Rolling bearings fault feature extraction based on ESWT

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Abstract

In order to solve the problems that the deficiency of FSWT extracting impulse fault features from strong noise background, a fault feature extraction method for rolling bearing was proposed based on energy slice wavelet transform(ESWT).Firstly, introduced energy slices into wavelet transform. Secondly, vibration signals was transformed by wavelet transform to get the time-frequency characteristic, the time-frequency region was selected on the basis of the characteristic of the signal energy distribution, separated the time-frequency region which contains fault feature. Finally, through inverse ESWT transformation, the signal component was reconstructed to separate the time-frequency characteristics of effective signals. The proposed method was applied in simulated fault signals and actual fault signals of rolling bearings. The results showed that this method can extract fault characteristic frequency information of rolling bearings, the effectiveness of the proposed method is verified.

Keywords

ESWT; energy slice; rolling bearing; fault diagnosis.

1. Introduction

As the most widely used key component in rotating machinery, the working condition of rolling bearing affect the operational efficiency and service life of the machinery system directly[1-2].However, due to the internal excitation mechanism of bearings, complex background noise, and other interference sources, the fault characteristic information was weak and appeared in modulation form, result in difficult to extract fault features.

The time-frequency analysis method has been widely used in the diagnosis of vibration faults of rotating machinery since it could simultaneously extract local information in both the time and frequency domains of the signal.

Typical time-frequency analysis methods include short-time Fourier transform[3], Wigner Ville distribution[4], wavelet transform[5], and Hilbert-Huang transform[6], but they have their own limitations.

Frequency slice wavelet transform (FSWT), a new time-frequency signal analysis method proposed by Zhonghong Yan, (2009)[7]. which combines the advantages of STFT and wavelet transform. By introducing frequency slice functions, traditional Fourier transform can perform time-frequency analysis and achieve signal filtering and segmentation.

Chendong Duan et al. applied FSWT to the diagnosis of friction faults in refinery gearboxes and achieved good results[8]. The vibration signals collected on site contain strong narrowband pulses and random noise interference which reduced the frequency resolution of FSWT analysis,it can be concluded that there are serious shortcomings of FSWT in terms of noise resistance.

A rolling bearing fault diagnosis method based on energy slice wavelet transform was proposed in the article to address the shortcomings of frequency slice wavelet transform to extract impact fault features in strong background noise. This method can separate effective time-frequency features of signals in strong noise environments by introducing energy slicing.The experimental results of simulation data and rolling bearing data show that the method can effectively extract the fault characteristic frequency information of rolling bearings,the effectiveness of the proposed method is verified.

2. Energy Slice Wavelet Transform

For any $f(t) \in L^2(R)$, the Fourier Transform $\hat{\psi}(t)$ of function $\psi(t)$ exists, and the Energy Slice Wavelet Transform is stated as:

$$W(t,\omega,\lambda,\sigma) = \frac{1}{2\pi}\lambda\int_{-\infty}^{+\infty}\hat{f}(u)\hat{\psi}_c * [f(t)]e^{iut}du \tag{1}$$

$$\psi_c[f(t)] = \left(\frac{df(t)}{dt}\right)^2 - f(t)\frac{d^2 f(t)}{dt^2} = [\dot{f}(t)]^2 - f(t)\ddot{f}(t) \tag{2}$$

Where the σ is the scale factor and $\sigma \neq 0$;the λ is the energy factor and $\lambda \neq 0$,the σ、λ is constant or function of frequency ω、u and time t.In ESWT,the $\hat{\psi}_C[x(t)]$ is the energy form of the signal $\psi_C[x(t)]$,the $\hat{\psi}_C *[x(t)]$ is the conjugate function of $\hat{\psi}_C[x(t)]$.

From eq.1, ESWT extends the functionality of short-time Fourier Transform by introducing scale factor and translation factor to obtain a variable time-frequency window, which endows traditional Fourier transform with time-frequency analysis function by introducing $\hat{\psi}_C *[x(t)]$.

Applying Parseval equation,the frequency slice wavelet(eq.1) was translated to time domain:

$$W(t,\omega,\lambda,\sigma) = \sigma\lambda e^{i\omega t}\int_{-\infty}^{+\infty} f(\tau)e^{i\omega t}\hat{\psi}_c * [x(t)]d\tau \tag{3}$$

Time-frequency decomposition of signals was achieved by ESWT,and the original signal was reconstructd through inverse transformation.The inverse transformation was:

$$f(t) = \frac{1}{2\pi\lambda}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} W(\tau,\omega,\lambda,\sigma)e^{i\omega(t-\tau)}d\tau d\sigma \tag{4}$$

3. Rolling bearings fault feature extraction based on ESWT

A rolling bearing fault diagnosis method based on ESWT was proposed to address the shortcomings of FSWT in extracting impact fault features under strong background noise.

Firstly, energy slice[9] was introduced into wavelet transform.Secondly the time-frequency distribution of vibration signals in the entire frequency band was obtained by wavelet transform and the effective signal time-frequency features were separated to identify the working state and fault type of rolling bearings.The specific steps for implementation:

1)Collecting vibration signals through acceleration sensors;

2)Introducing energy slicing $\psi_C(x)$;

3)Estimate the frequency resolution ratio η and amplitude expected response ratio υ based on the signal characteristics, and calculate the preliminary time-frequency resolution coefficient k;

4)Based on the characteristics of bearing faults, zero to three times the characteristic frequency of bearing faults was selected as the frequency slice interval to refinement analyse by ESWT. Then the signal was transformed to time-frequency through Fourier inverse transform.Proceed to the next step,fault features were extract.

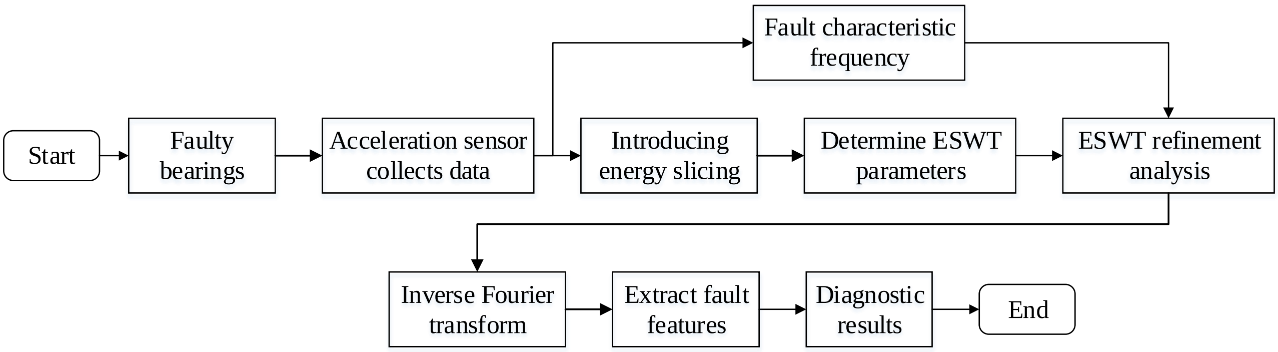


Fig.1 Flow Chart for Fault Diagnosis of Rolling Bearings

4. Simulation signal analysis

In order to verify the effectiveness of ESWT in feature extraction of bearing faults, the simulated signal of rolling bearing faults in eq.6 with a sampling frequency of 2048 Hz and a sampling duration of 1 second was analyzed . The simulated signal is:

$$x(t)=x_1(t)+x_2(t)+n(t) \tag{6}$$

Where $x_1(t)=\sin(20\pi t)+\cos(60\pi t)$ is harmonic signal to simulate low frequency interference in bearing systems, $x_2(t)$ is the periodic exponential decay shock signal which impact frequency is 70Hz to simulate damage fault of inner ring of rolling bearing.The weekly impact function is $1.3e^{-300t}\sin(2000\pi t)$, $n(t)$ is Gaussian white noise.Fig.2 shows the time-domain waveform and spectrum of the simulated signal. The low-frequency 10Hz and 30Hz components are prominent.Due to the interference of noise signals and low-frequency signals, the periodic characteristics of the pulse signal are not obvious in the time-domain waveform diagram.In addition,the amplitude of the 70Hz frequency component in the spectrum is too small to identify.

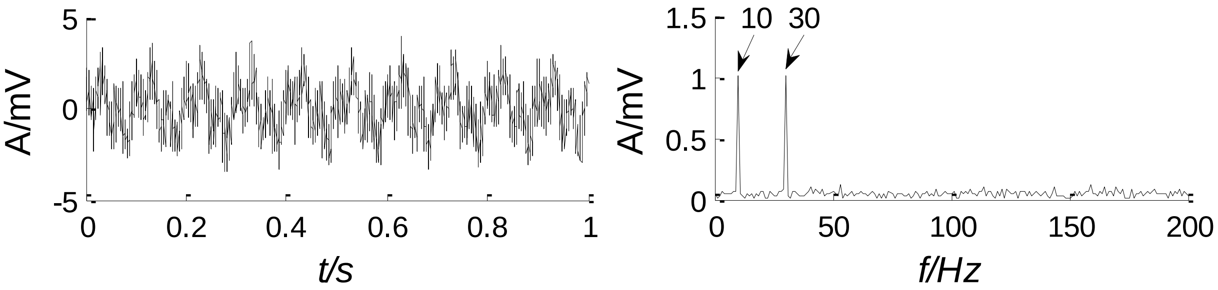
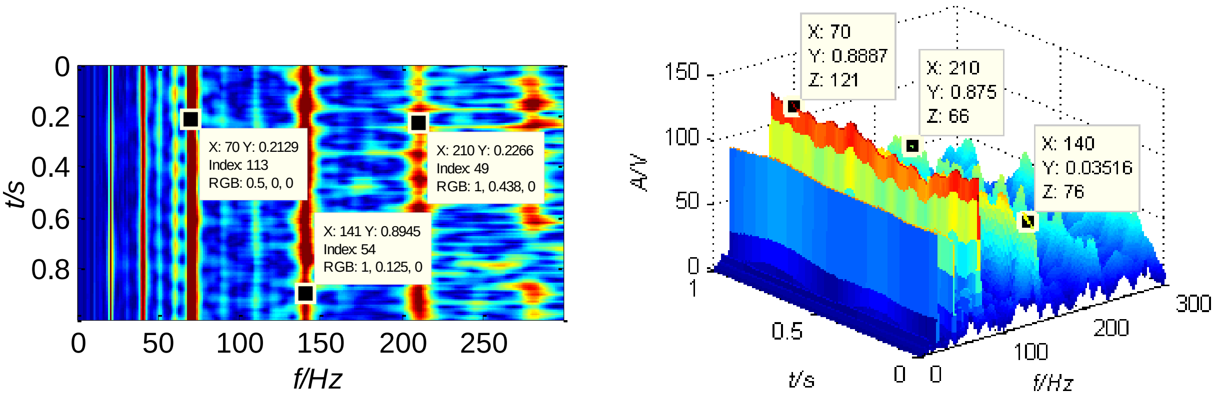


Fig.2 Time domain waveform and frequency spectrum of bearing fault simulation signal

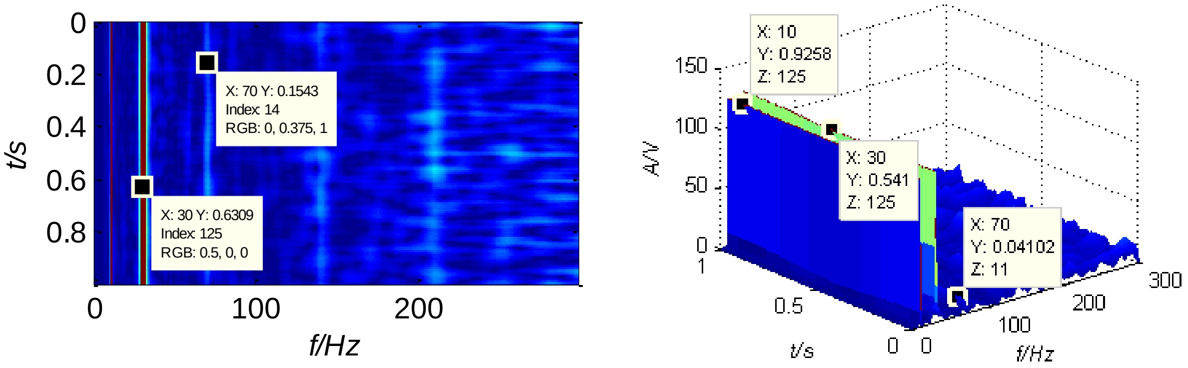
Analyzing simulated signals with the method of this article,the ESWT processing results of the signal in Fig.4.From the figure, it can be clearly seen that the fault characteristic frequency is 70Hz and its multiples. The fault impact characteristics have been strengthened based on ESWT,and the extraction of fault features enabling was achieved.



(a) Spectrogram of simulated signals (b) Time-frequency amplitude of simulated signals

Fig.3 Results of bearing fault simulation signals by ESWT

As comparison, Frequency Sliced Wavelet Transform was used to process the simulated signal, and the results show in Fig.4.From the figure,the amplitude of frequency components of 10Hz and 30Hz is prominent,bearing fault characteristics cannot be identified because of low-frequency interference.Compared to the analysis results of FSWT,the method used in this article is less affected by noise and overcome the shortcomings of FSWT in extracting impact fault features under strong background noise. the fault characteristic frequency is more obvious,the fault characteristics of various harmonic frequencies such as 1st harmonic (70Hz), 2nd harmonic (140Hz), and 3rd harmonic (210Hz) is clear, and the noise component is weak,the fault characteristics are prominent.It can intuitively and effectively analyze the fault type, which is consistent with the theoretical results.



Spectrogram of simulated signals (b) Time-frequency amplitude of simulated signals

Fig.4 Results of bearing fault simulation signals by FSWT

5. Examples of Bearing Diagnosis

In order to further verify the effectiveness of the proposed method in extracting fault features of rolling bearings, actual rolling bearing fault signals were used for verification. The experimental platform is shown in Fig.5, which is the QPZZ-II rotating machinery fault test-bed.The sampling frequency of the signal is 25600Hz, and the bearing speed is 314r/min. According to the parameters of the rolling bearing (Table 1), the theoretical fault characteristic frequencies are: outer ring fault characteristic frequency 37.5Hz.

Table 1 Parameters of Rolling Bearing N205EM

Internal diameter/mm	External diameter/mm	Thickness/mm	Number of rollers	Pitch Diameter	Contact angle/(°)
25	52	15	13	38.5	0

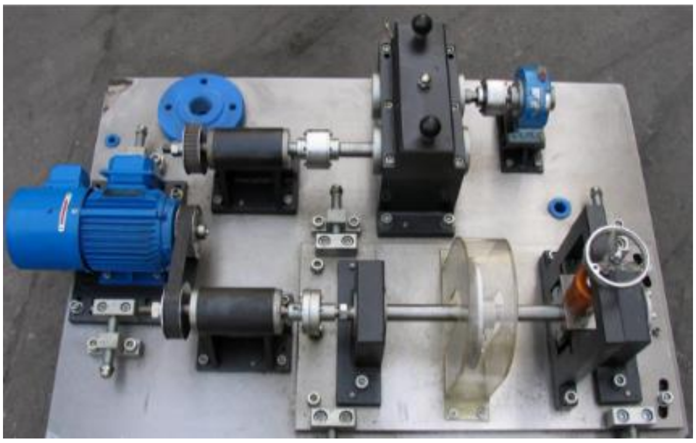
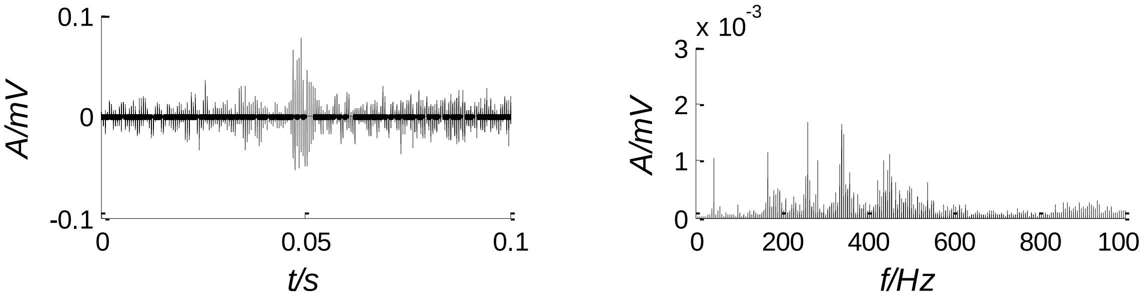


Fig.5 QPZZ-II rotating machinery fault test-bed

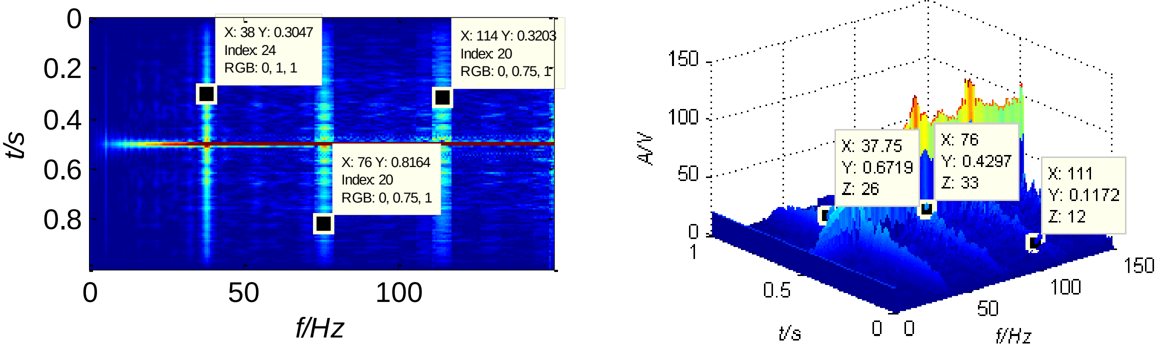
The rolling elements passing through the fault position will cause impact vibration when inner ring of rolling bearing break down. The impact vibration caused by the rotation of the inner ring shows periodic changes, and the fault surface impacts the surface of other components of the bearing, high-frequency vibration sequence with high peak values.is produced.

The actual collected vibration signals is processed by the method described of article.The time-domain and frequency-domain waveform of the inner circle fault signal are shown in Fig.6.From the figure,the time-domain waveform is relatively complex.In the spectrogram, the low-frequency characteristics of the fault signal are submerged in background noise, the fault characteristic frequency and its harmonics cannot be identified.Analyzed signal with ESWT, and the analysis results are shown in Fig.7.From the figure, the first harmonic (37.5Hz) and second harmonic of fault characteristic frequency is obvious.From this,the fault impact characteristics was enhanced and the extraction of fault features was achieved by the method.



(a) Inner circle fault vibration signal waveform (b) Spectrum of Inner Ring Fault Vibration Signal

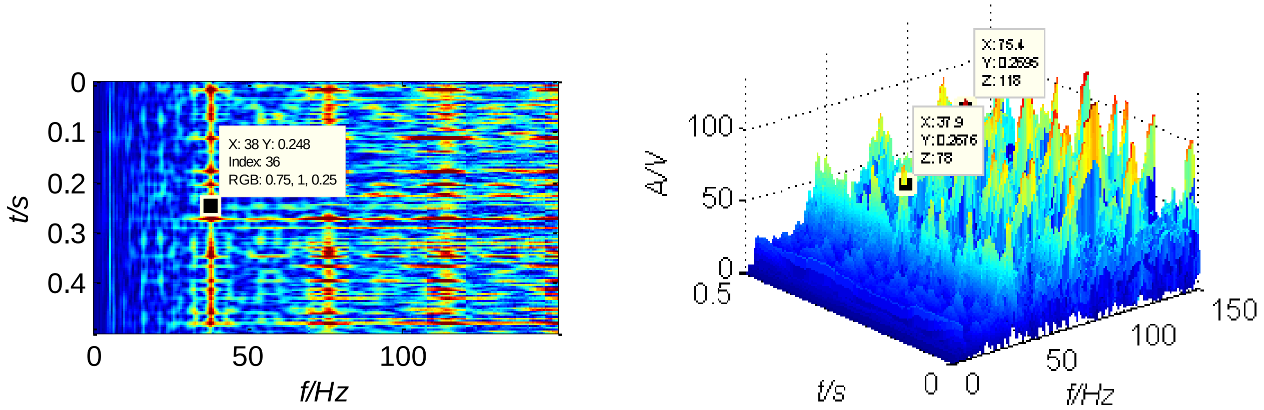
Fig.6 Waveform and Spectrum of Inner Ring Fault Signal



(a) Spectrogram of nner circle fault signal (b) Time-frequency amplitude of nner circle fault signal

Fig.7 Results of bearing inner circle fault signal by ESWT

As comparison,FSWT was used to analyze the same fault signal, and the results are shown in Fig.8.From the figure,ESWT is less affected by noise and has significantly stronger noise resistance than FSWT. The fault characteristic frequency is more obvious, and the 1st harmonic (38Hz), 2nd harmonic (76Hz), and 3rd harmonic (114Hz) of the fault characteristics can be seen clearly,and the noise component is weak, the fault characteristics are prominent.The method can intuitively and effectively analyze the types of faults, consistent with theoretical results.



(a) Spectrogram of nner circle fault signal (b) Time-frequency amplitude of nner circle fault

Fig.8 Results of bearing inner circle fault signal by FSWT

6. Conclusion

Through the fault diagnosis test of rolling bearings that rolling bearings fault feature extraction based on ESWT is feasible.The main conclusions drawn from this article are as follows:

(1) In the early stage of rolling bearings, weak fault signals were drowned out by strong noise,extracting fault features was difficult. The rolling bearing fault diagnosis method based on ESWT can effectively extract fault features.

(2) Compared with the FSWT, ESWT can effectively eliminate the interference of background noise on feature signals, making the feature signals prominent and beneficial for feature extraction of weak feature signals.The feasibility and effectiveness of the method have been verified through simulated fault bearing signals and rolling bearing experiments.

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