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Research Article

A Fault Detection Method of Rolling Bearing Based on Wavelet Packet-cepstrum

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Abstract: In this study, we put forward a fault detection method of rolling bearing based on the wavelet packet-cepstrum. Firstly, the original signal is decomposed using the wavelet packet. Secondly, calculate the energy of the decomposed sub-band reconstruction signal and select the relatively band which is concentrated on the fault energy. Finally, calculate cepstrum of the reconstruction signal to detect fault. The actual normal and fault data of the rolling bearing's outer ring is analyzed in applying this method in the MATLAB simulation circumstance. The result shows that the outer ring's failure frequency measured by the experiment is consistent with the theoretical calculation result.

Keywords: Cepstrum, energy feature, fault detection, wavelet packet decomposition and reconstruction

INTRODUCTION

Rolling bearing is very important parts in the rotating machinery. It is also one of the easily damaged equipment. According to statistics, 30% of the rotating machinery fault is caused by the rolling bearing fault. Some reasons may cause the local damage of the rolling bearings, such as wear, fatigue, corrosion, overload and so on, when the equipments are operating. The bearing defect will cause the violent vibration and noise and even serious accidents of the whole system (Zhong and Huang, 2006). Therefore, the fault diagnosis research of the rolling bearing has great significance.

The fault vibration signal of the rolling bearing is a usually non-stationary signal. It generally expressed as aliasing of complex and random periodic pulse signal (Zhang *et al.*, 2000; Yang *et al.*, 2004). In the actual operation, the local damage fault is often covered by the large noise and vibration signal. So extraction of the corresponding fault characteristic frequency is particularly critical. Due to the advantage of wavelet multi-resolution and cepstrum which is good at detecting the cycle composition in the power spectrum and separate side band signal, both of them have been widely used in the field of mechanical fault diagnosis. The cepstrum has also been used as theoretical tool to detect the fault diagnosis of bearing (Zhang *et al.*, 2000; Yang and Hui, 2005). Wavelet (Wavelet packet) theory has successfully applied to extract the fault feature of the rolling bearing to diagnose fault (Cheng *et al.*, 2004; Yuan *et al.*, 2012; Kanlar *et al.*, 2011). A rolling bearing fault detection method based on the wavelet packet-cepstrum is put forward in this study. The method combines wavelet packet advantages with cepstrum advantages. The experiment results show that the method can well diagnose the outer ring fault of rolling bearing.

THE FAULT PRINCIPLE AND REALIZATION PROCESS OF THE WAVELET PACKET-CEPSTRUM

In the wavelet packet-cepstrum fault detection, first step is the wavelet packet decomposition and reconstruction of the detected signal, then select frequency band depending on energy feature. Second step is the cepstrum analysis of reconstruction signal. The following is a brief description about the wavelet packet decomposition reconstruction, the process of the energy feature extraction, cepstrum realization principle and the specific implementation process of detection method using wavelet packet-cepstrum.

The wavelet packet decomposition reconstruction and process of the energy feature extraction: Wavelet packet analysis can decompose and reconstruct a signal meticulous. Compared with wavelet analysis, wavelet packet analysis can not only decompose the low frequency part but also achieve secondary

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decomposition of the high frequency part. So, its signal analysis ability is stronger (Tang and Cai, 2009).

Subspace U^n_j defined by the closure space of the $U_n(t)$ function and $g^n_j(t) \in U^n_j$ is assumed. The $g^n_j(t)$ is given as:

$$g_j^n(t) = \sum_l d_i^{j,n} u_n(2^j - l) \tag{1}$$

Wavelet packet decomposition algorithm: We can calculate $d_j^{j,2n}$ and $d_j^{j,2n+1}$ through the $d_j^{j+1,n}$:

$$d_l^{j,2n} = \sum_k a_{k-2l} d_k^{j+1,n} \tag{2}$$

$$d_l^{j,2n+1} = \sum_k b_{k-2l} d_k^{j+1,n} \tag{3}$$

where, α_{k-2l} and α_{k-2l} are the conjugated filter coefficient of Wavelet packet decomposition.

Wavelet packet reconstruction algorithm: We can calculate $d_l^{j+1,n}$ through $d_l^{j,2n}$ and $d_l^{j\ 2n+1}$:

$$d_l^{j+1,n} = \sum_k [h_{l-2k} d_k^{j,2n} + g_{l-2k} d_k^{j,2n+1}] \tag{4}$$

where, h_{k-2l} and g_{k-2l} are the conjugated filter coefficient of Wavelet packet reconstruction.

The rolling bearing default will lead to changes of energy of some signals which come from some bands of the vibration signal wavelet packet decomposition. Some band's energy decreases and other's increases. We can roughly judge whether faults have occurred based on the energy distribution of the vibration signal within each band. At the same time, the changing of energy can be the basis of selecting reconstruction frequency band. It can improve the accuracy of the subsequent diagnosis method. The detected signal will implement 3 layers wavelet packet decomposition in the study and select corresponding reconstruction frequency band through energy changing of frequency band of the third layer. The following steps specifically explain the process:

- Decompose the detected signal by 3 layers wavelet packet decomposition. The $X_{3,j}$ is defined by the decomposition coefficients of the j^{th} ($j = 0, 1, \ldots, 2^3 - 1$) node of the third layer.
- Calculate the reconstruction signal of each frequency band of third layer. The $S_{3,j}$ is defined by the Corresponding reconstruction signal of $X_{3,j}$ ($j = 0, 1, \ldots, 2^3 - 1$).
- Calculate the energy of the Corresponding frequency band of the third layer. Defined as:

$$E_{3,j} = \int \left| S_{3j}(t) \right|^2 dt = \sum_{k=1}^{n} \left| x_{jk} \right|^2 \tag{5}$$

- Reconstruct the original signal by selecting the Corresponding frequency bands which energy is concentrated and have furious changing of energy ($E_{3,j}$). Defined as:

$$x = \sum S_{3,j} \tag{6}$$

The theory of cepstrum: The transmission way has less affect on cepstrum and due to the advantage of cepstrum which can do better detect the cycle composition in the power spectrum, separate side band of signal and be less affected by of the signal (Zhang *et al*., 2000). The cepstrum has been widely used in the field of mechanical fault diagnosis.

There are many deformations of cepstrum. The real cepstrum which is usually used in the engineering is selected for finishing the subsequent analysis in this study. The cepstrum of a signal is defined as the inverse Fourier transform of the log power spectrum of a signal (Zhang *et al*., 2000; Johan and Maria, 2012):

$$C_x(\tau) = F^{-1}\{\log |S_x(f)|\} \tag{7}$$

where,

$C_x(\tau)$ = The cepstrum
$F^{-1}\{\}$ = The inverse Fourier transform of the signal
$S_x(f)$ = The power spectrum of a signal
τ = A time variable of the cepstrum which unit is s or ms, also known as the inverted frequency

The implementation process of the fault detection method of the wavelet packet-cepstrum: A fault detection method of rolling bearing which is based on the wavelet packet-cepstrum is put forward in this study. The method combined wavelet packet advantages with cepstrum advantages. The following steps specifically describe the implementation process of this method:

- Decompose the original vibration signal x by wavelet packet.
- Reconstruct the each node coefficient of Wavelet packet decomposition, calculate the energy of the reconstructed signal and achieve the distribution map of energy.
- Selecting the Corresponding frequency bands which is energy concentrated and have furious changing of energy are used to restore the original signal x' which is the approximation value of the truly original vibration signal.
- The x' analyzed by cepstrum and power spectrum. Then compare the advantages and disadvantages of the spectrum result of the experiments.

EXPERIMENTAL VERIFICATION

The theoretical calculation of the fault characteristic: The experimental analysis data is Case Western Reserve University's experiment data of the

Table 1: The fault characteristic frequency is multiple of running speed in HZ

The position of fault	The fault characteristic frequency is a multiple of running speed in HZ
Inner ring	5.41520
Outer ring	3.58480
Cage train	0.39828
Rolling element	4.71350

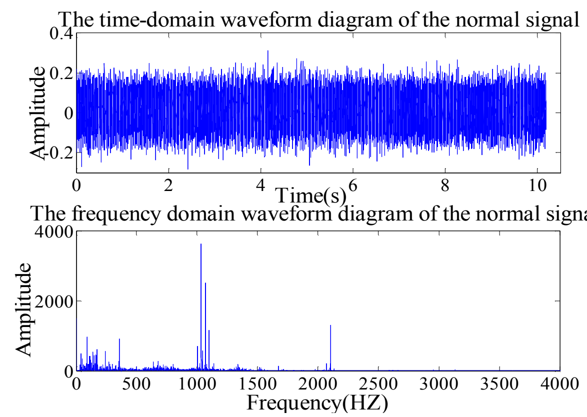

Fig. 1: The time-domain and frequency-domain waveform diagram of the normal signal

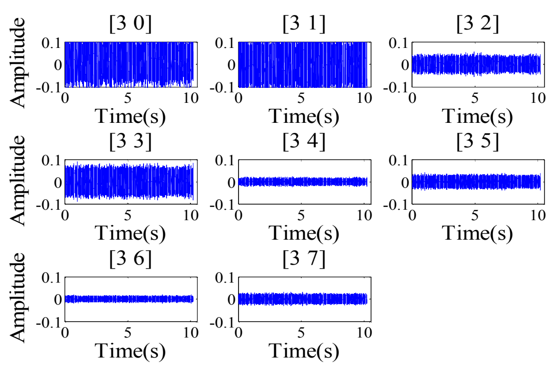

Fig. 2: Reconstruction signal of the third layer wavelet packet coefficient of the normal

rolling bearing in USA (Loparo, 2008). We can calculate the fault characteristic frequency according to the theoretical formula which is presented in the literature (Gao, 2008). The relationship between the calculated fault characteristic frequency of experimental data (drive end) and the running speed is shown in Table 1. The table represents that the fault characteristic frequency is a multiple of running speed in HZ.

Experimental verification and analysis: In experiment, the normal and outer ring fault (single point failure diameter is 0.007 inches) in the motor no-load situation data of rolling bearing which model is 6205-2RSJEMSKF is analyzed. The no-load speed of the motor is 1797 rpm. The data sampling frequency is 12 KHZ. Analyze the data using the presented method

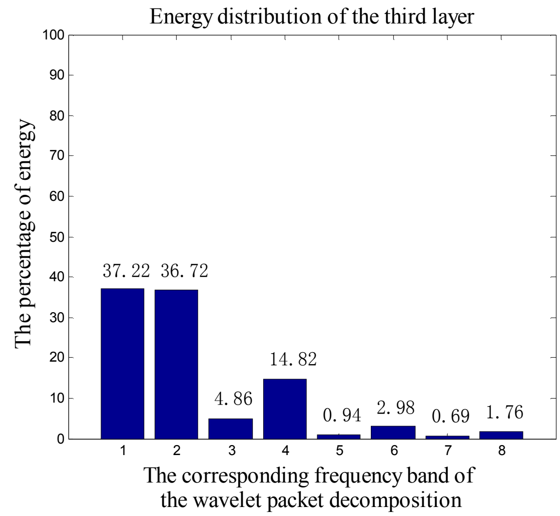

Fig. 3: Percentages of energy of the third layer of wavelet packet for the normal signal

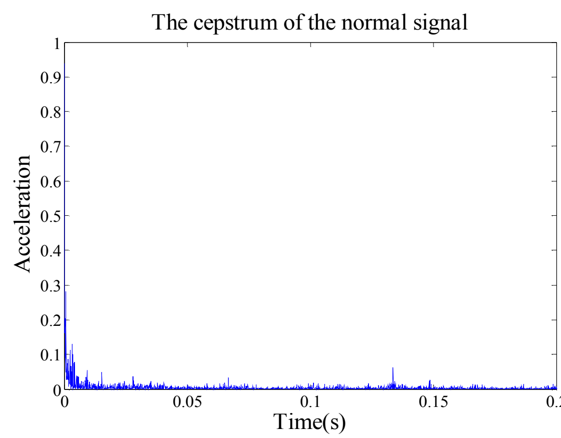

Fig. 4: Cepstrum of the wavelet pocket reconstruction signal for the normal situation

in this study and the method of wavelet packet-power spectrum. Compared with the two experiment results verify the superiority of the proposed method.

In the Fig. 1, the time domain waveform amplitude of the normal vibration signal stably changes with the time and no o obvious impact composition. And the frequency mainly concentrated in the below 1 KHZ and the most of amplitude is relatively small in the frequency domain.

The original signal implements the 3 layers wavelet packet decomposition and reconstruction by using the db1 wavelet which is regarded as the basic wavelet in the following waveform analysis of the experiments. Selecting the Corresponding reconstruction signal of frequency bands according the changing of energy and restore the original signal, then implement the subsequence analysis of cepstrum and power spectrum and compare the two finally experimental results.

In the Fig. 2 and 3, the energy of the normal vibration signal of bearing mainly concentrated in the first, second and 4th frequency band in the third layer. So, the original signal can approximately regarded as the sum of the reconstruction signal of the several frequency bands. So, we can gain the reconstruction signal (x'). Defined as $x' = S_{3,0} + S_{3,1} + S_{3,3}$. It will improve the accuracy of the subsequent diagnosis method.

The Fig. 4 and 5 are Cepstrum and power spectrum of the wavelet packet reconstruction signal for the normal situation. The Fig. 4 shows that the cepstrum of vibration signal of the normal situation do not have obvious peak, period composition and the fault characteristic frequency. The most frequency focus on the below 1 KHZ, in addition to the individual impact component and the amplitude is relatively small in the power spectrum.

Analyze the vibration signal of outer ring of the rolling bearing using the above method and process. The fault characteristic frequency of outer ring of the bearing by the theoretical calculation is 3.5848 times of running speed. The calculation formula is defined as f_o = 3.5848* 1797/60 HZ = 107.365 HZ. The following verifies the calculation result by the simulation experiment.

In the Fig. 6, the time domain waveform amplitude of the fault vibration signal furiously changes with the time and has obvious impact composition. There has added many frequency components with large amplitude in the frequency domain. They are different from the normal situation. So we only can understand the fault's happening, but we don't know the fault category and position. It needs to further analysis.

The energy has shifted when the faults occur. Some frequency bands' energy sharply reduces and some increase in the Fig. 7. We know that the fault information is mainly focus on the third, 7th frequency band through the energy distribution of the wavelet packet decomposition reconstruction in the Fig. 8. So, we restore the initial signal by selecting the reconstruction signal of the third, 7th frequency band.

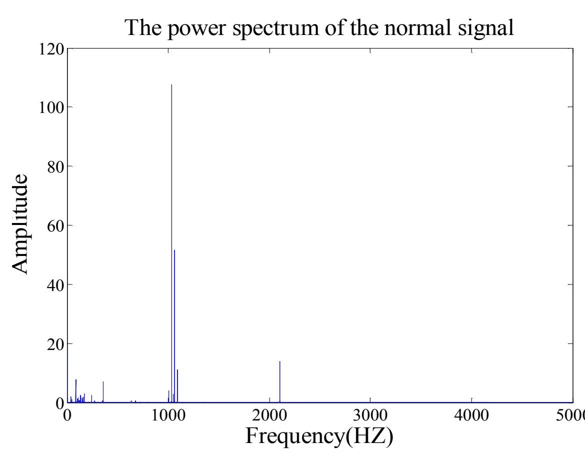

Fig. 5: The power spectrum of the wavelet pocket reconstruction signal for the normal situation

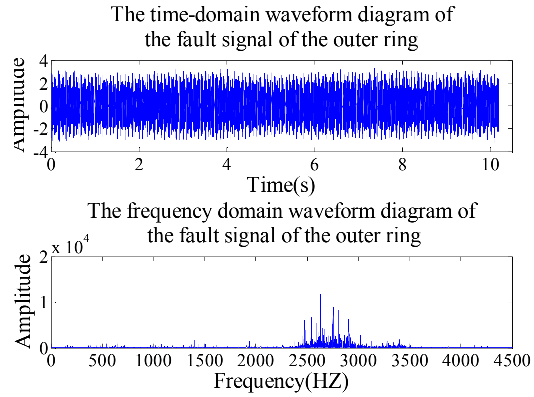

Fig. 6: The time-domain and frequency-domain waveform diagram of the fault signal of the outer ring

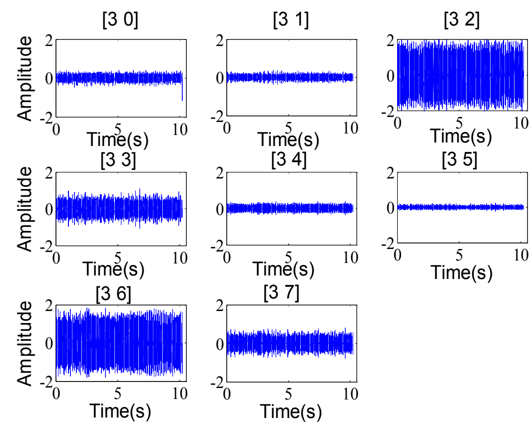

Fig. 7: Reconstruction signal of the third layer wavelet packet coefficient of the fault signal of outer ring

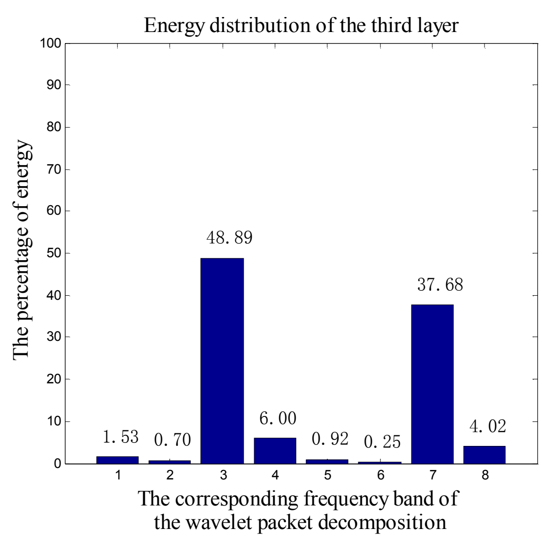

Fig. 8: Percentages of energy of the third layer of wavelet packet for the fault signal of outer ring

So, we can gain the reconstruction signal (x'). Defined as $x' = S_{3,2} + S_{3,6}$.

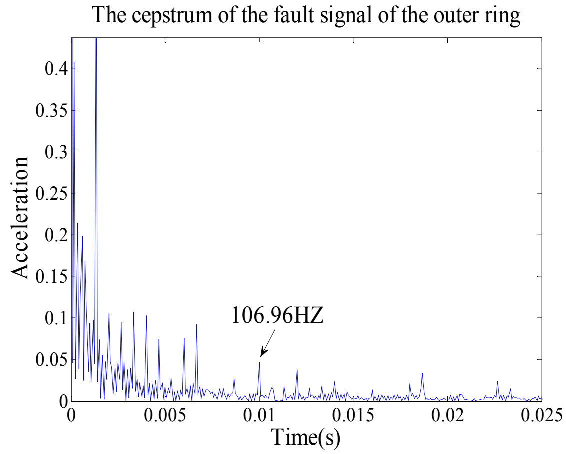

Fig. 9: Cepstrum of the wavelet pocket reconstruction signal of the fault signal of the outer ring

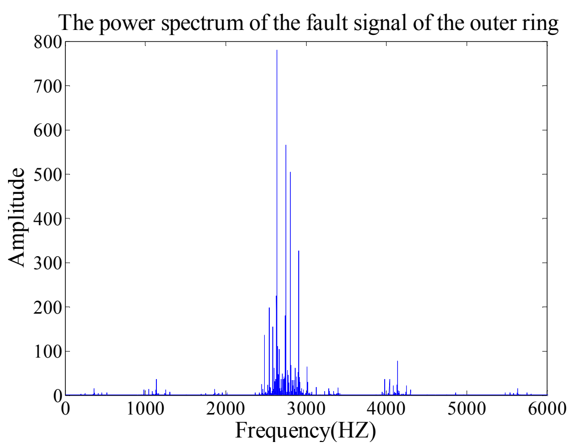

Fig. 10: Power spectrum of the wavelet pocket reconstruction signal of the fault signal of the outer ring

The Fig. 9 and 10 are Cepstrum and power spectrum of the wavelet packet reconstruction signal of the fault signal of the outer ring. It appears a peak in 0.00935s accompany with the frequency doubling and frequency division in the cepstrum. The frequency (1/0.00935 HZ = 106.95 HZ) of the corresponding time of peak and the characteristics of the frequency doubling and frequency division are consistent with the fault characteristic frequency of outer ring. It can be regarded as the outer ring fault. But we cannot distinguish in the power spectrum.

CONCLUSION

The result shows that the accuracy can be improved by introducing the energy feature in the detection method of wavelet pocket-cepstrum. This method can successfully detect the fault of outer ring. The cepstrum implements a spectrum analysis on the basis of power spectrum to detect the cycle composition and separate side band of signal. Its performance is better than the power spectrum. So, combine the cepstrum advantages of detecting cycle component and separation side band of the complex signal with the advantages of advanced signal processing will be a new way and be widely applied in the in the field of fault detection

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