Motor Fault Diagnosis Based on Wavelet Transform

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Abstract

The wavelet transform theory is used to motor fault diagnosis in this paper, considering its characteristics of multi-resolution and stronger feature extraction ability than Fourier. The paper emphasizes de-noising and eliminating the singular value point of the wavelet transform in the non-stationary signal. And it makes a detailed and in-depth analysis about how to detect the frequency components of weak signal by using equivalent power spectrum of reconstruction signal, which is acquired by using the wavelet transform. Through the comparison analysis of the simulation signal and motor vibration signal's experimental data, the corresponding energy of original signal's equivalent power spectrum and reconstructing signal's equivalent power spectrum are compared to determine the fault frequency, so as to accurately find out the motor fault.

Keywords: wavelet transform, motor, equivalent power spectrum, weak signal

1. Introduction

The normal operation of the motor is of great significance for the safety, high efficiency, high quality and low consumption operation in the process of manufacturing and production. In the operation process, the performance of the motor gradually deteriorates, influenced by various factors, such as electrical, thermal, mechanical factors and the surrounding environment, which ultimately make the motor break down. Thus the requirement of early diagnosis and early warning is becoming increasingly urgent. Through analysis of the vibration collection signal, the fault source separation and fault pattern recognition in motor running state, the motor fault can be detected and further deterioration can be prevented, reducing production losses caused by unexpected incidents.

The research of motor fault diagnosis technology has begun since the 1960s abroad; the importance of the motor equipment fault diagnosis technique has already been recognized in China. But until the 1980s, we are dedicated to the study of electrical equipment failure online diagnosis system. In recent ten years, motor fault diagnosis technology has been developed rapidly; the analytical model method, signal processing and expert knowledge are accounted the main research components of fault diagnosis technology, including relevant function higher-order statistics, spectrum analysis, etc. However, these methods are only confined to the fault appearing in the stable operation process of the motor. People pay more and more attention to real-time diagnosis of the faults under dynamic conditions such as in the starting, acceleration, braking and other dynamic periods of the motor. For the failure of the motor stator, the Hilbert transform is used to signal preprocessing, adopting wavelet packet decomposition to achieve stator fault features extraction. The reconstructed coefficients using sub-band node RMS rate of change are considered as the fault feature indicator [1]. It adopts Park's vector method to diagnose motor phase failure, making stator three phase current from (a, b, c) coordinates down-conversion (d, q) coordinates. The vector trajectory of normal operation motor can only be close to a circle, it becomes an ellipse when there are all kinds of faults [2]. But only when the faults go to a certain extent, and it will have a certain influence on the trajectory.

Wavelet transform is a hot technology in signal processing. Because it has good time-frequency localization characteristics, and can accurately grasps the transient signal [3], it is very suitable for the analysis of the motor dynamic signal. The results of the study show that: the wavelet decomposition and reconstruction can not only be able to remove the singular point

of acquisition signal, according to the high-frequency coefficients also can accurately determine the location of the point appearing singular value ,which is the time point of failure. By the equivalent power spectrum of the wavelet coefficients, useful frequency information can be extracted and thus the motor fault is diagnosed accurately.

2. Wavelet Transform

As a new signal processing method [4], wavelet analysis makes the various frequency components decomposed into non-overlapping band, providing an effective way for signal filtering, signal-to-noise separation and feature extraction. After wavelet transform, the signal characteristics (such as singular point) have the same time domain location at different decomposition scales, and remain unchanged with original signal analysis frequency. In the time domain, the total information of every decomposed is more than the original signal, the time-domain characteristics of the original signal can be maintained; and has a good filter characteristic in the frequency domain, each scale band between the overlapping.

Figure 1 is wavelet transform principle of 3 scales. The $\lambda_1(t)$, $\lambda_2(t)$ and $\lambda_3(t)$ is the approximation coefficients and the $\gamma_1(t)$, $\gamma_2(t)$ and $\gamma_3(t)$ is the detail coefficients when the scale j = 1, 2 and 3. And the $h(z)$, $h(z^2)$ and $h(z^4)$ is the low-pass and the $g(z)$, $g(z^2)$ and $g(z^4)$ is the high-pass filter. Here:

$$\begin{aligned} x(z) &= \lambda_1(z) + \gamma_1(z) \\ &= \lambda_2(z) + \gamma_2(z) + \gamma_1(z) \\ &= \lambda_3(z) + \gamma_3(z) + \gamma_2(z) + \gamma_1(z) \end{aligned} \tag{1}$$

Like this constantly decomposition, so it can realize the signal multi-resolution decomposition.
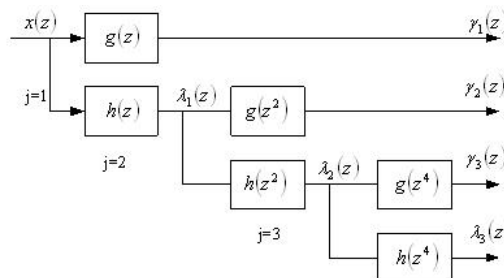

Figure 1. Wavelet Transform Principle

2.1. Wavelet Transform De-noising

Signal noise reduction processing is an important application of wavelet analysis. In the practical engineering applications, the analyzed signal may contain many peaks or mutation parts, and the noise is not smooth white noise. To the noise reduction processing of such signals, the traditional Fourier transform analysis method appears helpless, because it cannot give the changes of the signal at a point in time.

Because the engine signal of each state is present interference, and the interference affects the extraction of characteristic parameters of fault, the interference signal should be removed first. We can remove the interference signal by using the excellent filtering properties of the wavelet transform, and get the characteristic information of the different states.

2.2. Wavelet Transform Discontinuous Point Detection

The abrupt change point of the signal often contains important information for equipment operating status; they reflect the failure caused by the crash, oscillations, friction and structural deformation, etc. The abrupt change point of the signal is also known as singular

point. Judging the emergence moment of singular values of status signal to realize quantitative description of the signal singularity has important meaning in the field of signal processing and fault diagnosis.

Generally speaking, if the function is somewhere discontinuity or the derivative of a given order is discontinuous; it says the function has the characteristic of singularity at this point [5]. In order to investigate the relationship of different scale wavelet transform and singularity, we adopt the convolution of the wavelet transform. Treated scale a as independent variables, thus expression of wavelet transform is as follows:

$$Wf(a,x) = \int_R f(t)\frac{1}{a}\psi\left(\frac{x-t}{a}\right)dt = f * \psi_a(t)$$

$$a \in R^*, \quad x \in R$$

(2)

When wavelet ψ has compact support, i.e. there is $k > 0$. If $|x| > k$, $\psi(x) = 0$. For the formula (2), if $\left|\frac{x-t}{a}\right| > k$, $\psi\left(\frac{x-t}{a}\right) = 0$. Thus formula (2) equals to zero outside $(x - ak, x + ak)$. Namely:

$$Wf(a,k) = \int_{x-ak}^{x+ak}\frac{1}{a}f(x)\psi\left(\frac{x-t}{a}\right)dt$$

(3)

When $a \to 0$, wavelet transform is on the reaction of the localized states in the point x, namely we can take advantage of wavelet transform to judge the local singularity of function.

Since the Fourier transform converts the signal into a pure frequency domain signal, it does not have time resolution, so the change point of the signal frequency can't be detected by it. The time point of the signal mutation can be accurately detected by using wavelet transform. Through the signal's multi-scale analysis, when the signal appears mutation, the coefficients of its wavelet transform have modulus maxima. We can determine the point in time of the failure through the modulus maxima point detection.

2.3. Signal Identification of Wavelet Transform

In the actual problem, signals that need to be addressed are often mixed with other elements, for example, the high-frequency information like noise. Generally, the general factors of reacting system itself nature are often some slowly changing information. Through wavelet transform, along with the increasing number of layers of the wavelet transform decomposition, approximate coefficients contain less high frequency information. With the high frequency component filtered out step by step, the remaining ingredients are getting close to the overall trends of the signal.

2.4. Identification Signal Spectrum Components

In the actual signal processing, the signal often contains a lot of frequency components. If the accurate position of the signal component is need not to determine, the traditional Fourier transform method is very effective to solve this problem. Because after the wavelet decomposition, different scales have different time and frequency resolutions, and thus the different frequency components in signal can be separated by using wavelet decomposition. By means of equivalent power spectrum, most of frequency components contained in the signal can be revealed.

Then, through an example, we prove the possibility and usefulness of wavelet transform applied in practice. Constructs a signal, like:

$$x(t) = x_1(t) + x_2(t)$$
$$x_1(t) = 0.08\cos(2\pi f_1 t) + 10\cos(2\pi f_2 t)$$
$$x_2(t) = 0.2\cos(2\pi f_3 t) + 0.5\cos(2\pi f_4 t)$$

(4)

Here, $f_1 = 25Hz$, $f_2 = 50Hz$ $f_3 = 150Hz$ and $f_4 = 300Hz$. In the simulation signal, random white noise following a normal distribution is added. Sampling frequency is $2000Hz$. The simulation signal and its power spectrum are shown in Figure 2. In the power spectrum diagram, only frequency f_2 can be seen.
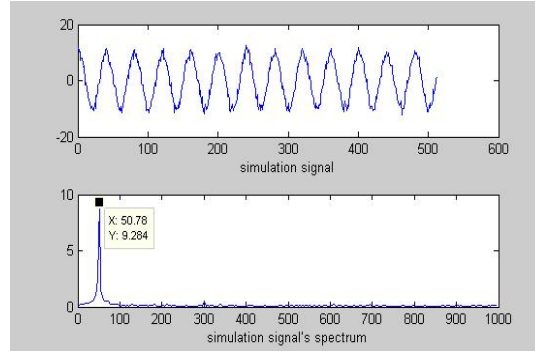

Figure 2. Simulation Signal and its Power Spectrum

The simulation signal is analyzed by using 5 layer multi-resolution through the selection of mother wavelet $db5$ and the result is shown in Figure 3. $a5$ is a low frequency coefficient of scale 5 and $d1 \sim d5$ is respectively the low frequency coefficient of scale $1 \sim 5$. Due to the sampling frequency is $2000Hz$, the main frequency band range of $d1 \sim d5$ is respectively $500Hz \sim 1000Hz$, $250Hz \sim 500Hz$, $125Hz \sim 250Hz$ $62.5Hz \sim 125Hz$ and $32.125Hz \sim 62.5Hz$. The frequency band range of $a5$ is $0Hz \sim 32.125Hz$. Clearly, $500Hz \sim 1000Hz$ does not contain the main components of the signal, and its main component is the noise. Because of the interference of noise, the development trend of the signal is not visible. The development trend of the signal after wavelet de-noising is clearer.

The frequency spectrum of a signal means that the signal is transformed from time domain to a frequency domain, and it is only different representation method of the same kind of signal. But the signal is studied by the power spectrum [6, 7] that is from the energy point of view, which shows the unit band signal power changes with frequency conversion. The Fourier transform of the random signal does not exist; therefore, we study its power spectrum.
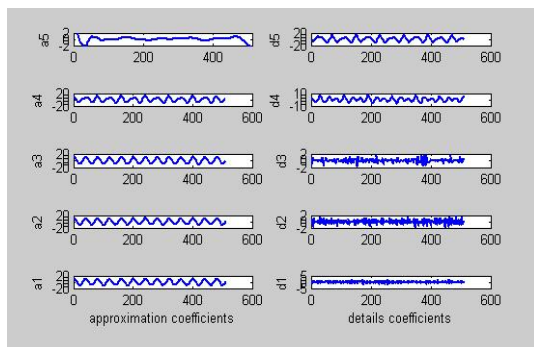

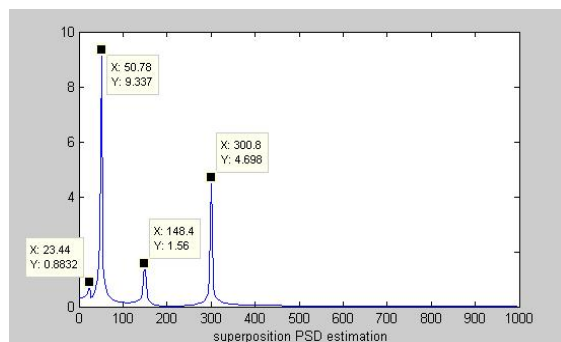Figure 3. Wavelet Analysis of Simulation Signal

Figure 4. Equivalent Power Spectrum Diagram of Simulation Signal

In order to effectively extract the weak component of the signal, high-frequency noise component $d1$ is ignored. The power spectrum of $d2 \sim d5$ and $a5$ are obtained separately. The power spectrum diagram is normalized to determine the maximum value of each spectrum.

Since the sampling frequency of each scale is the same, so they have the same frequency. The equivalent power spectrum can be obtained by the superposition of the power spectrum graph. The result is shown in Figure 4. The power spectrum peak of $f_1 = 25Hz$, $f_2 = 50Hz$, $f_3 = 150Hz$ and $f_4 = 300Hz$ of the simulation signal can clearly be observed in Figure 4. Through equivalent power spectrum of the wavelet transform coefficients, the weaker frequency components in the original signal can be detected.

3. Application of Wavelet Transform in Motor Fault Diagnosis
3.1. Acquisition Parameters of Vibration Signal
The sampling frequency is:

$$f_s = 2000Hz \tag{5}$$

Sampling points is:

$$N = 1024 \tag{6}$$

According to the Nyquist sampling theorem, it is known that the highest standard frequency:

$$f_{max} = f_s / 2 = 1000Hz \tag{7}$$

3.2. Fault Identification and Treatment
Compared the actual measured characteristics with the archival characteristic information, whether the failure occurred can be determined. If no failure occurs, continue to monitor the motor status. If there are some faults, analyze data and determine the fault types. Localized features of wavelet analysis make it widely applied in the signal preprocessing. Figure 5 is a signal preprocessing process.
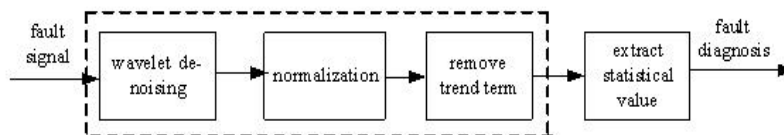

Figure 5. Signal Preprocessing

3.3. Motor Faults
There are various faults [8, 9] in the operation process of the motor and the vibration is a widespread phenomenon of all equipment during operation. The vibration of the motor during operation is divided into two kinds: mechanical vibration and electromagnetic vibration. Mechanical vibration will be caused when the motor rotor imbalance, rolling bearings abnormalities, the plain bearings abnormal, installation bad and adjustment adverse, among it the rotor unbalance is the most common. The reason that cause the rotor imbalance mainly has: rotor parts fall off or shift, rotor coil shift or loose due to insulation contraction, coupling imbalance, as well as the cooling fan and the rotor surface evenly fouling, etc. The latter is related to the motor assembly, such as stator inter-turn short circuit, broken rotor bars and uneven air gap.

4. Experimental Results and Analysis
In this paper, the main pump motor of hydraulic station is taken as an example. The application of wavelet transform in the motor fault diagnosis is expounded. The main pump motor of hydraulic station is a three-phase asynchronous motor, and its rated speed is 1480 RPM.

Motor fault diagnosis signal that is got through the experiment is preprocessed at first in the paper. Then the wavelet transform technique is applied to analyze the signal and get rid of the singular points. By equivalent power spectrum of the reconstructed signal, three sub-band signal components $1 \times RPM$, $2 \times RPM$ and $4 \times RPM$ of the fault signal can be extracted. The results confirm that the method of equivalent power spectrum of the wavelet analysis coefficients can effectively improve the frequency domain aliasing phenomenon and achieve good harmonic extraction results.

The original signal is shown in Figure 6. It is evident that there are two singular value points in $n = 500$ and $n = 800$.
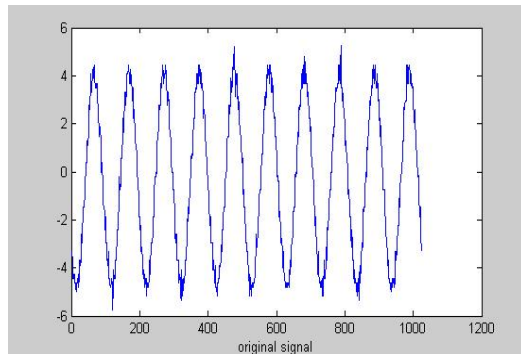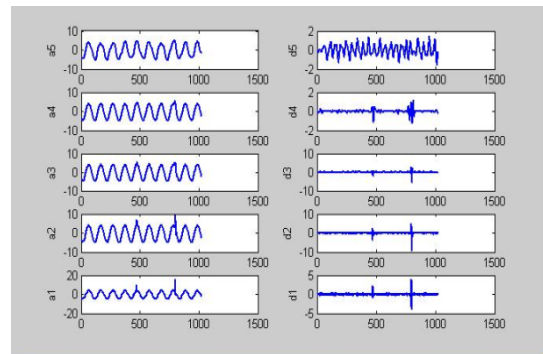

Figure 6. The Original Signal

Figure7. Wavelet Transform Results of Original Signal

The original signal is done by 5 layer decomposition using mother wavelet $db5$. The wavelet coefficients are shown in Figure 7. We can find the singular value points are contained in the detail signal $d1$, $d2$, $d3$ and $d4$, and the singular values are in good agreement with in the original signal.

In order to eliminate singularities and get reconstruction signal, $d1$, $d2$, $d3$ and $d4$ are equal to zero. The resulting signal waveform is as shown in Figure 8. Comparing Figure 6 and Figure 8, the singular value point is not very obvious after this method.

Equivalent power spectrum of reconstruction signal after eliminating the singular value point is shown in Figure 9. By contrast Figure 9 and Figure 2, the result can be got that if the original signal of motor vibration is analyzed by power spectrum directly, only the signal with large energy can be got. The energy of the weak signal is relatively small and its spectrum is not so obvious. Through the equivalent power spectrum of reconstruction signal after the wavelet coefficients, power spectrum peak of the weak signal is easier to be seen. This provides a new method for extracting weak signals in the motor fault diagnosis.
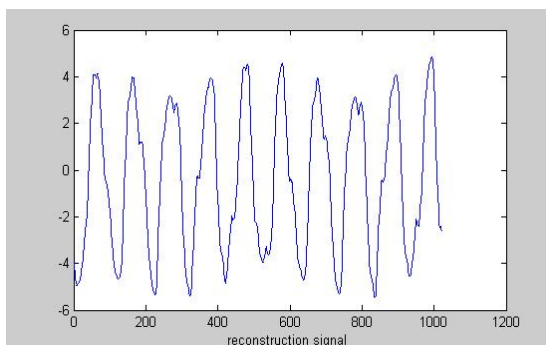

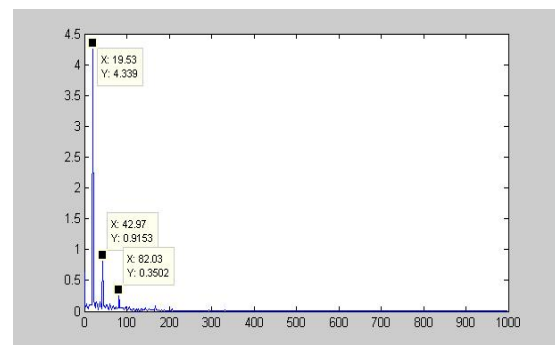Figure 8. Waveform after Eliminating Singularities

Figure 9. Equivalent Power Spectrum of Reconstruction Signal

As the motor speed is $1480 RPM$, the motor rotation frequency is $1480 \div 60 = 24.7 Hz$. In Figure 9, $19.53 Hz$ is around $24.7 Hz$. Due to the frequency accuracy of spectral analysis, there is often not peak in the theoretical rotational frequency. If there are obvious frequency component in the theory rotation frequency $\pm \Delta f$ range, then it can be considered as the rotational frequency of the motor. Therefore $19.53 Hz$ can be identified the rotational frequency of the motor. It can be seen that signal energy in $1 \times RPM$ is biggest, also the signal energy is bigger in $2 \times RPM$ and in $4 \times RPM$. Contrast to the characteristic frequency table [10] shown in Table 1, rotor unbalance and bearing looseness can be ascertained as the fault of the motor preliminarily. And because the signal energy in $1 \times RPM$ is biggest, the rotor imbalance is deemed to the main motor failure.

Table 1. Part Characteristic Frequency of the Motor Vibration

Fault type	Characteristic frequency
rotor unbalance	1×RPM
rotor misalignment	1×RPM,2×RPM
bearing looseness	various frequency doubling fraction frequency doubling
clearance vibration	0.4~0.5×RPM,1~5×RPM
rotor and stationary parts friction	higher harmonic, Low harmonic and combination harmonic

5. Conclusion

Based on wavelet transform, the fault diagnosis method has incomparable advantages in the aspect of fault diagnosis. It does not need the mathematical model of the object, the calculation is small and its ability to overcome the noise is strong. It has good time-frequency localization characteristics and it has the ability to make adaptive zoom and multi-resolution analysis of signals.

A simulation signal is taken as an example firstly. Through the selected mother wavelet function $db5$, the simulation signal is analyzed with wavelet transform. With the help of the equivalent power spectrum of the wavelet coefficients that already has got, we can verify the effectiveness and practicality of this method in extracting signal characteristic frequency. The weak signal in motor vibration is the research object in this paper. The weak signal in the original signal has been effectively extracted by this method and its power spectrum peak also has been clearly shown. Comparing power spectrum of the original signal and equivalent power spectrum of the reconstructed signal, most of the signal frequency contained in the original signal has been accurately acquired, especially the frequency of weak signal that is not easy to find by general method. By the comparative analysis of the signal frequency corresponding to each power spectrum peak and part of the characteristic frequency of vibration motor, motor fault diagnosis based on wavelet transform has been accurately realized.

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