Magnetic Bearing Rotor Vibration Analysis Based on the Harmonic Wavelet Package Algorithm

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***Abstract*—Analysis of the magnetic bearing rotor vibration is the base of the optimizing design, supervise and diagnosis of the magnetic bearing. Harmonic wavelet package was used for the analysis of the vibration signal, the 1 dimension time domain signal was mapped to 2 dimension time-frequency plane, and the 3 dimension time-frequency domain energy graph was constructed, then the analysis of the rotor vibration became intuitionistic and convenient. Via analysis of the time-frequency graph, the vibration in each time and each frequency was obtained. After the feature extraction from the time-frequency graph, the supervise and the diagnosis of the magnetic bearing can be realized.**

I. INTRODUCTION

The real-time analysis of magnetic bearing rotor operating conditions is the basis and premise of the monitoring and fault diagnosis of the magnetic bearing. Many scholars have conducted research on this issue, the methods used are mostly based on frequency domain analysis, usually through the rotor vibration signal FFT transform to analyze the operating conditions of the rotor. Because Fourier analysis is a kind of overall transformation, either in the time domain completely, or in the frequency domain completely, it can't organically combine signal's nature in two domains. This is because the signal waveform in the time domain does not contain any information of frequency domain, and the Fourier spectrum has no function of localized signal analysis, don't have any information of time domain. Thus signal analysis faced with a pair of fundamental contradiction: the localization of time domain and frequency domain. In the actual signal processing, especially for non-stationary signal such as vibration signals, the frequency domain characteristics of the signal at any time points are important. This prompts us to adopt time-frequency analysis method, so time and frequency domains can be combined to describe the joint characteristic of the two domains, and the time-frequency spectrum can be constituted. Wavelet analysis is an ideal time-frequency domain analysis, it is a kind of time-scale(time-frequency) analysis method. It has the characteristic of multi-resolution analysis, and has the ability to characterize the local features of time and frequency domain. It is a kind of time and frequency localized analysis method with variable time window and frequency window. I.e., in the low frequency portion it has higher frequency resolution and lower time resolution, while in the high frequency portion it has higher time resolution and a low frequency resolution, known as microscope of signal analysis. It is because of this feature, that wavelet analysis is self-adaptive. In engineering applications, particularly in signal processing, image processing, pattern recognition, seismic exploration, fault diagnosis and other monitoring field, wavelet transform is considered to be a major breakthrough on the tools and methods in recent years. It has become another sharp essential mathematical tools for technology workers. Magnetic bearing rotor vibration is a typical random signal, many of its important features are reflected in the details of some transient small-signals. As a time-frequency domain analysis method, wavelet transform can decompose the signal in time and frequency domain simultaneously, can easily capture the transient characteristics of the signal, particularly suitable for the analysis of random signal of the magnetic bearing rotor vibration. Although ordinary wavelet function is compactly supported in frequency domain, but its frequency domain characteristic is not ideal box-shaped, when multi-scale analyzing of signal, spectrum between adjacent scale aliased to each other, resulting in specific band signal extraction and analysis difficult. In this paper, harmonic wavelet with ideal frequency characteristics was introduced, and improved algorithm was given and was used to the analysis of the rotor vibration signal, the problems mentioned above were resolved. Experimental results show that the harmonic wavelet packet analysis is very suitable for the magnetic bearing rotor vibration analysis.

II. IMPROVED HARMONIC WAVELET ANALYSIS

Harmonic wavelet is a kind of complex wavelet raised by Cambridge university professor Newland[4], it has a desired box-shape property in frequency domain, Which avoids the spectrum leak and aliasing between adjacent subspace, maintains their respective independence, and greatly facilitates the analysis of signal characteristics.

Generating function of the harmonic wavelet is:

$$\psi(t) = \frac{\exp(i4\pi t) - \exp(i2\pi t)}{i2\pi t} \qquad (1)$$

Its box-shape spectrum was shown in Figure 1 .

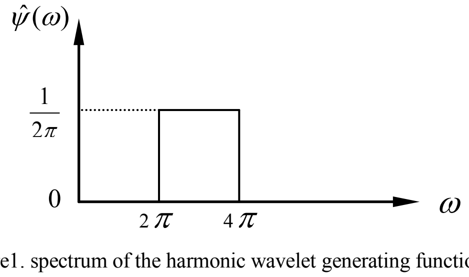


Figure1. spectrum of the harmonic wavelet generating function

Define harmonic wavelet's scale $m,n \in R^{+}$ ($m<n$) and translation k, then harmonic wavelet function is:

$$\psi(m,n,k)=\frac{\exp\left\lfloor i2n\pi(t-\frac{k}{n-m})\right\rfloor-\exp\left\lfloor i2m\pi(t-\frac{k}{n-m})\right\rfloor}{i2\pi(n-m)(t-\frac{k}{n-m})} \quad (2)$$

For the time-series signal $f(r), r=1,2,\cdots,N-1$,the discrete harmonic wavelet transform expression is:

$$W_d(m,n,k)=\frac{n-m}{N}\sum_{r=0}^{N-1} f(r)\bar{\psi}_{m,n}(r-\frac{k}{n-m}) \quad (3)$$

The traditional harmonic wavelet packet algorithm was divided by progressive one-half octave band split [4]. In the case of a certain sampling frequency, the frequency band division mode was fixed. In order to decompose the signal to either fine scale required, harmonic wavelet packet algorithm must be improved .

Define Hilbert space $\varphi_1,\varphi_2,\cdots\varphi_\infty$,where φ_j is generated by the translation series $\psi(m_j,n_j,k)$ ($1\le j<\infty$),and $n_j=m_{j+1}$. Let $n_j-m_j=n_{j+1}-m_{j+1}$,then $\varphi_1,\varphi_2,\cdots\varphi_\infty$ split the entire band evenly, each function space occupied band width $2\pi(n_j-m_j)$ .Can be proved:

1)The translation functions in a certain scale are mutually orthogonal.

2)Function $\psi(m_{j1},n_{j1},k)$ and $\psi(m_{j2},n_{j2},k)$ ($j1\ne j2$) belong to different scales are mutually orthogonal.

Therefore, when $b=n_j-m_j$ changing from small to large, decomposition of an time discrete signal by Formula(3) constitutes a different resolution harmonic wavelet packet analysis, this wavelet packet analysis can decompose the signal to any fine scale needed.

In this paper, Newland fast algorithm was used to fulfill the harmonic wavelet packet decomposition. The implementation process is as follows :

1)Determining the frequency resolution and time resolution according to the need, determining the sampling sequence length according to the sampling frequency.

2)Fulfill FFT to the sampling sequence, obtain frequency domain sequence having the equal length of time domain sequence.

3)According to the frequency and time resolution split the frequency domain sequence to segments with equal length .

4)Fulfill IFFT to each segment separately.

III. THE CONSTRUCTION OF THE HARMONIC WAVELET PACKET TIME-FREQUENCY GRAPH

Complex Fourier coefficients are obtained through the Fourier decomposition to signal, and the results can be visually displayed using spectrum graph. Similarly, the complex wavelet coefficients obtained through harmonic wavelet packet transform can be visually represented using wavelet packet time-frequency graph. Wavelet time-frequency graph is a diagram of time frequency grid, it is the three-dimensional graphic representation of the energy distribution of the signal in time-frequency domain. The construction approach of harmonic wavelet packet time-frequency graph is: Using wavelet coefficient number k (corresponding to the time t) as the horizontal axis, and the wavelet decomposition level j (corresponding frequency) as vertical axis to construct a plane, a surface is composed with the plane as reference plane. The height $H_{j,k}$ (expressed energy) of each point on the surface based on the plane is $H_{j,k}=2|a_{j,k}|^2$,where $a_{j,k}$ is the harmonic wavelet package coefficient. This makes the wavelet time-frequency grid graph. $H_{j,k}$ is chose in such a way so as to make the volume enclosed between the surface and the reference plane is exactly equal to the energy of the discrete signal $f(r)$, which meet the Parseval theorem.

Time-frequency energy distribution graph obtained by above method is dramatic ups and downs. In this paper , the log of the $H_{j,k}$ was took , so the grid graph is not so obtrusive, which is more conducive to observe less energy peaks , namely $H_{j,k}=\log(2|a_{j,k}|^2)$. When we are more concerned about the overall characteristics of the signal, the general form of the wavelet time-frequency graph is more appropriate, it can clearly shows the real energy distribution in each band of the signal. When we are more concerned with the details of local signals with weak energy , using the logarithmic form of wavelet time-frequency graph is more appropriate, it can prominently display the details of the high and low frequency component of the signal.

Select a number of rotor vibration signal segment from eddy current sensor output signal, and apply spectral analysis to them, a section of the spectrum was shown in Figure 2.

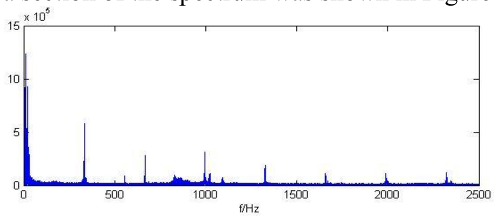


Figure2. Rotor vibration signal spectrum

As can be seen from Figure 2, at the frequency corresponding the rotor speed frequency (333Hz) and its high harmonic frequencies , the spectrum has high narrow peak , which is mainly caused by the active magnetic bearing rotor's imbalance. Besides these peaks, the spectrum of the rotor vibration is mainly concentrated within the low frequency of 100Hz, in addition, there are several peaks at high frequencies, mainly within 1500Hz.

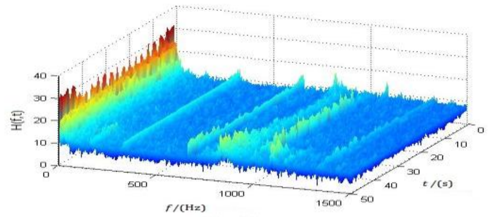
Figure 3 shows the harmonic wavelet packet decomposition time-frequency graph of several rotor vibration signal segment. Since the effective band of the signal is mainly within 1500Hz, the frequency range in graph is 0-1500Hz.

Low-frequency part of the time-frequency graph, i.e. waveform 0Hz nearby along the time axis provides an overview of the signal analyzed, the trends of the rotor vibration can be clearly seen from this section. High-frequency part of the time-frequency graph represents the vibration intensity of the signal in different time and frequency point on the basis of the signal profile. Therefore, harmonic wavelet package analysis has very good positioning capability in both time domain and frequency domain, the transient characteristics of the signal can be vividly demonstrated.

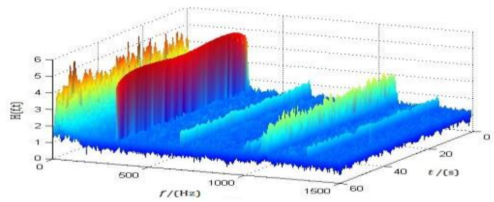
IV. ELECTROMAGNETIC BEARING ROTOR VIBRATION ANALYSIS BASED ON HARMONIC WAVELET PACKET FREQUENCY GRAPH

In order to finely analyze the time-frequency characteristics of the rotor vibration signal, frequency resolution and time resolution should be as high as possible, but the two resolutions are mutually constrained. In a certain sampling frequency, the two resolutions can be increased simultaneously by increasing the sampling length of digital series. But in order to ensure real-time analysis, the length of the sample sequence must be limited.

Considering the rotor vibration signal is mainly concentrated in the low frequency band , the frequency resolution is determined as 5Hz, in addition , restricted by the real-time constraints and the processor processing speed, the time resolution is determined as 0.2s. In the case of systematic sampling frequency of 5000Hz , a complete characteristics analysis cycle is 1s. Magnetic bearing rotor vibration signal wavelet packet frequency time-frequency graph of several different work conditions are shown in Figure 3.



(a)



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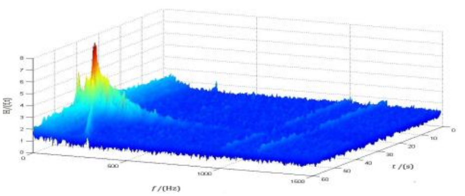

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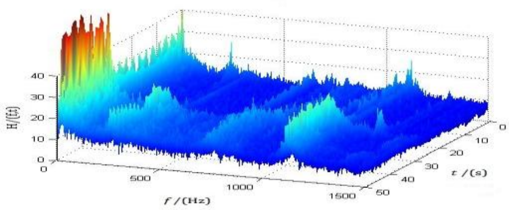

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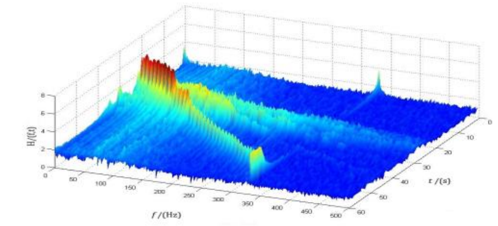
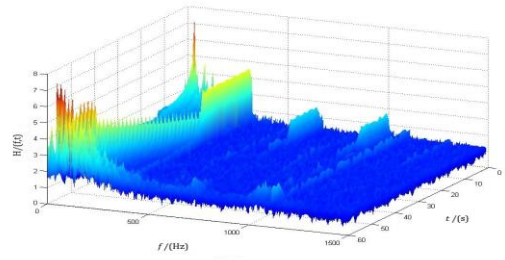


(e)



(f)

Figure3. Harmonic wavelet package time-frequency graph of rotor vibration signal in several different work conditions

Figure 3 (a) shows harmonic wavelet packet time-frequency graph of a normally rotating electromagnetic bearing. As can be seen from the figure, the vibration of the rotor are mainly concentrated in low frequency, rotor imbalance vibration in rotor rotating frequency (333Hz) and its 2,3,4 order harmonic are obvious distributed parallel to the time axis , but the magnitude is not very high, this shows the working condition of the rotor is well. In Figure (b) , the vibration amplitude with rotating frequency becomes large significantly, the unbalance vibration became the dominant vibration of the rotor, this means poor balancing of the rotor, the rotor still works stable, although there is a larger vibration amplitude. In Figure (c), the amplitude of the time-frequency graph mutated at about 35 seconds, and soon returned to normal levels, indicating that the intermittent collision failure occurs between rotor and auxiliary bearing. The failure vibration frequency range was 0-500Hz, and the peak was at around 100Hz. In Figure (d) , the amplitude mutated from about 35 seconds in each different frequency bands, the amplitude became significant large, and continued along the time axis , indicating the occurrence of a falling accident of the rotor. Figure (e) is the time-frequency graph during the startup of motor. It could be seen from the figure, from the startup of the motor at about 20 second, the rotating speed was straight up in the first 50 seconds until reached predetermined speed of 20000rpm (333Hz), and maintain that speed along the time axis. Within the first 10 seconds after starting of the motor, the rotor amplitude is large, but the amplitude becomes smaller along the time axis. Throughout the startup process, the vibration of 2,3,4 order harmonics were very obvious. Figure (f) is the time-frequency graph of the process of the motor was stopped, it can be seen from the figure, the rotor began linear deceleration from 20 second, and the rotor was completely stopped at 56 second. After the motor power was turned off, the vibration of the 2,3 order harmonics disappeared immediately. When approaching the rotor's stop, there was significantly large vibration amplitude, and the vibration frequency was mainly concentrated in the 0-250Hz.

V. CONCLUSION

Harmonic wavelet has Box-shape frequency domain characteristic, and it has fast algorithm based on FFT, this makes it gets successful applications in the vibration signal characteristic analysis of magnetic bearing rotor.

The grid time-frequency graph constructed based on harmonic wavelet packet fast algorithm can reflect the intuitive and specific information in each time-frequency point of the vibration signal, indicating the harmonic wavelets time-frequency graph has great value in engineering.

On the basis of harmonic wavelet packet decomposition of magnetic bearing rotor vibration signal, extracting rotor vibration characteristics from time-frequency expansion coefficients can further achieve real-time monitoring and fault diagnosis of the rotor operating conditions .

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