characteristics of bearing faults, which are often effective indicators of early faults of bearing. The experimental conclusions display that the wavelet de-noising technology based on the best IRW can effectively detect rolling element bearing localized fault.

5. References
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