A Wavelet-based Method for Extracting Rolling Bearing Vibration Signal Envelope

Pi jun, Liao ming-fu
(Institute of Monitoring and Control for Rotating Machinery and Windturbines)
(Northwestern Polytechnical University, Xi'an 710072, China)
Address: 2#2225,Wang Yuan student department, No.88 of Lao Dong south street, Xi'an city ,ShannXi province, China.)
Postcode: 710068
Country :China

Abstract: -The rolling bearing signal is investigated according to the principal that the Wavelet can extract the signal envelope. A Wavelet-based self-information extracting envelope method (WSEM) is applied. Application of the method demonstrates that the method is effective to extract the rolling bearing signal envelope and is useful to analysis the rolling bearing faults.

Key words: Wavelet analysis , rolling bearing, extracting envelope, self-information

1.Introduction

Bearings are among the most important and frequently encountered components in the vast majority of rotating machines, their carrying capacity and reliability being prominent for the overall machine performance[1]. Vibration analysis is wildly used in rolling bearing fault diagnosis. Many methods have been developed for this purpose [2-6] .In bearing failure analysis, the low frequency phenomenon is the impact caused by a defect of a bearing , the high frequency carrier is a combination of the natural frequencies of the associated rolling element or even of the machine. In general, the Hilbert transform is used to extract the envelope of the vibration signal, but the Hilbert transform has no ability of exhibiting local features of signals[7].And this method is of leak error[8].

A major advantage of the wavelets is that this method can exhibit the local features of the signals and give an account of how energy distribution over frequencies changes from one instant to the next. They have already been used in specific case studies for bearing fault detection[9-11]. The method based on the wavelet to exact the envelope is proposed in this paper.

In section 2 of the paper, a brief review of the basic concepts of wavelet analysis is performed. The procedures of the proposed method are described in section 3. In section 4, the implementation of this method is provided, verifying the effectiveness of the method. The conclusion is given in section 5.

2.Basic concept of wavelet

(1) Wavelet function

Usually, wavelet function $\psi(t)$ is a band-pass filter. Wavelets refer to a family obtained from a single function $\psi(t)$ by translation and dilation:

$$\psi_{a,b}(t) = |a|^{-1/2}\psi\left(\frac{t-b}{a}\right) \quad a,b \in R, a > 0 \tag{1}$$

Where $\psi(t)$ is so-called ‘mother wavelet’, the functions $\{\psi_{a,b}(t)\}$ obtained from $\psi(t)$ are called the wavelet which is bi-parameter band-pass filters. Where a is the so-called scaling parameter, which changes the width of the filter frequency. The parameter b is the time localization parameter, which balance the information of time domain. As seen from above, the wavelet is the function with time and frequency domain localization. The wavelet transform of a finite energy signal $x(t)$ is following:

$$W(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}x(t)\psi^*(\frac{t-b}{a})dt \qquad (2)$$

Where $\psi^*(t)$ denotes the complex conjugate of $\psi(t)$.

(2)Morlet wavelet :

The Morlet wavelet in the time domain is defined:

$$\psi(t)=(e^{i\omega_0 t}-e^{-\frac{\omega_0^2}{2}})e^{-\frac{t^2}{2a^2}} \quad a>0 \qquad (3)$$

where $\psi(t)$ is a sinusoidal wave multiplied by Gaussian function. The imaginary part is the Hilbert transform of the real part.The Fourier transform of $\psi(t)$ is:

$$\psi(\omega)=\sqrt{2\pi a}[e^{-(\omega-\omega_0)^2/2a^2}-e^{-\omega_0/2}e^{-\omega^2/2a^2}] \qquad (4)$$

According to Equation (4), if $\omega=0$ then $\psi(\omega)=0$,that is ,the wavelet function $\psi(t)=(e^{i\omega_0 t}-e^{-\frac{\omega_0^2}{2}})e^{-\frac{t^2}{2a^2}}$ satisfies the admissible condition.

If $\omega_0\geq 5$ then $e^{-\omega_0/2}\cong 0$ .The function $\psi(t)$ can be expressed as:

$$\psi(t)=e^{i\omega_0 t}e^{-\frac{t^2}{2a^2}} \qquad (5)$$

The Fourier transform of equation(5) is:

$$\psi(\omega)=\sqrt{2\pi a}e^{-(\omega-\omega_0)^2/2a^2} \qquad (6)$$

3.Procedures of envelope construction

The Morlet wavelet transform of the $x(t)$ ($x(t)\in L^2(R)$) is:

$$WT_x(a,b)=\frac{1}{\sqrt{a}}\int x(t)\psi^*(\frac{t-b}{a})dt=<x(t),\psi_{ab}(t)> \qquad (7)$$

where $\psi(t)$ is Morlet wavelet. $\psi^*(\frac{t-b}{a})$ is the complex conjugate of $\psi(t)$ .If taking b =0 then getting:

$$\psi_{i,a,0}(t)=\frac{1}{\sqrt{a}}e^{-1/2(t/a)^2+j\omega_i(t/a)} \qquad (8)$$

substitute (8) into (7), the envelop of signal $x(t)$ is formed:

$$E_\psi(i,a)=\sqrt{\frac{1}{2\pi a}}|WT_x(i,a,0)| \qquad (9)$$

where $\sqrt{1/2\pi a}$ is to keep the amplitude of $x(t)$ the same. Fig.1 shows that the spectrum of envelope of Morlet wavelet when $a=0.2, f=160$.

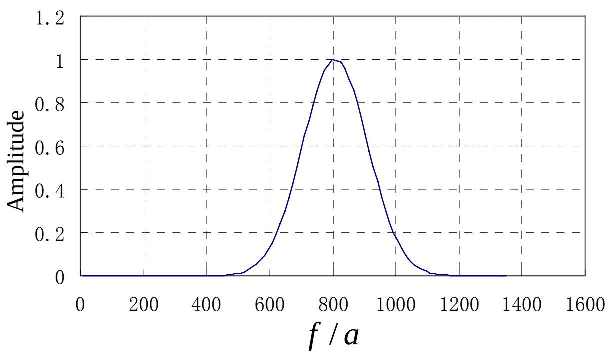

Fig.1 The spectrum of envelope of Morlet wavelet

As shown in Fig.1, the spectrum can extract the signal of the harmonics frequency equal to f/a. The parameter a balances the width. When a increases, the decay ratio of the Morlet wavelet in time domain increases. The decay ratio of corresponding Gaussian window increase too.

(1) Choosing a criterion:

The self-information of signal $x(t)$ is defined as:

$$I(x_k) = \sum_{k=1}^{N} \log \frac{1}{P(x_k)} = \sum_{k=1}^{N} -\log(P(x_k)) \tag{10}$$

where:

$$P(x_k) = \frac{|c_k|}{\sum_{i=1}^{N} |c_i|} \tag{11}$$

The self-information of signal $x(t)$ presents that the information amount of the signal(x_k) when the signal(x_k) happens. First choosing the certain frequency band at $0.2 f_{Nyq} \sim 0.8 f_{Nyq}$ (f_{Nyq} is Nyquist frequency of the signal $x(t)$).Calculation the self-information of the every series wavelet transform coefficients $C_w(i_0, j)$ when changing the parameter a. The optimal value of the parameter a is the one that leads to the minimal value of $I(x_i)$ of $C_w(i_0, j)$.

(2)The envelope of the signal

The final envelope of the signal $x(t)$ is formed as follows:

Expression(2) can take the following alternative form:

$$W(i, j) = F^{-1}\{X_j(f)\psi_i^*(f)\} \tag{12}$$

where:

$X_j(f)$: the Fourier transform of the discrete signal $x(j)$, $j = 1, 2, \cdots, n$.

$$\psi_i(f) = \psi_i^*(f) = \sqrt{2\pi a} e^{-2\pi^2 (f - f_i)^2 / a^2} \tag{13}$$

$$f_i = f_0 + (i-1) f_h, i = 1, \ldots N. \tag{14}$$

The wavelet coefficients of the signal $x(t): C_w(i, j) = |W(i, j)|$,the element of the matrix $C_w(i, j)$ is the certain frequency i envelope value at the certain time j. Keep the max value of the $C_w(i, j)$:

$$x_{\max}(j) = \max(C_w(i, j), i = 1, \ldots, N), \quad j = 1, \ldots, M \tag{15}$$

determining the final envelope of the signal $x(t)$.

The value of the parameter N is 20, $f_0 = 0.2 f_{Nyq}$.

4.Implement and result

The single outer ring fault point bearing of the experiment is of the type 307, the rotor speed is $534 r/\min$, the sampling frequency is 4.6kHz. The sensor is mounted near the bearing in radial direction.

The measured signal is presented in Fig.2. Fig.3 is the Hilbert transform envelope of the signal. Fig.4 shows the spectrum of the envelope of the Hilbert transform. The variation of the Morlet wavelet coefficients self-information as the parameter a range from 0.1~1.6 is presented in Fig.5. From the Fig.5 , the minimal value of $I(x_i)$ =5.142 is at $a = 0.2$ .So the optimal value of the parameter a is 0.2. The WSEM is shown in Fig.6.The spectrum of the WSEM is presented in Fig.7.The impulse series in time domain can be seen clearly in Fig.6 through comparing the Fig.3 and Fig.6.Comparing Fig.4 and Fig.7, the spectrum of WSME can be clearly seen the resonance amplitude of the frequency $f = 25.03$ corresponding to the frequency of the ball passing the outer ring f_{Bo} (24Hz).

The single inner ring fault points bearing of the experiment is of the type 307, the rotor speed is 2396 $r/\min$, the sampling frequency is 40.9kHz. The sensor is mounted near the bearing in radial direction.

The measured signal is presented in Fig.8. Fig.9 is the Hilbert transform envelope of the signal. Fig.10 shows the spectrum of the envelope of the Hilbert transform. The variation of the Morlet wavelet coefficients self-information as the parameter a range from 0.1~1.6 is presented in Fig.11。From the Fig.11 , the minimal value of $I(x_i)$ =9.0517 is at $a = 0.6$ .So the optimal value of the parameter a is 0.6. The WSEM is shown in Fig.12.The spectrum of the WSEM is presented in Fig.13.The impulse series in time domain can be seen clearly in Fig.12. through comparing the Fig.9 and Fig.12.Comparing the Fig.10 and Fig.13, the spectrum of WSME can be clearly seen the resonance amplitude of the frequency $f = 175$ corresponding to the frequency of the ball passing the inner ring f_{Bi} (175Hz).

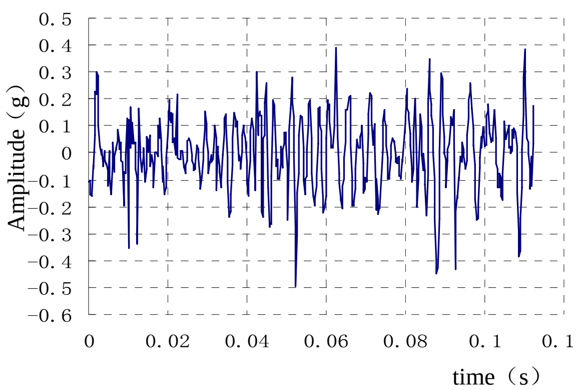

Fig.2 The measured signal(outer fault)

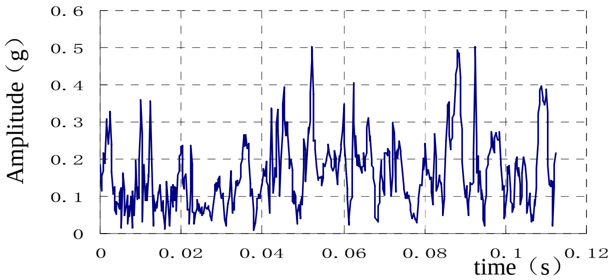

Fig.3 The Hilbert envelope(outer fault)

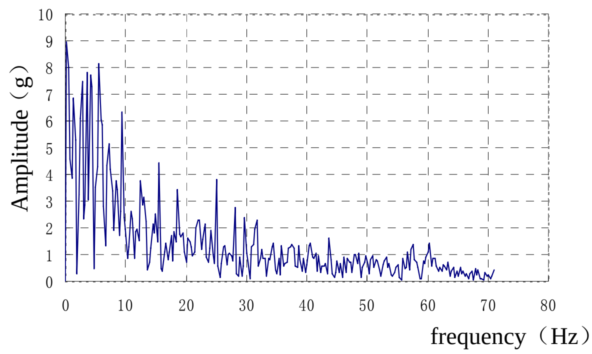

Fig.4 Spectrum of the Hilbert envelope(outer fault)

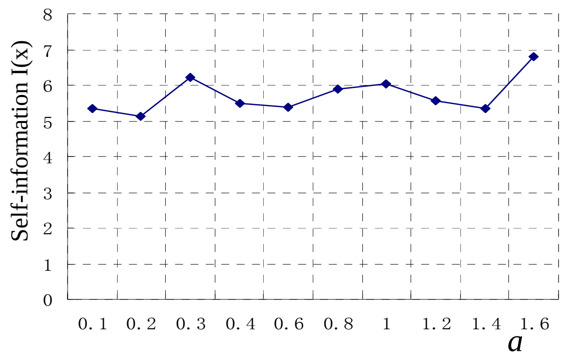

Fig.5 Variation of $I(x_i)$ as parameter a (outer fault)

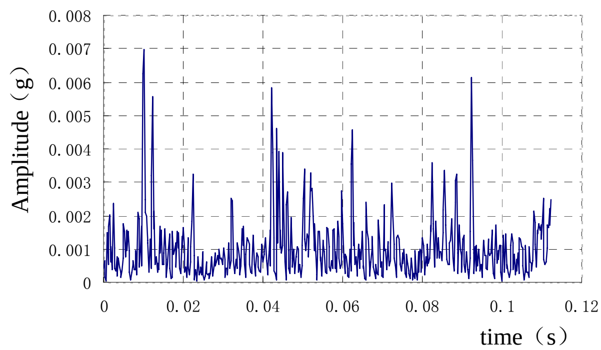

Fig.6 The envelope of WSEM(outer fault)

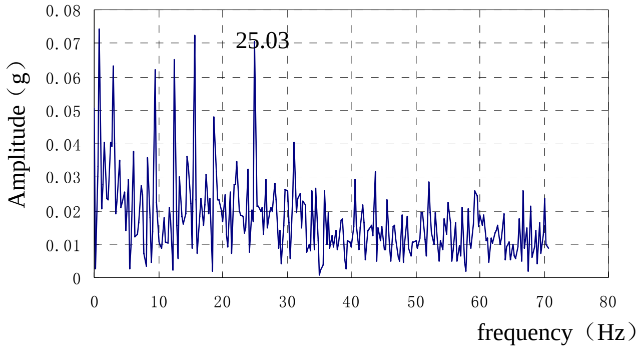

Fig.7 Spectrum of WSEM(outer fault)

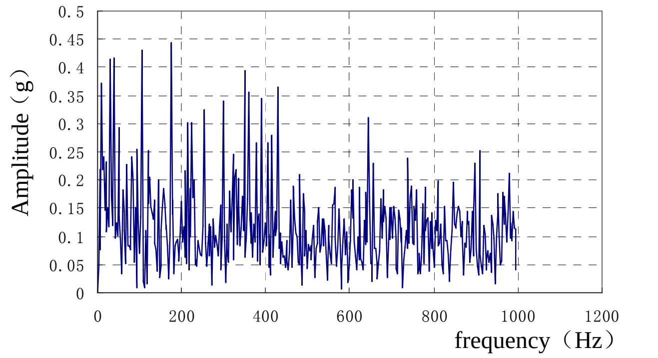

Fig.10 Spectrum of the Hilbert envelope(inner fault)

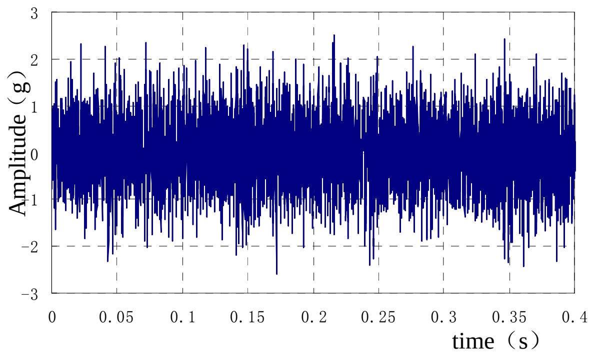

Fig.8 The measured signal (inner fault)

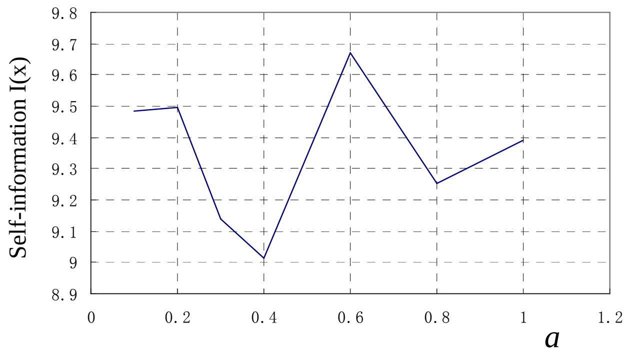

Fig.11 Variation of $I(x_i)$ as parameter a (inner fault)

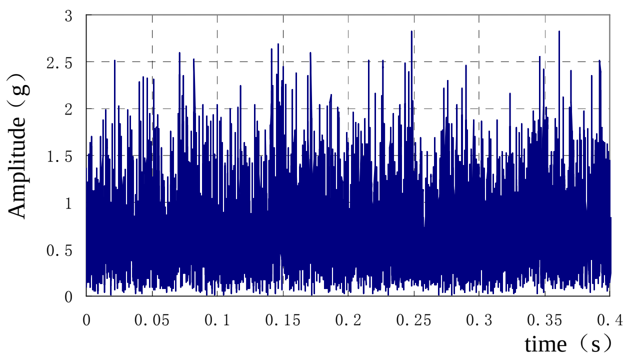

Fig.9 The Hilbert envelope (inner fault)

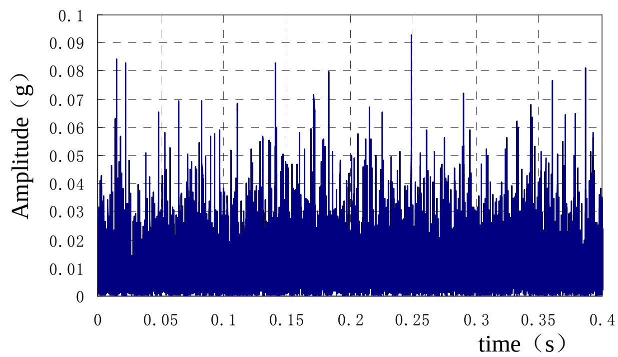

Fig.12 The envelope of WSEM(inner fault)

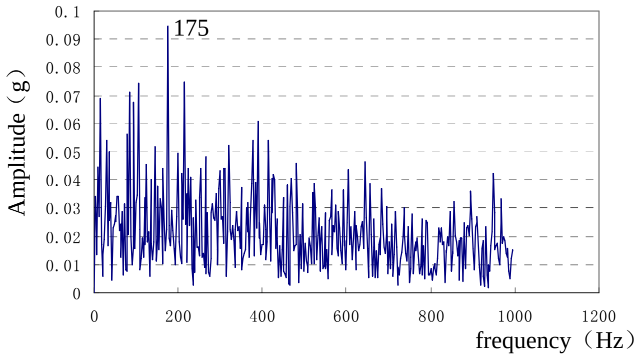

Fig.13 Spectrum of WSEM(inner fault)

5.Conclusion

The complex Morlet wavelet can be effectively construct the envelope of the signal. The implement of the WSEM is an effective demodulation method . After processing the vibration data using the proposed wavelet-based envelope analysis method, the corresponding fault characteristic frequency can be recognized easily .It can isolate the main impulses from the rest of the frequency of the signal. In generally, the envelope obtained from WSEM can retain all the corresponding necessary information.

REFERENCES:

[1] N.G.Nikolaou and I.A.Antoniadis, Demodulation of Vibration Signals Generated by Defects in Rolling Element Bearing Using Complex Shifted Morlet Wavelets. Mechanical Systems and Signal Processing,Vol 16,Issue 4,July 2002,pp 677-594.

[2] C.Cempel and W.J.Staszewski, Signal demodulation techniques in vibroacoustical diagnostics of machinery, Machine Dynamics Problems, Vol.2, 1991,pp.161-174.

[3] SK.Lee and P.R.White, Higner-order time-frequency analysis and its application to fault detection in rotating machinery,Mechanical Systems and Signal Processing,Vol.11,no,4, 1997,pp.637-650.

[4] R.Rubini and U.Meneghetti, Application of the envelope and wavelet transform analysis for the diagnosis of incipient faults in ball bearing, Mechanical Systems and Signal Processing, Vol.15, No.2, 2001,pp.287-302.

[5] W.J.Wang, Wavelets for detecting mechanical faults with hign sensitivity, Mechanical Systems and Signal Processing, Vol.15, No.4, 2001,pp.685-696.

[6] A.Agneni, On the use of the Gauss filter in modal parameter estimation. Mechanical Systems and Signal Processing ,Vol,14,2000,193-204.

[7] Liu ChongChun,Qiu Zhengding, A method based Morlet wavelet for extracting vibration signal envelope,Proceedings of the Fifth International Conference on Signal Proceeding, Vol.1,2000,pp.337-340.

[8] Huang Dishan, A wavelet-based algorithm for the Hilbert transform, Mechanical Systems and Signal Processing 10(2)(1996) ,pp125-134.

[9] C.J.Li and J.MA , Wavelet decomposition of vibrations for detection of bearing-localized defect.1997 NDT&E International 30,143-149.

[10] K.Mori, N.kasashima, T.Yoshioka and Y.ueno,Prediction of spalling on a ball bearing by applying the discrete wavelet transform to vibration signals. Wear 195,1996,pp.162-168.

[11] D.L.Donoho, De-noising by soft-thresholding, IEEE Transactions on Information Theory,Vol.41,No.3,1995,pp.613-627.