Bearing Fault Diagnosis Method Based on Hilbert Envelope Demodulation Analysis

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Abstract. A digital envelope analysis method based on Hilbert transform is proposed to solve the problems of bearing fault signals such as non-stationary, faintness and non-linearity. This method firstly compares the power spectrums between the fault signal and the normal signal. In order to improve the signal-to-noise ratio, a frequency band with a large difference between the two power spectrums is selected. Secondly, the frequency band is used to remove the high frequency carrier and retain the low frequency part which contains fault information only. In order to avoid the wrapping effect in the circular convolution, the tail of the frequency band is filled with zero to double its length. Then the inverse Fourier transform and the Fourier transform are applied to the transformed signal. Finally, the fault diagnosis is made for its envelope spectrum. This method is applied to the bearing fault signal of case Western Reserve University in the United States. The results show that this method can diagnose the fault type and fault location well and has high sensitivity.

1. Introduction
Rolling bearing is one of the most commonly used parts in all kinds of rotating machinery and one of the vulnerable parts of rotating machinery. According to statistics, 30% of the fault of rotating machinery is caused by bearing failure, so it has significant effects on the working condition of the machine greatly. Bearing defects may cause severe vibration and noise of the machine, and even the equipment damage. Therefore, it is very necessary for us to carry out research in condition detection and fault diagnosis for bearings [1].

At present, scholars at home and abroad have done a lot of research on the diagnosis method of bearing vibration analysis. In the literature [2], a bearing fault diagnosis method based on variational modal decomposition and envelope demodulation is proposed. Literature [3] has proposed an improved fault diagnosis method for rolling bearing with envelope spectrum based on empirical mode decomposition and spectral kurtosis. Literature [4] combines wavelet packet with approximate entropy to diagnose cylindrical roller bearing. Literature [5] combines harmonic wavelet packets transform with information entropy and is successfully used in the diagnosis of three bearing conditions. These methods for fault diagnosis provides the necessary means, its basic principle is based on the actual situation to choose a high frequency vibration mode as the research object, through the center frequency is equal to the natural frequency of the band pass filter to the analysis of vibration signal is extracted, and then through the envelope detector detection, remove the high frequency attenuation vibration frequency components, get only contains the fault feature information of low frequency envelope signal, then carries on the envelope analysis [6]. The method of envelope demodulation analysis based on Hilbert transform is applied to bearing fault diagnosis. From the fault mechanism of
rolling bearing, the failure characteristic frequency can be clearly seen by analyzing the signal with the method of Fourier transform. The fault location is determined by filtering the vibration signal and detecting the envelope signal by envelope demodulation.

2. Vibration signal characteristics of rolling bearings

The vibration of rolling bearings can be caused by external vibration sources or by the structural characteristics and defects of the bearings themselves. The vibration signal has rich frequency components and wide frequency band, including bearing failure characteristic frequency and vibration characteristic frequency caused by machining and assembling error. This frequency band is susceptible to the influence of other parts and structures in the machine tool, and the energy of the characteristic frequency component information reflecting the damage type of fault impact is small at the initial stage of failure, and the signal-to-noise ratio is low. Medium frequency band (1-20 kHz), includes the natural vibration frequency of bearing outer ring caused by the surface damage of bearing original. By analyzing the vibration signal in this frequency band, the damage fault of bearing can be diagnosed. Due to bearing damage caused by shock induced bearing high frequency vibration generally in more than 20 kHz, if measuring sensor resonance frequency is higher, bearing fault can also be diagnosed by analysis of this band [7].

The calculation formula of bearing failure characteristic frequency is obtained by analyzing the relative motion relation between bearing elements. Let the rotation frequency of the bearing be \( f \), the bearing pitch is \( D \), the diameter of the rolling body is \( d \), the contact Angle is \( \varphi \), the number of stroller is \( n \), then we can get:

\[
BPFI_{\text{inner ring fault}} = \frac{n f}{2} \left(1 + \frac{d}{D} \cos \varphi \right)
\]

(1)

\[
BPFO_{\text{outer ring fault}} = \frac{n f}{2} \left(1 - \frac{d}{D} \cos \varphi \right)
\]

(2)

\[
BSF_{\text{rolling body failure}} = \frac{D f}{2d} \left[1 - \left(\frac{d}{D} \cos \varphi \right)^2 \right]
\]

(3)

\[
FTF_{\text{cage failure}} = \frac{f}{2} \left(1 - \frac{d}{D} \cos \varphi \right)
\]

(4)

Generally speaking, the failure characteristic frequency of rolling bearing is less than 1 kHz, which is one of the important characteristic information of rolling bearing failure. When the bearing fails, the fault characteristic frequency spectral line will appear in its vibration spectrum in theory, but in practice, these spectral lines cannot always appear in the theoretical value accurately. In general, the edge frequency band of the characteristic frequency spectrum line and its harmonic center line is modulated by the rotation frequency of the shaft. These phenomena are mainly caused by the error of bearing installation and other conditions, but generally will not affect the diagnosis of rolling bearing.

3. Data Envelopment Analysis

3.1. Hilbert demodulation analysis

When there is a fault in the rolling bearing, each time the rolling body passes through the fault position, an impulse of impact will be generated, which will cause the high frequency natural vibration of the bearing. With the vibration frequency as the carrier, the passing frequency of the impulse is modulated by the modulated wave. Make the bearing vibration waveform eventually showed the characteristics of amplitude modulation and frequency modulation, using band-pass filter to remove low frequency interference, only by modulation of the high frequency component, through demodulation technique to fault information separated from complex amplitude modulation signal.

The Hilbert transform of the vibration signal and the original signal are used to form a set of analytic signals, which are envelope signals.

Its Hilbert transform is defined as:
\[ x(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau = \frac{1}{\pi} \int_{-\infty}^{\infty} x(t - \tau) d\tau \]
\[ = x(t) \ast \frac{1}{\pi t} \quad (5) \]

The analytic signal is composed of Hilbert transform and original signal:
\[ z(t) = x(t) + j \hat{x}(t) = a(t)e^{jf(t)} \quad (6) \]
\[ a(t) = \sqrt{x^2(t) + \hat{x}^2(t)} \quad (7) \]
\[ \phi(t) = \arctan \left( \frac{\hat{x}(t)}{x(t)} \right) \quad (8) \]

It can be seen from the formula that the envelope of the analytic signal is the envelope of the original vibration signal with certain transformation in amplitude. Fault information can be obtained by envelope demodulation of this analytic signal. In order to improve the signal-to-noise ratio of the modulated signal, the demodulation analysis is carried out for a certain frequency band with a large difference between the fault signal and the normal signal.

(1) The band pass filter is used to extract the frequency range that needs to be modulated and move to 0 frequency, as shown in fig.1.

As can be seen from figure 1, the amplitude of the analytic signal after passing through the band pass filter has not changed.

(2) From the Fourier transform of the analytic signal, we can see
\[ Z(j\Omega) = X(j\Omega) + j\hat{X}(j\Omega) = X(j\Omega) + jH(j\Omega)X(j\Omega) \quad (9) \]

So
\[ Z(j\Omega) = \begin{cases} 2X(j\Omega) & \Omega > 0 \\ 0 & \Omega < 0 \end{cases} \quad (10) \]

The amplitude of the analytical signal in the positive frequency part is twice that of the original signal, and the analytical signal at the negative frequency is 0. So we can move the low frequency part that contains the fault information to the left of the sampling frequency, the inverse Fourier transform to the time domain. Or as \(c\) and \(d\) in figure 2 multiply their amplitude by 2, and add 0 to double their length.

Figure 1. Extraction of a frequency band by a zoom processor.
Figure 2. Block shift procedure for selection of frequency band for inverse transformation.

(3) Inverse Fourier transforms the shifted frequency to the time domain. At this time, the time domain signal contains amplitude modulation information caused by failure.

\[
x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(f) e^{j2\pi f_0 df}
\]

(11)

(4) Take the envelope of the signal and make the Fourier transform.

\[
X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt
\]

(12)

By analyzing the envelope spectrum of the signal, it can be clearly seen that the envelope of the signal at some frequency points presents a mutation, which is the result of amplitude modulation.

Envelope analysis is one of the most effective methods in fault diagnosis. It can clearly indicate the location and severity of the failure. The filtering, translation and transformation of vibration signal are also called envelope demodulation. Envelope mediation can mediate fault related signals from high frequency modulation signals, so as to avoid confusion with other low frequency interference, and has high diagnostic reliability and sensitivity.

3.2. Bearing fault diagnosis process based on Hilbert transform

The bearing fault diagnosis method based on Hilbert transform is one of the most effective and direct methods.

Based on the selected frequency signal is a series of Fourier transform and inverse Fourier transform, used in the final frequency spectrum of the signal envelope diagram has a corresponding frequency point mutation compared with different types of fault characteristic frequency, in order to complete fault diagnosis.

The method steps are shown in figure 3:

Figure 3. The flow chart of bearing fault diagnosis based on envelope analysis.
4. Bearing fault diagnosis example

4.1. Introduction to the experimental platform

According to the vibration signal measured by Case Western Reserve University [8, 9], the feasibility of this method is verified. The experimental table is shown in figure 4:

![Figure 4. Bearing fault simulation test bench of CWRU.](image)

The test bearing is a deep groove ball bearing of SKF 6205-2rs type. The specific specifications are shown in table 1 (unit: mm). The fault of bearing is the pitting failure caused by electric spark on the bearing surface. The vibration signal of the bearing is collected by the vibration acceleration sensor mounted on the drive end of the motor and above the bearing seat of the fan end.

| Inner ring diameter | outer ring diameter | Rolling diameter | Pitch diameter | Number of rolls |
|--------------------|--------------------|------------------|----------------|----------------|
| 25.0012            | 51.9989            | 7.94             | 39.0398        | 9              |

The bearing fault data used in this paper include the vibration signals of outer ring, inner ring, rolling body fault and normal state [10-12]. These signals are collected at the motor drive end with a sampling frequency of 12000Hz and a motor speed of 1750r/min. The outer ring due to the influence of load and show the fault status is different, so the external circle respectively at 3 o'clock and 6 o'clock direction orthogonal direction, namely the fault processing center direction and the opposite direction.

4.2. Vibration signal envelope analysis results

By comparing the power spectrum of fault signal and normal signal, it can be found that there is a big difference between them. This provides convenience for the extraction of the frequency band. In this paper, the power spectrum analysis of the inner ring signal and the normal signal is carried out. The comparison results are shown in figure 5:

![Figure 5. Inner ring signal is compared with the normal signal power spectrum.](image)
104.56 Hz, the inner ring of the fault characteristic frequency of 157.94 Hz, fault characteristic frequency of 137.48 Hz, roller cage fault characteristic frequency of 11.63 Hz, in addition to turn the frequency of 29.3 Hz. The analysis process of the third part of the paper is used to further process the signal. The envelope analysis results are shown in figure 6:

![Figure 6. Envelope analysis result of inner ring signals.](image)

It is clearly observed from the figure, 29.3 Hz, 158.2 Hz, 316.4 Hz, and 158.2 Hz four obvious peaks, 29.3 Hz frequency corresponds to the transform, and 158.2 Hz, 316.4 Hz and 316.4 Hz is very close to the inner ring fault frequency of 157.9 Hz and its frequency doubling, so it can conclude that the bearing inner ring failed.

The same method is used to analyze the outer ring signal and the rolling body signal respectively. The analysis results are shown in figure 7 and 8:

![Figure 7. Envelope analysis result of outer ring signals](image)

Figure 7 is the spectral envelope line bearing outer ring fault feature component, can be seen in the figure at 29.3 Hz, 105.5 Hz and 210.9 Hz obvious peaks, of which 105.5 Hz and 210.9 Hz very close to the outer ring fault characteristic frequency of 104.56 Hz and twice the frequency of 209.12 Hz, it can be concluded that the outer ring failure frequency. However, there is a certain gap between the failure frequency and the theoretical value, which is mainly caused by skidding, friction and inaccurate measurement of bearing parameters. 29.3Hz corresponds to the frequency of revolution, because the outer ring rotates on the axis, and it can be found that there are equally spaced modulation spectral lines on both sides of 105.5Hz, which is the modulation effect of frequency conversion.

![Figure 8. Envelope analysis result of rolling element signals](image)

Figure 8 is the envelope spectrum line of the fault feature components of the bearing rolling body.
It can be clearly seen from the figure that 29.3Hz, 11.56Hz, 99.61Hz, 129.1Hz and 158.4Hz are respectively. While 29.3Hz corresponds to the frequency conversion, 11.56Hz corresponds to the fault characteristic frequency of the cage. For 99.61Hz, 129.1Hz and 158.4Hz, the difference between them is 29.3Hz. At the same time, it can also be found that the fault characteristic frequency of 129.1Hz is close to 137.48 Hz of the rolling body, so it can be known that there is a fault in the rolling body. Compared with the former two kinds of fault, fault features of rolling frequency differ with the theoretical value is bigger, this is because the rolling element distribution, outer ring and cage, is strongly influenced by them, own roller rotation phenomenon at the same time, so the information contained in the vibration signal is much more complicated.

5. Conclusion
(1) Since the vibration signal of rolling bearing is periodic, the periodic vibration pulse caused by bearing fault causes high frequency natural vibration of bearing. So, the fault information can be attached to the high frequency vibration signal, and the vibration signal has the characteristics of frequency modulation and amplitude modulation due to the modulation effect.
(2) Digital envelope demodulation method used in this article can automatically calculate the maximum frequency in the power spectrum contrast difference, improve the signal-to-noise ratio in the analysis and facilitate subsequent fault information diagnosis research.
(3) To avoid the surround effect in the cyclic convolution, we has carried on the zero padding to move after the frequency operation, thus making the transform length doubled, and sampling frequency to twice, so the frequency resolution is ensured by this way.

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