

Applications of Wigner high-order spectra in feature extraction of acoustic emission signals

Xiao Siwen¹, Liao Chuanjun¹, Li Xuejun^{1,2}

(1. Key Lab of Health Maintenance for Mechanical Equipment of Hunan Province, Hunan Science and Technology University, Xiangtan, Hunan 411201, China; 2. Department of Precision Instruments, Tsinghua University, Beijing 100084, China)

Abstract: The characteristics of typical AE signals initiated by mechanical component damages are analyzed. Based on the extracting principle of acoustic emission (AE) signals from damaged components, the paper introduces Wigner high-order spectra to the field of feature extraction and fault diagnosis of AE signals. Some main performances of Wigner binary spectra, Wigner triple spectra and Wigner-Ville distribution (WVD) are discussed, including of time-frequency resolution, energy accumulation, reduction of crossing items and noise elimination. Wigner triple spectra is employed to the fault diagnosis of rolling bearings with AE techniques. The fault features reading from experimental data analysis are clear, accurate and intuitionistic. The validity and accuracy of Wigner high-order spectra methods proposed agree quite well with simulation results. Simulation and research results indicate that wigner high-order spectra is quite useful for condition monitoring and fault diagnosis in conjunction with AE technique, and has very important research and application values in feature extraction and faults diagnosis based on AE signals due to mechanical component damages.

Key words: acoustic emission ; Wigner spectra; Wigner binary spectra; Wigner triple spectra; feature extraction; rolling bearing

1 Introduction

The phenomenon of releasing quickly local energy and generating transient elastic wave in materials is called acoustic emission (AE). The technique to detect, record and analyze AE signals with instruments and look for AE sources from AE signals is called AE detection technique. Mechanical fault diagnosis technique based on AE is a dynamic nondestructive detection method, which detects active flaws of materials by the AE principles of materials. AE signals initiated by damages originate from certain changes of materials, and can offer real-time and continuous information that active damages vary with external variables, such as load, time, and temperature. AE techniques are used extensively to forecast and diagnosis mechanical faults especially when faults are at the stage of earlier period. It is difficult for AE instruments to capture transient waveform and process real-time AE signals due to the limits of collecting and processing capacity before. The parameter analysis method of AE signals is therefore used mainly in the early AE signal analysis. With the inventions and improvements of full-waveform AE detection instruments, it becomes possible to process and analyze AE waveforms using modern signal processing

techniques, and will become main analysis methods of AE signals. So signal processing techniques related to waveform analysis of AE signals needs to be studied, which are the focuses of development and research in the field of fault diagnosis of AE signals^[1].

AE signals initiated by mechanical faults or damages are made up of a series of multi-frequency and multimode signals, which are a type of non-stationary and time-variation signals. Although many essential differences exist between AE signals and vibration signals, such as produce process, propagation rules, detection principles etc, the two signals all belong to the type of non-stationary and time-variation signals. So research findings about analysis methods of AE signals and vibration signals can be made references with each other. Wigner-Ville distribution (WVD) and Wigner high-order spectra are all applied successfully for mechanical fault diagnosis based on vibration signals^[2]. By analyzing the typical AE signal initiated by mechanical faults and its feature extraction principles, and borrowing ideas from Wigner high-order spectra in feature extraction of vibration signals, the paper introduces Wigner high-order spectra to the field of feature extraction and fault diagnosis of AE signals. The feasibility and validity of Wigner high-order spectra methods

are studied systematically through series of simulation study and experimental investigation.

2 Wigner high-order spectra and feature extraction of AE signals

2.1 Calculations of Wigner high-order spectra

Actual signal $s(t)$ is a real signal, thus $s(t)$ has to be converted into $x(t)$, which is the form of analytic signal prior to time-frequency analysis. Consequently, Wigner spectra based on complex-valued signals in the high-order spectra area can be defined as^[3]:

$$W_{kx}(t, f_1, \dots, f_k) = \int_{\tau_1} \dots \int_{\tau_k} x^* \left[t - \frac{1}{k+1} \sum_{m=1}^k \tau_m \right] \times \prod_{i=1}^k x \left(t + \frac{k}{k+1} \tau_i - \frac{1}{k+1} \sum_{j=1, j \neq i}^k \tau_j \right) \exp(-j2\pi f_i \tau_i) d\tau_i \quad (1)$$

In the above equation, the symbol k denotes the order number of Wigner high-order spectra. In Eq. (1) When $k=1$, the expression of WVD is described by

$$W_x(t, f_1) = \int_{\tau_1} x^* \left(t - \frac{\tau_1}{2} \right) x \left(t + \frac{\tau_1}{2} \right) e^{-j2\pi f_1 \tau_1} d\tau_1 \quad (2)$$

In Eq. (1) when $k=2$, the expression of Wigner binary spectra is described by

$$W_{2x}(t, f_1, f_2) = \int_{\tau_1} \int_{\tau_2} x^* \left[t - \frac{1}{3}(\tau_1 + \tau_2) \right] \times x \left[t + \frac{1}{3}(2\tau_1 - \tau_2) \right] x \left[t + \frac{1}{3}(2\tau_2 - \tau_1) \right] \times \exp \left[-j2\pi(f_1 \tau_1 + f_2 \tau_2) \right] d\tau_1 d\tau_2 \quad (3)$$

In Eq. (1) when $k=3$, the expression of Wigner triple spectra is described by

$$W_{3x}(t, f_1, f_2, f_3) = \int_{\tau_1} \int_{\tau_2} \int_{\tau_3} x^* (t - \tau) \times x(t - \tau + \tau_1) x(t - \tau + \tau_2) x(t - \tau + \tau_3) \times \exp(-j2\pi(f_1 \tau_1 + f_2 \tau_2 + f_3 \tau_3)) d\tau_1 d\tau_2 d\tau_3 \quad (4)$$

$$\tau = \frac{1}{4}(\tau_1 + \tau_2 + \tau_3) \quad (5)$$

Wigner binary spectra and Wigner triple spectra are the two main forms of Wigner high-order spectra, and the two diagonal slices of $f_1 = f_2$ and $f_1 = f_2 = -f_3$ only need be calculated respectively in practical applications. Additional properties of Wigner high-order spectra can be found in Ref. [3].

2.2 Feature extraction of AE signals based on Wigner high-order spectra

The intrinsic character of AE signals initiated by mechanical faults or damages is a kind of high frequency elastic wave, of which frequencies are generally above 20 kHz, and are made up of many impulse signals that present decaying oscillation phenomenon of expo-

ponential shape. So the key procedure of processing AE signals is how to adopt effective methods to extract the characteristic signals from acquired multi-frequency AE signals. The methods can be adopted to separate all the inherent decaying oscillations of AE signals from each other, and represent the key natural parameters of all the decaying oscillations, such as the number, intensity, frequency components and distribution in time-frequency plane etc, which will provide correct information for identifying the type, position and damage degree of damages. The characteristics and principles of feature extraction of AE signals are represented in detail in Ref. [4].

WVD is a two-dimensional combined function of time and frequency, and can be seen as an energy-density function of a signal in time-frequency plane. The time-bandwidth product of WVD reaches the lower boundary of Heisenberg uncertainty principle, which makes WVD have higher energy-accumulation performance and time-frequency resolution than linear time-frequency distributions, of which wavelet transform is one typical representative. And WVD has the characteristic of meeting time-frequency edge. Thus, WVD is very suitable for analyzing non-stationary and time-variation signals, and can improve greatly the accuracy of fault feature extraction of signals^[5]. The two-dimensional and three dimensional time-frequency distribution charts can attribute visually the feature information of AE signals, such as the number, strength, distribution conditions and frequency components etc. It is believed firmly that WVD will have very important research value and extensive application foreground in fault diagnosis based on AE techniques. However, for multi-component AE signals, it is unavoidable that cross items between multiple harmonic components will be mixed into WVD. So it is very necessary to adopt some measures to reduce cross items^[6].

However, AE signals initiated by mechanical faults have higher requests to signal analysis methods, which include of time resolution, frequency resolution and energy accumulation etc. There are three main reasons: one is that AE signals are high frequency signals, and time-intervals between each impulse of AE signals are very short, which are generally in the millisecond order. So the signal analysis methods are requested to have possibly high time resolution. The second one is that AE signals are broad frequency signals, and have the characteristics of multi-frequency, multi-mode and multi-modal spectrum, of which frequency ranges are generally between several ten-thousands Hz and several hundred-thousands Hz. So the signal analysis methods are requested to have possibly high fre-

quency resolution. The third one is that AE signals are sensitive to the varieties of materials and structures because acoustic emissions generate in the microscopic levels, and can be affected easily by the interference factors. So the signal analysis methods are requested to have possibly good energy accumulation and the capacity of noise immunization.

Wigner high-order spectra is the expansions of WVD in the field of high-order spectra, not only have the good characteristics of WVD, but also can reflect the characteristics of high-order spectra of signals in time-frequency plane. So more information of signals can be provided, and time-frequency resolution is improved also. Furthermore, focusing property of time-frequency distribution can be strengthened, and many interferences of noise signals can be also suppressed by themselves^[2]. So it is better for Wigner high-order spectra to satisfy the requests of feature extraction of AE signals.

3 Simulations

Two main problems must be solved first, before using Wigner high-order spectra to process AE signals containing abundant fault information. One is the reduction of cross items because AE signals are a kind of multi-component broadband signals. The other is the noise elimination because the fault information attributed by AE signals is very weak, and there exists large number of interfering signals. A simulation AE signal is proposed and designed to study the reduction of cross items and the elimination of noise signals in Wigner high-order spectra of AE signals.

3.1 Reduction of cross items

It is unavoidable that cross items will be mixed into quadratic or bilinear time-frequency distributions, which initiate from cross actions between multiple harmonic components of multi-component signals^[7]. According to the simulation model of the AE signal proposed in Ref. [8], the signal $x(t)$ consisting of three decaying oscillation components is used to simulate one AE signal, and $x(t)$ is expressed as

$$x(t) = 2\exp\left[-2\pi\left(\frac{(t-t_1)}{\sigma_1}\right)^2\right]\sin[2\pi f_1(t-t_1)] + 2\exp\left[-2\pi\left(\frac{(t-t_2)}{\sigma_2}\right)^2\right]\times\sin[2\pi f_2(t-t_2)] + 2\exp\left[-2\pi\left(\frac{(t-t_3)}{\sigma_3}\right)^2\right]\times\sin[2\pi f_3(t-t_3)] \quad (6)$$

Where $x(t)$ is made up of three pulse signals. The three parameters f_1, f_2 and f_3 are the frequencies of the three harmonic waves, and t_1, t_2 , and t_3 are three time variable centers of the pulses respectively. The

specified values of all the parameters of Eq. (6) are as follows: $f_1 = 60$ kHz, $f_2 = 70$ kHz, $f_3 = 80$ kHz, $\sigma_1 = 0.0001$, $\sigma_2 = 0.00015$, $\sigma_3 = 0.0002$, $t_1 = 0.6$ ms, $t_2 = 0.8$ ms, $t_3 = 1.0$ ms. The signal is sampled at 500 kHz. The simulation AE signal based on Eq. (6) is shown in Fig. 1. Wigner binary spectra, Wigner triple spectra and WVD of the simulation signal are shown in Fig. 2, Fig. 3 and Fig. 4 respectively.

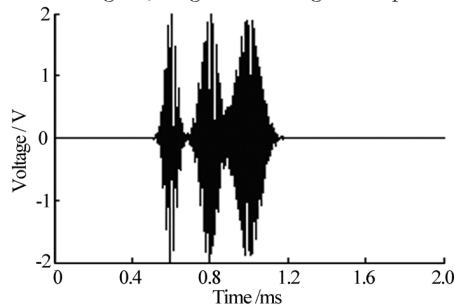


Fig. 1 Simulation AE signal

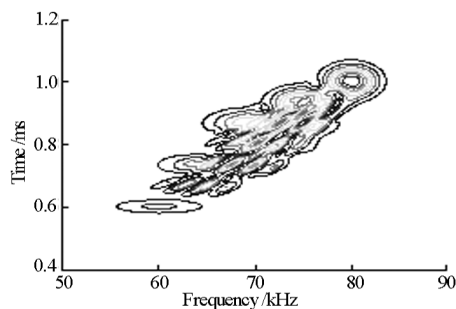


Fig. 2 Wigner binary spectra of simulation AE signal

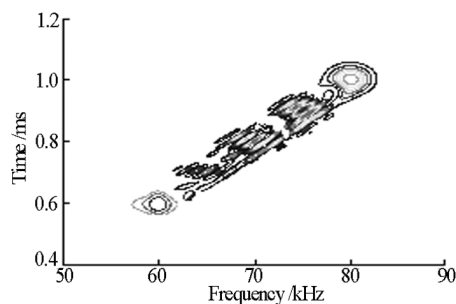


Fig. 3 Wigner triple spectra of simulation AE signal

Fig. 2, Fig. 3 and Fig. 4 indicate that Wigner binary spectra, Wigner triple spectra and WVD all can't extract effectively features of the simulation AE signal if cross items don't be reduced in advance. The cross items between the forward and backward harmonic components of $x(t)$ have influenced seriously the physical explanations to the simulation AE signal. Not only each two harmonic components can generate a cross

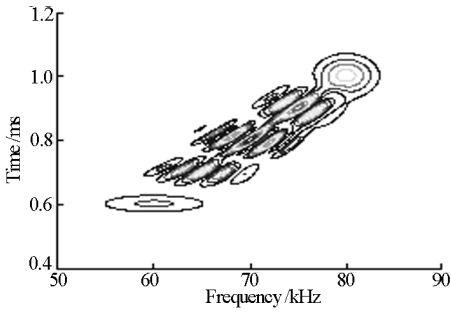


Fig. 4 WVD of simulation AE signal

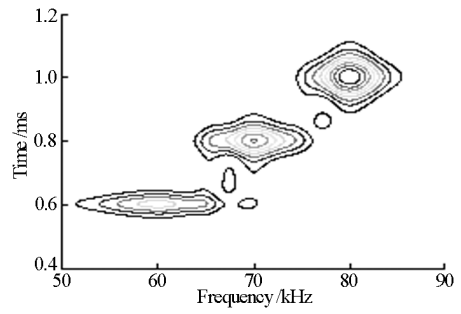


Fig. 7 WVD of reduction of cross items

term, but also the amplitude of cross items are all higher than that of the harmonic components.

In our case, two procedures are employed to reduce the cross items. One is to adopt analytical signal to replace real signal, and the other is to use Choi-Williams kernel as the time-frequency analysis kernel to finish it. Wigner binary spectra, Wigner triple spectra and WVD of the simulation AE signal $x(t)$ is shown in Fig. 5, Fig. 6 and Fig. 7 respectively, of which using Choi-Williams kernel has reduced the cross items.

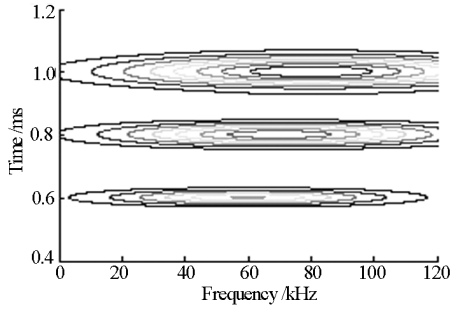


Fig. 5 Wigner binary spectra of reduction of cross items

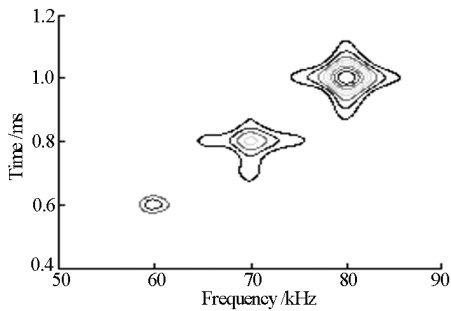


Fig. 6 Wigner triple spectra of reduction of cross items

Fig. 5 indicates that cross items have been reduced effectively when Wigner binary spectra of the simulation AE signal used Choi-Williams kernel as the time-frequency analysis kernel, but autocorrelation items of the signal generate deformations. So Wigner binary spectra can't be used as the tool of feature extrac-

tion of AE signals. Fig. 6 and Fig. 7 indicates that not only cross items are reduced effectively, but also deformations of autocorrelation items don't generate when Wigner triple spectra and WVD of the simulation signal use Choi-Williams kernel as the time-frequency analysis kernel. there are three pulses shown respectively by three contour line maps of which the centers respectively are (60, 0.6), (70, 0.8) and (80, 1.0) on the frequency-time plane. Comparisons of Fig. 6 with Fig. 7 indicate that not only effectiveness reducing cross items of Wigner triple spectra is better than that of WVD, but also time resolution, frequency resolution and energy accumulation property of Wigner triple spectra are all higher than that of WVD.

3.2 Noises elimination

It is unavoidable that AE signals acquired in working conditions contain a large number of noise signals. Because fault information included in AE signals is very weak, these noise signals mixed in AE signals make it very difficult to extract the fault features of AE signals. The simulation AE signal $x(t)$ is still regarded as an important subject to be investigated. One Doppler noise signal of random bandwidth is added into $x(t)$. The mixed signal is also sampled at a rate of 500 kHz. The Doppler noise signal is shown in Fig. 8, and the simulation signal including the Doppler noise is shown in Fig. 9, of which Wigner triple spectra and WVD are shown in Fig. 9 and Fig. 10 respectively.

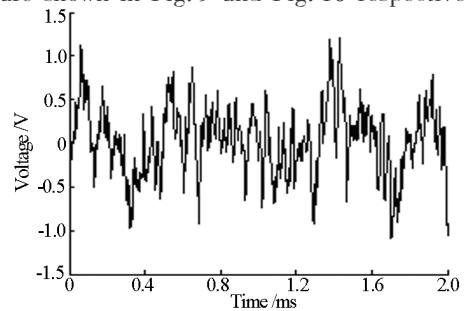


Fig. 8 Doppler noise signal

Fig. 10 and Fig. 11 indicate that the Doppler noise

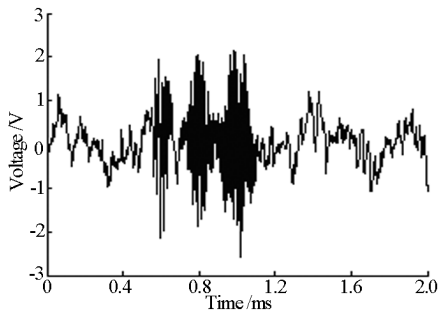


Fig. 9 Simulation AE signal including Doppler noise signal

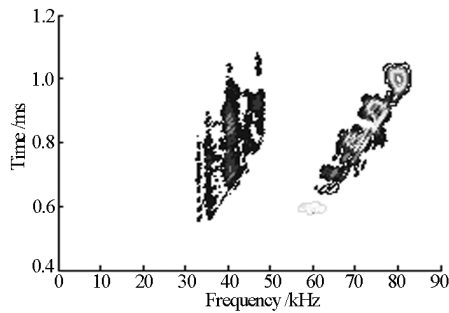


Fig. 10 Wigner triple spectra of simulation AE signal including Doppler noise signal

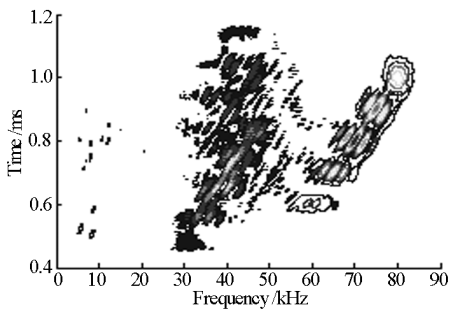


Fig. 11 WVD of simulation AE signal including Doppler noise signal

signal greatly influences the Wigner triple spectra and WVD of the simulation signal, and have influenced seriously the physical explanations to the signal. Comparisons of Fig. 10 with Fig. 11 indicate that the capacity of noise elimination of Wigner triple spectra is obviously higher than that of WVD.

Another Wigner triple spectra and WVD of the simulation AE signal with de-noise are shown in Fig. 12 and Fig. 13 respectively, in which de-noising measure has been carried out using the Choi-Williams wave filter.

According to Fig. 12 and Fig. 13, although the interferences of noise signals have not been eliminated completely after adding Choi-Williams wave filter, the influences of noise signals on the Wigner triple spectra

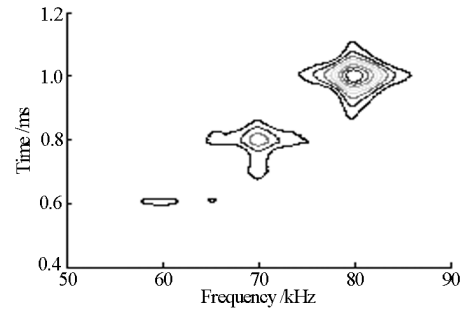


Fig. 12 Wigner triple spectra after de-noising

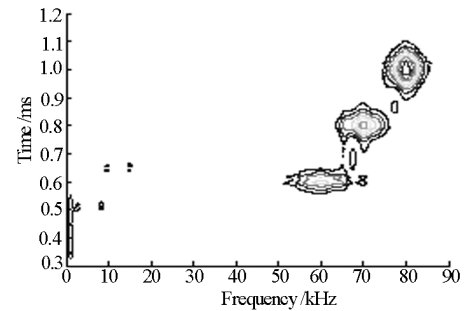


Fig. 13 WVD after de-noising

and WVD were very small. Comparisons of Fig. 12 with Fig. 13 indicate that the influences of the noise signal to Wigner triple spectra are very minute. So it can be believed firmly that effectiveness of noise elimination of Wigner triple spectra is obviously better than that of WVD.

It can be concluded from the simulations that Wigner binary spectra can't be used to analysis AE signals because autocorrelation items of AE signals in Wigner binary spectra will generate deformations. Wigner triple spectra and WVD can extract effectively the features of AE signals, and the former not only has better time resolution, frequency resolution and energy accumulation, but also has better effectiveness of reduction of cross items and noises elimination. Therefore, Wigner triple spectra is a very strong tool used to extract features of AE signals.

4 Experimental studies

Under normal working conditions, a real-time diagnosis to a rolling element bearing of which the model number is 6 220 is carried on. The outer race of the experimental bearing has a pre-made damage. The main parameters of the experimental bearing are shown as follows: the angle of contact is $\alpha = 0^\circ$, the rolling number is $z = 11$, the rolling diameter is $d = 22.8$ mm, and the pitch diameter is $D = 148$ mm. The detection device using in the experiment is an SWAES full-waveform AE detection instrument. The main constituents of

the detection instrument are: two SR15 AE sensors of which harmonic frequency is 150 kHz and sensitivity is greater than 65 dB, a NuDAQ PCI-9812/10 20 MHz simultaneous 4-CH analog input card, two PAI head amplifiers of which frequency bandwidth is 0.02 ~ 2 MHz and gain is 40 dB, an SA4 main amplifier of which frequency dimension is 0.02 ~ 2 MHz and input impedance is greater than 50 M Ω . The corresponding experimental conditions are: the rotational speed of rotor is 440 r/min, so that the rotation frequency of the shaft f_s is 3.67 Hz; radial load of the bearing is 300 N; sampling frequency is 1 MHz, and sampling time is 0.2 s. The experimental AE signal is shown in Fig. 14.

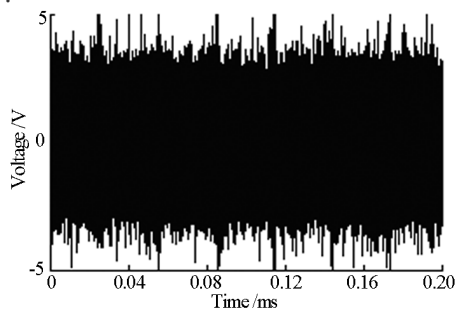


Fig. 14 The experimental AE signal

When some one component of a rolling bearing has a local fault or damage, certain impacts will happen between the fault component and other components during operating under load. Thus, the AE signals picking up from the bearing are superpositions, which are made up of pulse signals of exponential decaying with high frequency and periodic properties. The periodic of these pulse signals is correspondence with the fault characteristic frequency of the bearing. Fault characteristic frequencies of typical position faults of the same rolling bearing including internal race, outer race, rolling element and retainer have very big differences, of which theoretical calculation formulas are shown in the Ref. [9]. When assay value and calculation value of fault characteristic frequencies are compared, then fault locations of the bearing can be identified. According to other information during the course of analysis, conditions of the faults such as magnitude, damage degree and trend in development etc can be judged. Using the specified experimental conditions, the fault characteristic frequency of outer race of the experimental bearing f_0 is 34.06 Hz.

Because the data size of the experimental signal is very large, which has 200 k. So the envelope signal of the experimental signal is studied. After adding the Choi-Williams kernel, Wigner triple spectra of the experimental signal is shown in Fig. 15. From Fig. 15, it

can be found that the time-frequency plane isn't very clear because trend items of the signal exist in Wigner triple spectra.

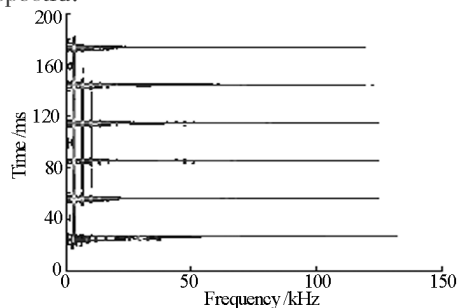


Fig. 15 Wigner triple spectra of reduction of cross items and noises

In the course of AE testing, the data of AE signals usually deviate the baseline, so that the size of side-play amount will also vary with time. This problem is mainly caused by three factors: zero drift produced by amplifier varying with temperature, the instability of low-frequency performance out the range of sensors frequency, and the interferences originating from surrounding environment of sensors. The whole course that data deviates baseline varying with time is called trend item of signals. Therefore, it is necessary to cancel the interferences of trend items of the experimental AE signals. The two-dimensional and three-dimensional spectra charts of Wigner triple spectra of the experimental signal after reduced trend items are respectively shown in Fig. 16 and Fig. 17.

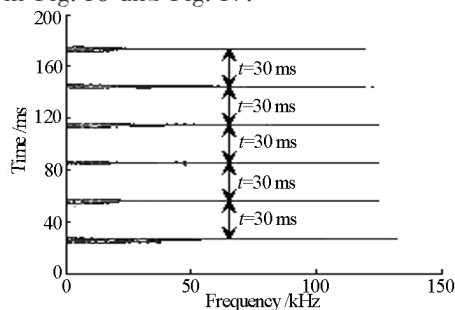


Fig. 16 Two-dimensional spectra chart of Wigner triple spectra of the experimental AE signal after picking out trend items

Fig. 16 presents the fault features of the experimental bearing completely. Six pulse shocks named six AE events together take place at the time of 25, 55, 85, 115, 145, 175 ms respectively during the sampling time, and the time-interval between two AE Events all is 30 ms. So the fault characteristic frequency of the experimental bearing can be obtained, which is reciprocal value of time-interval t , and the value is

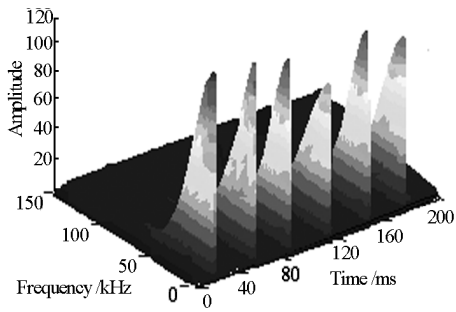


Fig. 17 Three-dimensional spectra chart of Wigner triple spectra of the experimental AE signal after picking out trend items

33.3 Hz. The fault characteristic frequency f_0 is 34.06 Hz. Thus, the two results obtained by theoretical calculation and experimental analysis are very close, which illustrates that the outer race of the experimental bearing got out of order. From Fig. 17, more information of the fault such as magnitude, damage degree and trend in development can be obtained.

The experimental results indicate that Wigner triple spectra of the experimental signal represents effectively the fault features of the experimental bearing, and precision diagnosis to the fault location of the experimental bearing were implemented clearly, visually and accurately. The experimental results agree quite well with theoretical results. It shows that Wigner triple spectra can be used for fault diagnosis of rolling bearing based on acoustic emission techniques, and is a very effective and practical method.

5 Conclusions

1) Wigner binary spectra of AE signals uses Choi-Williams kernel as the time-frequency analysis kernel will generate deformations of autocorrelation items. So the paper suggests that Wigner binary spectra don't be used as the diagnostic tool of AE signals.

2) After using Choi-Williams kernel as the time-frequency analysis kernel, Wigner triple spectra and WVD can extract effectively the features of AE signals, and reduce effectively the interferences of cross items and noise signals. Wigner triple spectra have better time-frequency resolution, energy accumulation and

capacities of Reduction of Interference items and noises elimination than WVD. So it is more suitable for Wigner triple spectra to be used as the tool of feature extraction of AE signals.

3) Wigner triple spectra can visually show the number, intensity, frequency component and distribution in time-frequency plane of all the pulses, which are contained in AE signals initiated by mechanical faults or damages. Thus, Wigner triple spectra can provide effective information for judging the type, position, and damage degree of faults. The simulation and experimental results all prove that the Wigner triple spectra used as the tool of AE signals is very effective. It is necessary to carry on further researches on Wigner triple spectra in the field of condition monitoring and fault diagnosis based on AE techniques.

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Author

Xiao Siwen, female, was born in 1968, graduated from Hunan Science and Technology University, and now is a senior engineer in Key Lab of Health Maintenance for Mechanical Equipment of Hunan Province, Hunan Science and Technology University, Xiangtan, China. Ms. Xiao has published over twenty papers. Her current research is fault diagnosis and health maintenance of mechanical equipments. She can be reached by E-mail: xiao_s_w@yahoo.com.cn

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