Defect Diagnosis for Rolling Element Bearings Using Acoustic Emission

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Rolling element bearings are very common components in rotating machinery. Hence, condition monitoring and the detection of defects are very important for the normal and safe running of these machines. Vibration based techniques are well established for the condition monitoring of rolling element bearings, although they are not so effective in detecting incipient defects in the bearing. Acoustic emission (AE) is receiving increasing attention as a complementary method for condition monitoring of bearings as AE is very sensitive to incipient defects. This paper presents an experimental study to investigate the AE characteristics of bearing defect and validates the relationship between various AE parameters and the operational condition of rolling element bearings. To analyze the characteristic vibration frequency of the bearing using the AE signal, short-time rms and autocorrelation functions are integrated to extract the actual characteristic frequency. The AE signal is then analyzed using standard parameters of the signals to explore the source characteristics and sensitivity of typical rolling element bearing faults. The results demonstrate that the proposed method is very effective to extract the actual characteristic frequency of the bearing by AE signal. Furthermore the AE parameters are always sensitive to the running and fault conditions, which have a strong influence on the strain and deformation within the bearing material. [DOI: 10.1115/1.4000480]

Keywords: acoustic emission, rolling element bearing, condition monitoring, autocorrelation function, parameter analysis

1 Introduction

Rotating machinery is widely used and is key equipment in many industries. The importance of condition monitoring and fault diagnosis of such equipment has been extensively recognized by both industry and the research community [1]. Rolling element bearings are often used components in rotating machinery because of their low cost and high reliability. However the correct condition of the bearings is required to guarantee the normal and safe running of the machines. Any failures in the bearings (such as fatigue cracks, pitting, spalling, etc.), must be detected quickly, otherwise they may cause malfunctions or even a catastrophic accident. As a consequence, condition monitoring and defect diagnosis of rolling element bearings are required to provide an assurance for the reliable running of rotating machines and efficient production. Many different techniques have been developed for monitoring and diagnosis of rolling element bearings in the last several decades [2,3]. Most of the developed methods are based on vibration signals, and these vibration based methods are effective when the defect in the bearings has already become severe. But the vibration signal is not sensitive to the incipient defect. Furthermore, the vibration signal caused by bearing defects will always be contaminated and distorted by other faults and mechanical noise. Hence, it is difficult for the vibration signal based methods to detect bearing defects at an early stage, and a more sensitive detection and diagnosis technique to provide an early and unambiguous indication of bearing defects would be extremely valuable.

Acoustic emission (AE) is a transient elastic wave generated when strain energy is suddenly released due to the relative motion among the particles or material at a small scale [4]. The small scale of the AE generation mechanisms mean that the frequencies generated are usually very high, although the source mechanisms are usually smaller than for vibration. Examples include the material fracture in crack propagation or the interaction of asperities in sliding surfaces. AE has been considered for many years as a prime candidate for the nondestructive examination, testing, or monitoring (NDT) of material faults or structural failure and has found broad applications in these fields [5–7]. When a rolling element bearing with defects operates, the defect (surface defect, cracking, spalling, etc.) will generate elastic impulses and strain on the contact surface between the roller and the race of the bearing. This will lead to a release of transient stress wave energy, that is, AE. This AE contains direct and abundant information about the bearing defect and thus could be used to effectively detect and diagnose such defects. In contrast to the vibration signal, AE generally covers a frequency range over 20 kHz and does not exhibit a significant spectral overlap with mechanical vibration signals from rotating machinery. This means that AE is not influenced or disturbed by other mechanical noise, and faults in rotating machinery, such as imbalance and misalignment, which cannot be eliminated easily and completely [8]. Thus AE based methods are superior in some areas to vibration based methods for defect detection, especially for incipient defect detection in rolling element bearings.

Balerston [9] was one of the first to introduce AE techniques for the defect diagnosis of rolling element bearings and proposed the AE source mechanism. Since then, and especially in recent years, more and more researchers have investigated the application of AE technique in the defect monitoring and diagnosis of rolling element bearings. Hawman and Galinaitis [10], Tandon and Choudhury [3], and Mba et al. [11] explored the causes, influence factors, styles, and the generating mechanisms of AE in rolling element bearings. Price et al. [12] used a four-ball lubricant test machine to simulate pitting fatigue and scuffing wear in bearings and utilized continuous AE signals to detect these two kinds of defect. This work also verified that AE signals are very effective

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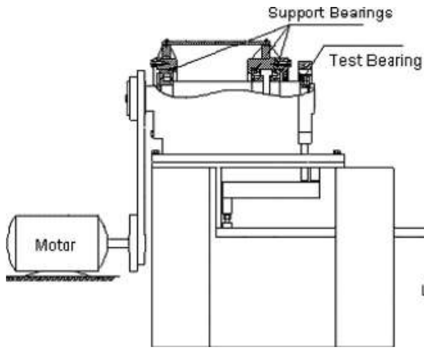

Fig. 1 The sketch of the experimental test rig

Fig. 2 The experimental test rig

for monitoring and detecting defects in bearings. Catlin [13] and Morhain and Mba [14] discussed the propagation characteristics of AE in rolling element bearings. Their work helps to make the AE technique more applicable and feasible for defect diagnosis in rolling element bearings. Although the waveform analysis method is becoming attractive for AE analysis, the parameter analysis method has always been used to analyze AE signals arising from bearing defects. The most commonly used parameters for AE are counts, amplitude, rms, energy, and duration time. Significant work has been performed to establish the relationship between these parameters and AE activities, and to develop corresponding defect diagnosis methods by using these parameters. Nishimoto and Kameno [15] analyzed the relation between the contact fatigue and AE event counts. Tan [16] found that AE event counts increased exponentially with increasing defect size and rotating speed. Tandon and Nakra [17] used AE ring-down counts and peak amplitudes to diagnose defects in SKF6002 rolling element bearings under varying radial load, rotating speed, and defect size and concluded that the peak amplitude was better for small defect diagnosis. Morhain and Mba [14] adopted rms, peak amplitude, energy, and AE counts to diagnose defects in rolling element bearings under high environmental noise. In their work, AE count threshold setting was first proposed. Al-Ghamdi et al. [18] investigated the relationship between AE duration time and the defect size and concluded that AE duration time can be used to identify the size of defects in rolling element bearings. In addition, comparison between AE and vibration signals was performed using rms and peak amplitude to demonstrate that AE is more sensitive to bearing defects. Al-Ghamd and Mba [19] conducted further research to compare the sensitivity of the kurtosis values of AE and vibration signals to defects, to validate that the kurtosis value of AE is more sensitive to the onset and growth of defects than vibration measurements.

In this paper, an experimental study is presented to investigate AE characteristics of bearing defects and further validate the relationship between various AE parameters and the running condition of rolling element bearings, for example, radial load, rotating speed, and defect size. First, short-time rms (STRMS) and autocorrelation functions are used to analyze the variation in characteristic frequency of the bearing with the defect. Then, AE parameters, such as counts, amplitude, energy, and Kurtosis, are utilized to analyze the AE signals from the bearing. The sensitivities of these AE parameters to the running condition of the bearing are also investigated.

2 Experimental Test Rig

Figure 1 shows a schematic of the test rig, which consists of a motor, a rotor-bearing unit, and a loading unit. The rotor-bearing unit is supported by one cylindrical roller bearing and two conical roller bearings. A deep ditch ball-bearing, of type 6220, is employed as the test bearing. The bearing has a roller diameter of $d=22.8$ mm, an effective diameter $D=141$ mm, and the number of rollers is $Z=11$. The radial load is applied to the test bearing by a lever system with a ratio of 1:200. The real experimental test rig is shown in Fig. 2.

The AE data acquisition system consisted of piezoelectric-type AE transducers, amplifiers, an A/D card, and the computer, which is illustrated in Fig. 3. SR15 broadband AE transducers were employed, with an operating frequency range of 20 Hz–300 kHz. A PCI-9812 A/D card was used, which is based on the 32 bit PCI bus with 12 bit accuracy and a 20 MHz maximum sampling rate for one channel.

The AE transducers are mounted on the outside surface of the outer race and on the bearing housing (see Fig. 4). The sampling rate is set to 500 kHz, and the sample time is 0.5 s. Electric spark erosion is used to seed a simulated corrosive pitting defect onto the races of the bearing artificially, and defect sizes of diameter 3 mm and 5 mm were prepared (denoted D1 and D2, respectively, and D0 denotes the undamaged bearing). Three load cases are considered, namely, 0 kN, 3 kN, and 7 kN (denoted L0, L1, and L2, respectively), and two rotating speeds of the test rig are chosen as 222 rpm and 444 rpm (denoted S1 and S2, respectively).

3 Experimental Study and Results

3.1 Characteristic Frequency Analysis of Bearings With Defects. The theoretical characteristic frequencies of the bearing with a defect on the inner race and the outer race can be calculated as

$$f_I = \frac{Z}{2}\left[1 + \frac{d}{D}\cos\alpha\right]f \qquad (1)$$

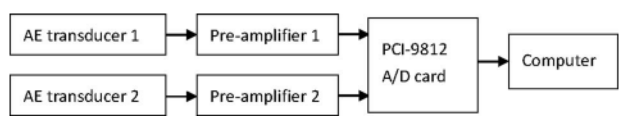

Fig. 3 AE data acquisition system

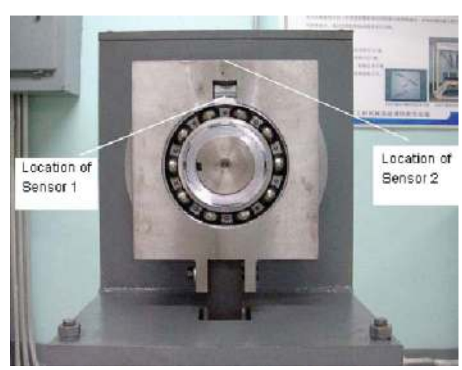

Fig. 4 Test bearing and location of AE sensors

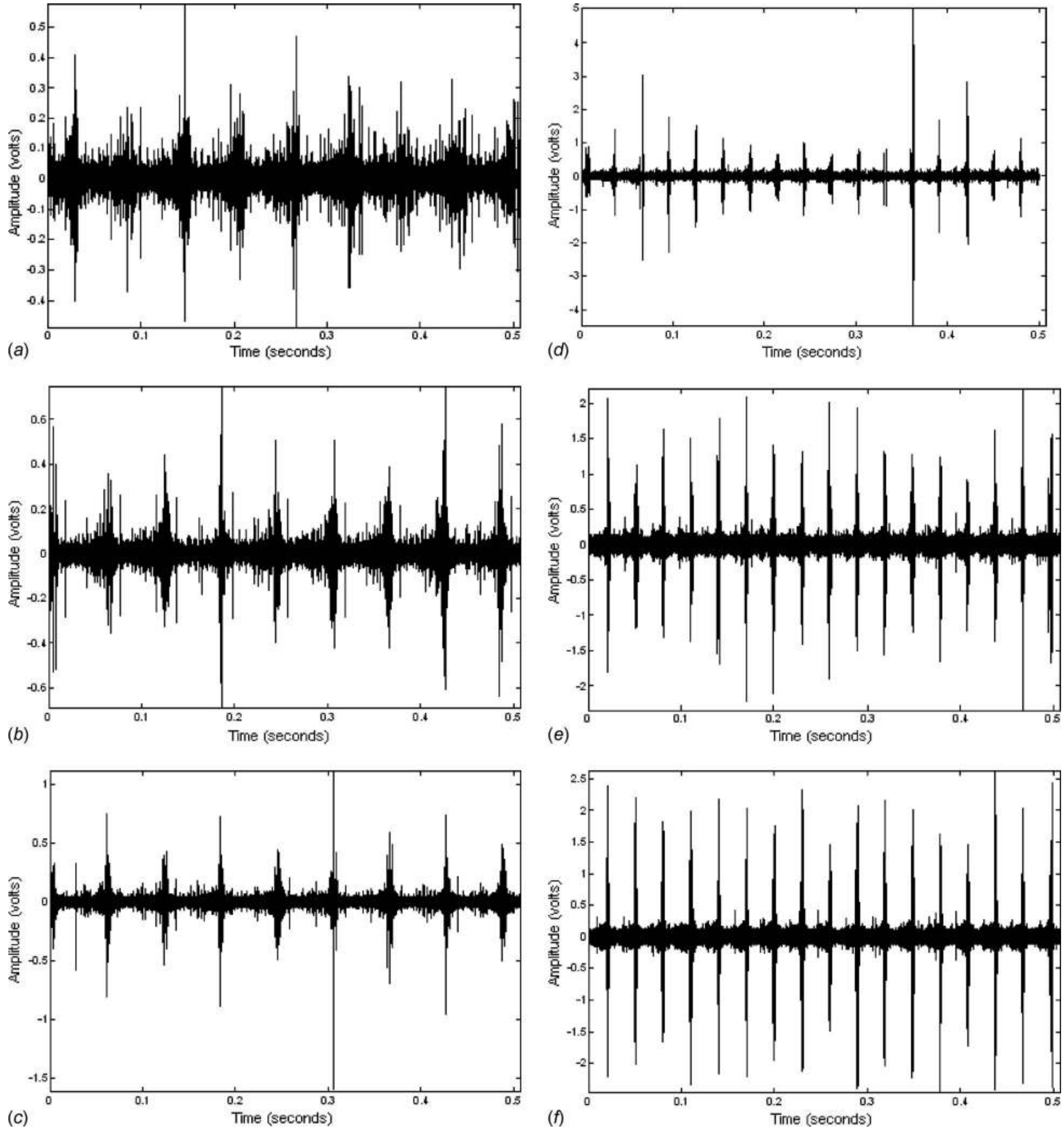

Fig. 5 AE signals with defect on the outer race from sensor 1: (*a*) condition (L0, S1, D1), (*b*) condition (L1, S1, D1), (*c*) condition (L2, S1, D1), (*d*) condition (L0, S2, D1), (*e*) condition (L1, S2, D1), and (*f*) condition (L2, S2, D1)

$$f_O = \frac{Z}{2}\left[1 - \frac{d}{D}\cos\alpha\right]f \qquad (2)$$

respectively, where f is the rotating frequency of the bearing, Z is the number of rolling elements, d is the diameter of the rollers, D is the effective diameter of the bearing, and α is the contact angle of the bearing. For the test bearing, these expressions give the characteristic frequencies of the bearing with inner and outer race defects as 23.6 Hz and 17.0 Hz (at 222 rpm), and 47.7 Hz and 34.4 Hz (at 444 rpm). Thus, the defect location can be identified by comparing the measured characteristic frequency with the predicted frequency. Note that the characteristic frequency gives no information concerning the character of the defect.

Initially a defect was seeded on the outer race, just under the location where the AE sensor was mounted. Therefore, the defect was located at a position of significant load. Figure 5 shows the waveforms of the AE signals from sensor 1 under various conditions. Clearly AE is released whenever the rollers roll over the defect point, and thus the AE signal has a periodic impact characteristic. The intensity of AE increases with increasing load and speed. Figure 6 shows the spectrum of the AE signal shown in Fig. 5(*b*) (condition (L1, S1, D1)), which is typical of other cases. From Fig. 6, it can be seen that the AE signal contains abundant high frequency components, the energy of which is mainly distributed in the range from 45 kHz to 200 kHz. It is difficult to distinguish the actual characteristic frequency directly in this spectrum because the characteristic frequency modulates the AE signal (thus not an additive component, but a multiplicative component in the AE signal) and hence is always a low frequency

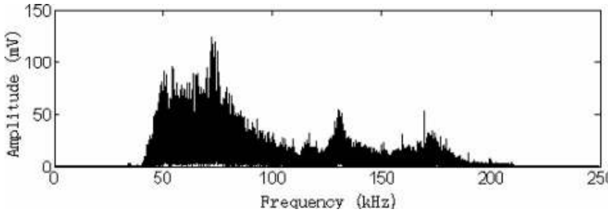

Fig. 6 The spectrum of the AE signal under condition (L1, S1, D1)

Table 1 Characteristic frequencies analysis for bearing with small defect on the outer race from sensor 1

Condition	Actual frequency (Hz)	Theoretical frequency (Hz)
L0, S1, D1	16.9	17.0
L1, S1, D1	16.7	17.0
L2, S1, D1	16.4	17.0
L0, S2, D1	33.3	34.4
L1, S2, D1	33.3	34.4
L2, S2, D1	33.3	34.4

compared with the AE frequency. However, the impact periodicity can be observed clearly in the corresponding AE waveform. It is also difficult and computationally demanding to estimate the characteristic frequency from the AE signal waveform directly using autocorrelation because the quantity of data in an AE signal is always very large and at a very high frequency. In this paper, short-time rms and autocorrelation functions are used to extract the actual characteristic frequency from real AE signals.

The mean-square value and the rms value of a voltage signal, $V(t)$, are defined as

$$V_{MS}(t) = \frac{1}{\Delta T}\int_{t}^{t+\Delta T} V^2(\tau)d\tau \tag{3}$$

$$V_{\rm rms}(t) = \sqrt{V_{MS}(t)} \tag{4}$$

If $V(t)$ is an AE signal, then V_{MS} reflects the energy distribution of the AE signal. The total energy within the time period $[t_1, t_2]$ of an AE signal is then

$$E \propto \int_{t_1}^{t_2} (V_{\rm rms})^2 dt = \int_{t_1}^{t_2} V_{MS} dt \tag{5}$$

If an AE signal is divided into many small segments (say, N points in each segment, equivalent to using a rectangular window of width N on the AE signal), and the rms value of each segment, that is, the short-time rms (STRMS) is calculated, then the STRMS reflects the energy characteristic of each segment. Thus, the new time series given by the STRMS preserves the low frequency energy distribution characteristic of the AE signal, and the data size is reduced significantly. The autocorrelation function is then utilized to extract the periodicity of the STRMS series and the characteristic frequency is then measured. As an example, Fig. 7 shows the STRMS time series and corresponding autocorrelation function of the AE signal shown in Fig. 5(*b*) (condition (L1, S1, D1)). The periodic bursts can be observed clearly in the STRMS time series and the autocorrelation function highlights this periodicity very clearly, which can be identified as 0.06 s. Thus, the actual characteristic frequency is $1/0.06 = 16.7$ Hz. This measured value is very close to the prediction of 17.0 Hz for the bearing with a defect on the outer race. By this method, all of the characteristic frequencies from AE signals in Fig. 5 may be measured and are shown in Table 1. Clearly all of the measured characteristic frequencies are very close to the corresponding predictions.

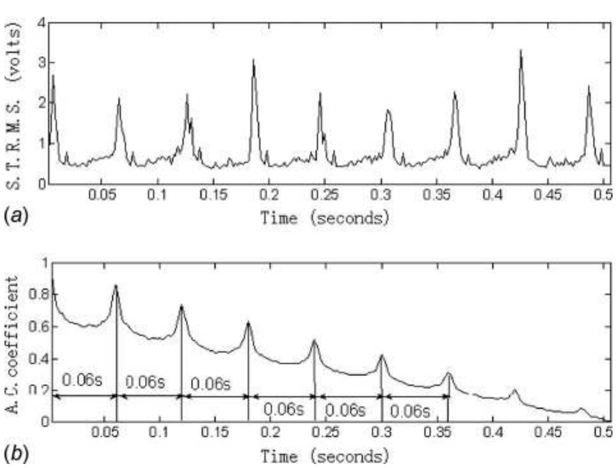

Fig. 7 STRMS and autocorrelation analysis of the AE signal for condition (L1, S1, D1) from sensor 1: (*a*) STRMS and (*b*) autocorrelation function

To investigate the propagation characteristics of AE in the bearing, Fig. 8 shows the AE signals from sensor 2 under various conditions. Comparing Fig. 8 with Fig. 5, it can be seen that the AE signal is attenuated severely. The impact periodicity of the AE signal almost disappears under some conditions (see Fig. 9, for example). Although sensor 1 is very close to sensor 2, there exist some interfaces between two sensors. Thus, this attenuation is caused mainly by the poor transmission through these interfaces and verifies that AE is very sensitive to interface transmission [8]. With increasing rotating speed and load, the AE signal gradually reveals the periodic impact characteristic. Figure 10 shows the results of the STRMS analysis and autocorrelation function of the AE signal under condition (L2, S1, D1), and clearly demonstrates that the autocorrelation analysis can extract the periodicity of AE signals, although the periodicity of the STRMS series is not obvious. The measured characteristic frequencies can be estimated and are shown in Table 2. The measured characteristic frequencies are close to the predictions except for two conditions. These results demonstrate that the proposed method to measure the characteristic frequency is very effective.

Now consider the situation with the defect on the inner race of the bearing. Figure 11 shows the AE signals from sensor 1 under various conditions. Comparing Fig. 11 with Fig. 5, shows that the AE signals have already become very weak, and the periodic impact characteristic almost disappears. This attenuation arises because the AE signal caused by the inner race defect reaches sensor 1 through the interface transmissions between the rollers and the inner race, and the roller and outer race. Theoretically speaking, the contact between the roller and the race is a line contact, and it is very difficult for AE to propagate through such a contact. Therefore, the AE signal is attenuated significantly before it reaches sensor 1.

It is well known that the vibration signal of a bearing with a single defect on the inner race has some obvious characteristics [20]. For example, in the spectrum of the envelope of the vibration signal, there are spectrum lines at the harmonics of the fault characteristic frequency with decreasing amplitude and modulating spectrum lines at two sidebands with the interval given by the rotating frequency. Some characteristics should also be found in the AE signal because the AE is also generated by the impact when the rollers roll over the defect on the inner race. But such characteristics cannot be found in the AE signals in our experiments. Instead, the AE signal with the defect on the inner race has similar characteristics to the AE signal with the defect on the outer race. Figure 12 shows a typical characteristic frequency analysis.

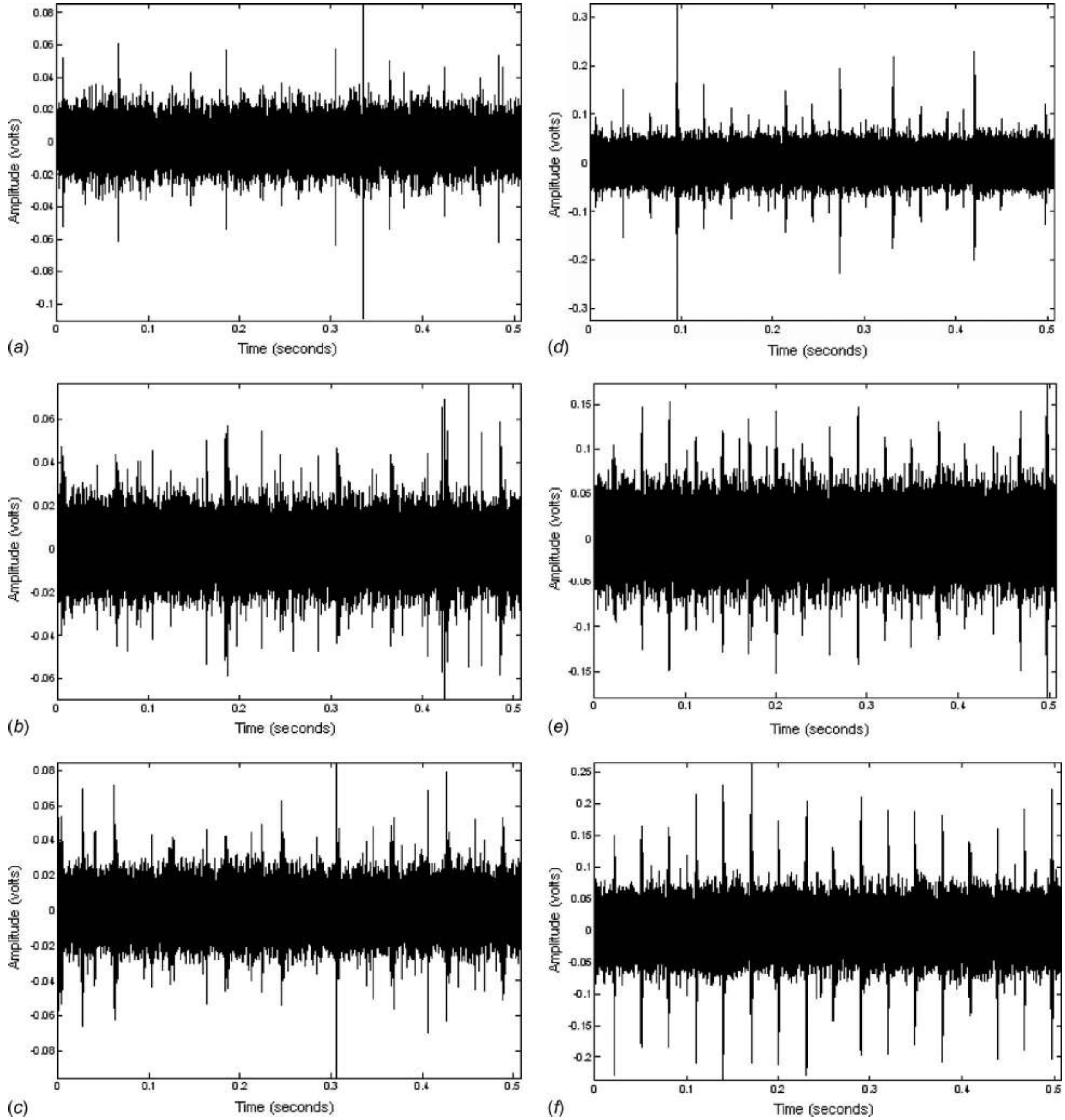

Fig. 8 AE signals with defect on the outer race from sensor 2: (*a*) condition (L0, S1, D1), (*b*) condition (L1, S1, D1), (*c*) condition (L2, S1, D1), (*d*) condition (L0, S2, D1), (*e*) condition (L1, S2, D1), and (*f*) condition (L2, S2, D1)

The characteristic frequency is measured as 33.7 Hz, which is close to the predicted frequency of 34.4 Hz for the defect on the outer race.

It is also possible that the AE signal may be modulated at the frequency of rotation. Thus if the AE signal is demodulated first, then the characteristic frequency analysis is shown in Fig. 13. Comparing Fig. 13 with Fig. 12 shows that the frequency characteristics are almost identical.

The above analysis shows that it is very difficult to obtain an effective AE signal when the defect is on the inner race and the sensor is on the outside surface of the bearing because of the transmission interface of almost point contact. Thus, Sec. 3.2 will concentrate on the AE analysis with the defect on the outer race.

3.2 Parameter Analysis of the AE Signal With a Defect on the Outer Race. Figure 14 shows the definitions of the AE parameters which are commonly used [21]. The waveform in Fig. 14 is the envelope waveform of the real AE signal. In this paper, counts, energy (i.e., rms), amplitude, and kurtosis are used to analyze the AE signal of the bearing with the defect on the outer race. All AE signals in this analysis are from sensor 1, and Table 3 gives the corresponding calculated parameters of the AE signals under various conditions.

3.2.1 Observation and analysis of AE counts under varying conditions. As illustrated in Fig. 14, the AE count is defined as the number of the AE impulses that exceed a set threshold voltage,

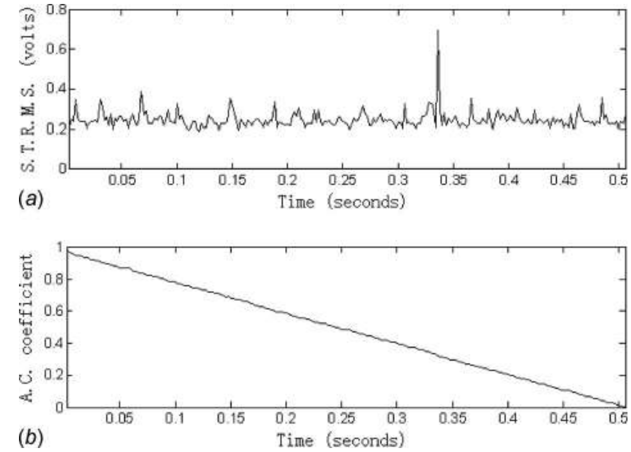

Fig. 9 STRMS and autocorrelation analysis of the AE signal for condition (L0, S1, D1) from sensor 2: (*a*) STRMS and (*b*) autocorrelation function

and thus AE counts reflect the activity level of the AE signal (oscillating frequency, for example). But AE counts is easily influenced by the test conditions, such as the geometrical shape of the specimen, the characteristics and mounting condition of the transducer, the set threshold voltage, and the performance of the amplifier and the filter. Figure 15 shows the comparison of AE counts under various conditions, and hence the sensitivity of AE counts to various conditions can be investigated.

(a) The influence of varying loads on AE counts. In Fig. 15, AE counts generally increase with increasing load; although such a trend is not obvious except under the condition (S2, D2). In contrast, AE counts sometimes decrease with increasing load under some conditions, for example, from condition (L0, S1, D1) to condition (L1, S1, D1) and from condition (L1, S2, D0) to condition (L2, S2, D0). This means that AE counts are not sensitive to the load.

(b) The influence of varying rotating speeds on AE counts. In Fig. 15, AE counts increase significantly under all conditions when the rotating speed increases from 222 rpm to 444 rpm. This means that AE counts are very sensitive to the rotating speed.

(c) The influence of defect size on AE counts. In Fig. 15, the change in the number of AE counts is not obvious from D0 to D1; even AE counts for D1 become smaller than that for D0 for a higher rotating speed of 444 rpm (for example, from condition (L2, S2, D0) to condition (L2, S2, D1). But when the defect size changes from D1 to D2, AE counts increase greatly. Therefore, AE counts are not very effective in identifying small or incipient defects, but it is very good for detecting larger defects.

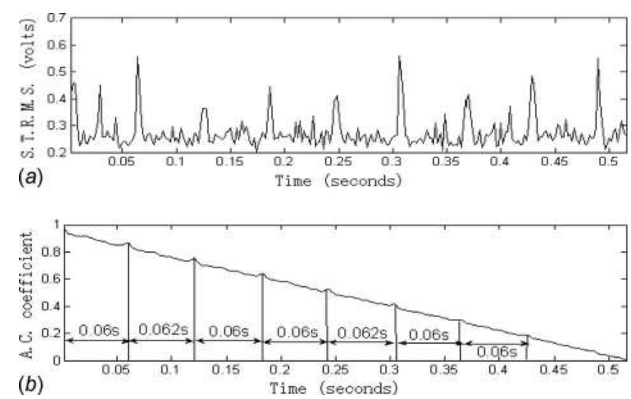

Fig. 10 STRMS and autocorrelation analysis of the AE signal for condition (L2, S1, D1) from sensor 2(*a*) STRMS and (*b*) autocorrelation function

Table 2 Characteristic frequencies analysis for bearing with small defect on the outer race from sensor 2

Condition	Actual frequency	Theoretical frequency (Hz)
L0, S1, D1	No	17.0
L1, S1, D1	No	17.0
L2, S1, D1	16.4 Hz	17.0
L0, S2, D1	34.5 Hz	34.4
L1, S2, D1	34.5 Hz	34.4
L2, S2, D1	33.3 Hz	34.4

From above observations and analysis, it can be summarized that AE counts are not sensitive to varying load applied to the bearing but is sensitive to the rotating speed, and especially to the defect size. Larger defects and increasing rotating speed will make AE counts increase significantly. A physical explanation for these observations may be postulated by noting that AE counts reflect the activity level of the AE source, and the activity of AE source is determined mainly by the material attributes, the defect condition, and the excitation manner. The load does not influence these factors and hence does not significantly affect the activity of AE source, especially at lower rotating speeds and for smaller defects. In contrast, increasing the rotating speed will increase the excitation frequency and the impact strength between the rollers and the defect and, hence, will significantly increase the AE counts. Similarly, defect size (and defect condition) does influence the activity level of AE source since a larger defect produces a higher excitation levels and produces a larger amplitude AE signal. Thus more signals will be above the count threshold. In addition, AE counts are easily influenced by the test conditions (such as the performance of the amplifier, as mentioned above). Thus, for a lower rotating speed and a smaller defect, the accuracy of AE counts will be influenced more seriously by the test conditions because AE counts are much smaller. Hence AE counts are more suitable to detect larger defects at higher rotating speeds.

3.2.2 Observation and analysis of AE amplitude under varying conditions. According to the definition, AE amplitude is the peak amplitude of AE envelope signal (see Fig. 14). AE amplitude is relative to the deformation mechanism of AE source in the material and reflects the characteristics of the AE source and AE strength generated in the material [22]. But AE amplitude is also influenced by test conditions, such as the response frequency and damping characteristics of the transducer, and the damping characteristic of the material. From Fig. 16, the sensitivity of AE amplitude to various conditions can be investigated.

(a) The influence of varying loads on AE amplitude. Figure 16 shows that AE amplitude is not sensitive to varying load, and no obvious trends can be observed with varying load under various conditions except for condition (S2, D1). Thus, there is no reason to regard that the increase in AE amplitude under condition (S2, D1) is caused just by increasing load alone.

(b) The influence of varying rotating speeds on AE amplitude. In Fig. 16 it can be seen that AE amplitude is very sensitive to varying rotating speeds and increases greatly with increasing rotating speed when a defect exists in the bearing (i.e., under conditions D1 and D2). But the rotating speed has almost no influence on AE amplitude if no defect exists in the bearing.

(c) The influence of defect size on AE amplitude. In Fig. 16 it can be seen that AE amplitude clearly increases when

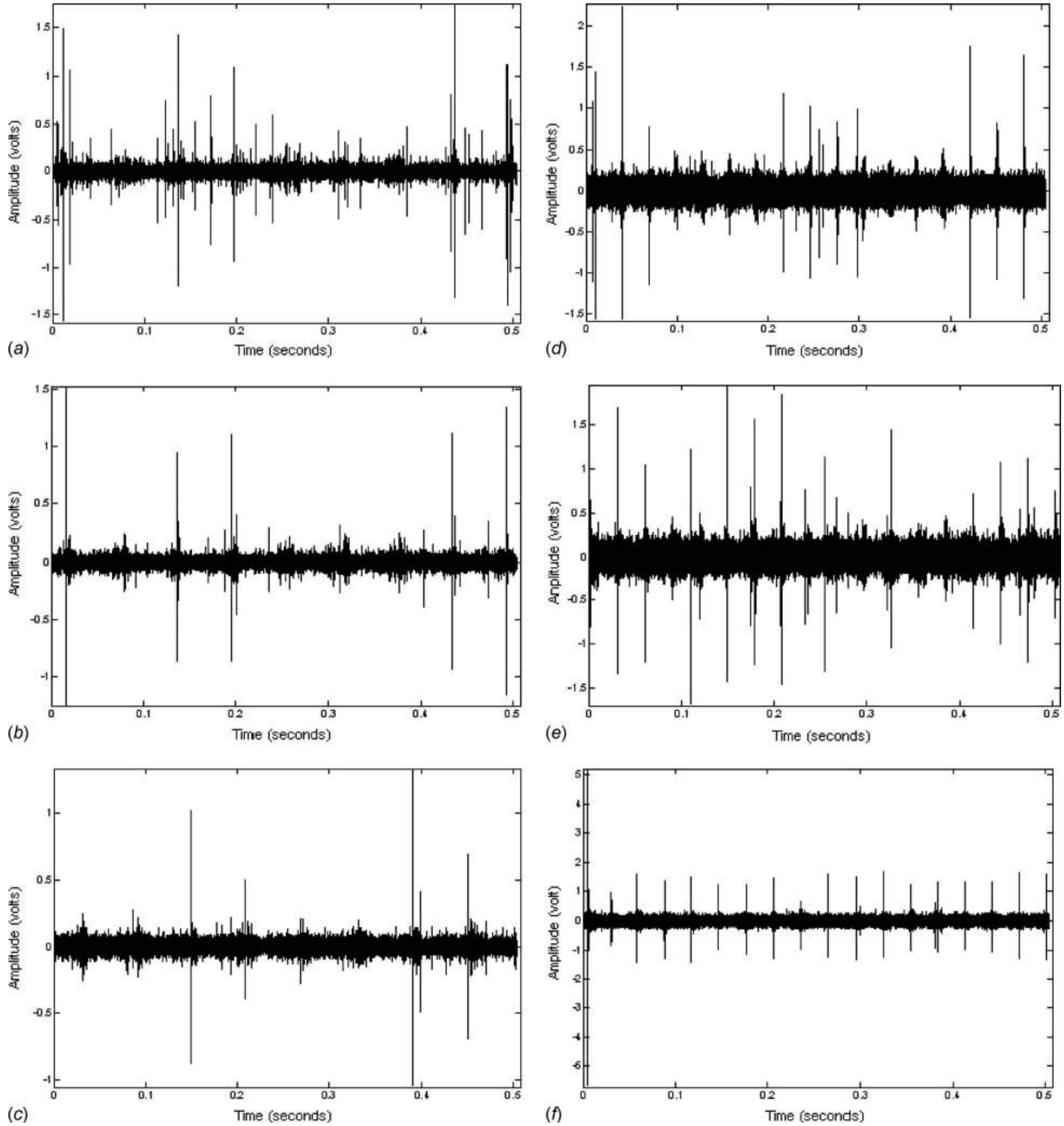

Fig. 11 AE signals with defect on the inner race from sensor 1: (*a*) condition (L0, S1, D1), (*b*) condition (L1, S1, D1), (*c*) condition (L2, S1, D1), (*d*) condition (L0, S2, D1), (*e*) condition (L1, S2, D1), and (*f*) condition (L2, S2, D1)

the condition changes from D0 to D1. But no trend of the AE amplitude can be clearly observed with varying defect size. These results mean that AE amplitude will increase obviously when the defect emerges in the bearing. But once the defect already exists, the AE amplitude is not sensitive to the defect size. Thus, AE amplitude cannot be used to identify the size and extent of the defect.

These observations and analysis are now summarized. If there is no defect in the bearing, then the AE amplitude is not influenced at all by varying conditions. When the defect initiates in the bearing, the AE amplitude will increase. Once a defect exists in the bearing, the AE amplitude is influenced only by the rotating speed, regardless of the defect size and the load. According to the physical meaning of AE amplitude illustrated above, when varying running conditions change, the deformation mechanism of the material then can influence the AE amplitude. Therefore, a possible physical explanation would imply that defect generation changes the deformation mechanism of the defect area, and such deformation mechanism of the defect area is not influenced by the defect size obviously. The constant load has no obvious influence on the deformation mechanism of the material. In contrast, the rotating speed has a strong influence on the deformation mechanism by changing the impact frequency and strength on the area around the defect in the bearing.

3.2.3 Observation and analysis of AE energy under varying conditions. As illustrated in Fig. 14, AE energy is defined as the rms of the AE signal, which is proportional to the area under the envelope waveform of the AE in Fig. 14. AE energy is directly

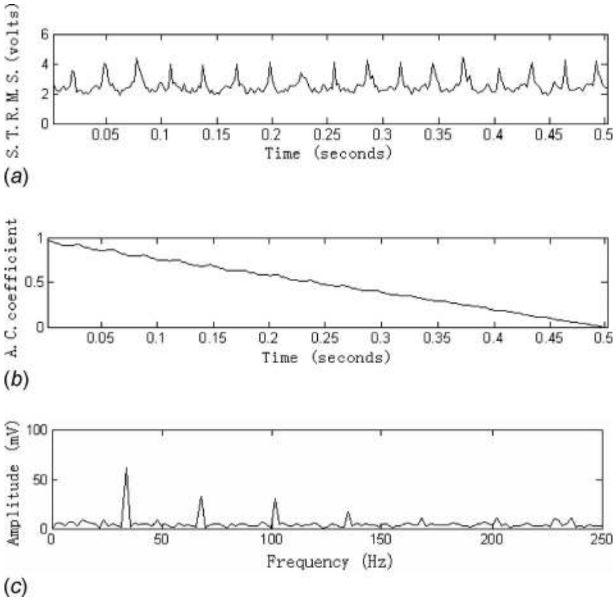

Fig. 12 Characteristic frequency analysis for condition (L2, S2, D1) from sensor 1: (*a*) STRMS, (*b*) autocorrelation function, and (*c*) spectrum of autocorrelation function

related to the mechanical energy, strain ratio, and deformation mechanism when strain energy is released in the material [22]. Therefore, AE energy is a suitable parameter to evaluate the failure and damage extent of the material and is an important parameter to be used in nondestructive examination by AE. rms voltage of AE (i.e., AE energy) is not sensitive to the electronic system gain and the coupling of the transducer to the machine and not influenced by the set threshold voltage. Therefore, the calculated AE energy from the AE signal will be more accurate and objective. The AE rms is calculated using Eqs. (3) and (4). From Fig. 17, the sensitivity of AE amplitude to various conditions can be investigated.

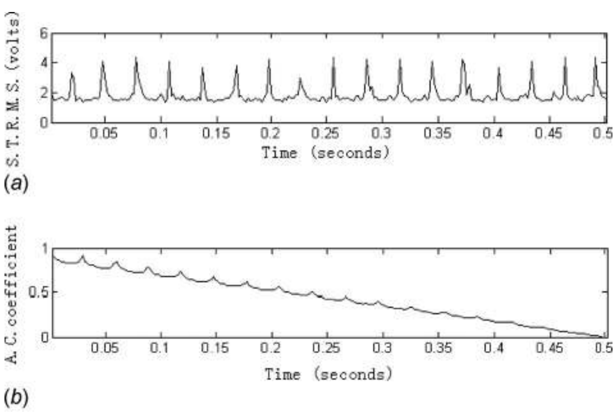

Fig. 13 Characteristic frequency analysis for condition (L2, S2, D1) after demodulation: (*a*) STRMS, (*b*) autocorrelation function, and (*c*) spectrum of autocorrelation function

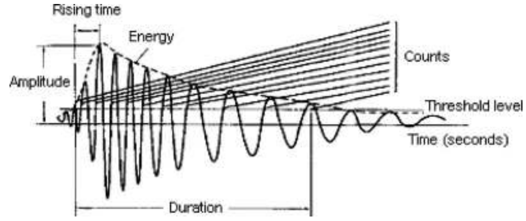

Fig. 14 Definition of AE parameters

Table 3 Calculated parameters of the AE signal under various conditions from sensor 1

Condition	Counts	Amplitude	rms	Kurtosis
L0, S1, D0	2308	0.31	10.77	14.58
L1, S1, D0	2643	0.21	10.38	6.53
L2, S1, D0	3155	0.21	11.21	5.92
L0, S1, D1	3069	0.35	10.88	23.18
L1, S1, D1	2927	0.50	12.89	54.12
L2, S1, D1	4241	0.60	14.78	93.42
L0, S1, D2	8397	0.71	17.83	186.75
L1, S1, D2	7569	0.44	15.69	24.87
L2, S1, D2	9182	0.34	16.83	10.50
L0, S2, D0	8816	0.30	14.56	4.08
L1, S2, D0	11,596	0.28	16.82	3.80
L2, S2, D0	10,347	0.30	16.18	4.10
L0, S2, D1	9003	1.55	30.16	151.01
L1, S2, D1	10,355	1.70	31.97	65.08
L2, S2, D1	10,390	2.05	40.60	62.53
L0, S2, D2	12,402	1.38	32.40	32.73
L1, S2, D2	13,781	1.42	38.23	27.67
L2, S2, D2	14,695	1.34	43.74	16.79

(a) The influence of varying loads on AE energy. In Fig. 17, no obvious trend of AE energy can be observed with varying conditions except condition (S2, D1) and condition (S2, D2). Under condition (S2, D1) and condition (S2, D2), AE energy increases with increasing load.

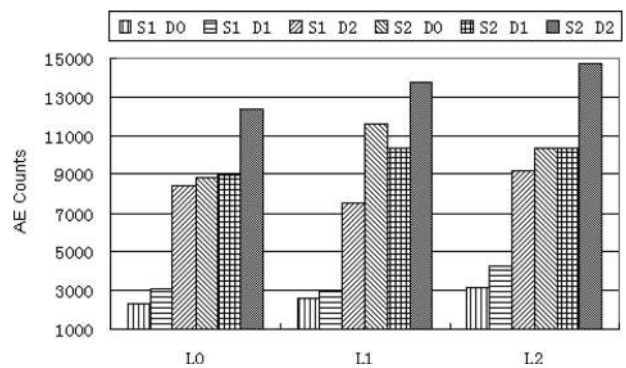

Fig. 15 Comparison of AE counts for various conditions

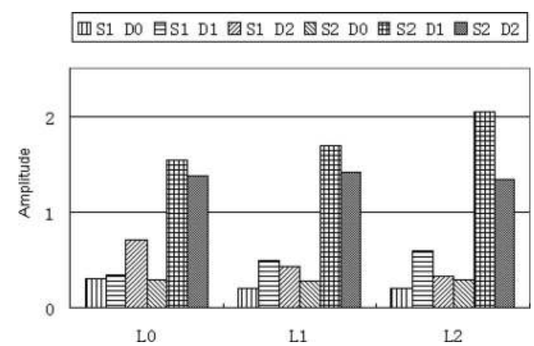

Fig. 16 Comparison of amplitude for various conditions

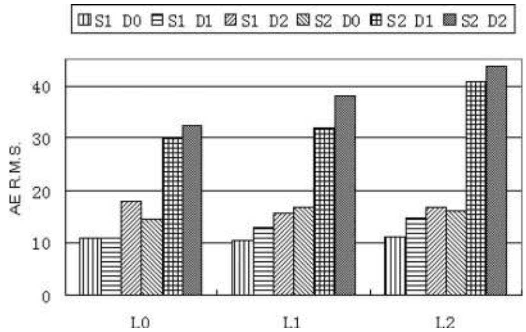

Fig. 17 Comparison of rms for various conditions

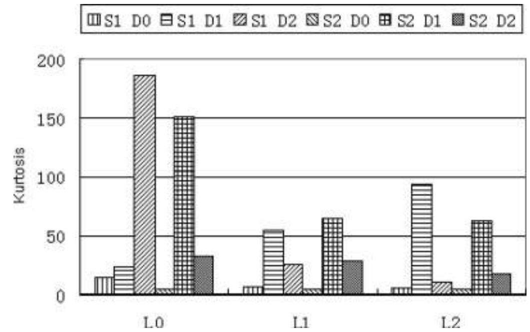

Fig. 18 Comparison of kurtosis for various conditions

Thus, we can say that AE energy is not sensitive to varying load under conditions of lower rotating speed and smaller defects.

(b) The influence of varying rotating speeds on AE energy. In Fig. 17, varying rotating speed has a strong influence on AE energy. AE energy increases greatly with increasing rotating speed under various conditions even under condition (D0) (no defect exists). Thus AE energy is very sensitive to varying rotating speed.

(c) The influence of defect size on AE energy. In Fig. 17, AE energy increases when the defect initiates and becomes larger, although this increase is not large. Thus AE energy is not very sensitive to the defect size.

From the above observations and analysis, in contrast to AE counts and AE amplitude, AE energy is much more sensitive to the varying conditions. Therefore, AE energy is regarded as a very important parameter in AE for defect detection and analysis. Compared with the rotating speed and the defect size, the load has less influence on the AE energy. For a lower rotating speed and smaller defects, the varying load has no obvious influence on AE energy, i.e., AE energy is also not sensitive to varying loads, just like AE amplitude. According to the physical explanation of AE energy, this verifies again that the constant load has very little influence on the deformation mechanism of the material and AE generation and, thus, has little influence on AE energy. However an increase in the rotating speed will cause impact frequency and strength to increase at the defect point and, thus, cause the AE energy to increase greatly. From the physical explanation of AE energy, this result also demonstrates that the excitation manner of the material will influence the strain characteristics and deformation mechanism of the material remarkably. The defect itself has much less influence on the AE source and its generating mechanism, and thus when the defect becomes larger, AE energy will increase but only slowly. This result coincides with the analysis result about the defect size in Sec. 3.2.2.

3.2.4 Analysis of AE kurtosis under varying conditions. The parameter kurtosis is a fourth-order statistic, which measures the crest shape of the probability density function of the sample. For the detection of defects in the bearing, kurtosis indicates the probability of the generation of periodic impulses with large amplitudes and is very sensitive to these periodic impulses. Kurtosis is defined as

$$k = \frac{E[V(t)-\mu]^4}{\sigma^4} = \frac{1}{N}\sum_{i-1}^{N}\left[\frac{V_i-\mu}{\sigma}\right]^4 \tag{6}$$

where μ is the mean, and σ is the variance of the signal $V(t)$.

Kurtosis of the vibration signal has been used to evaluate the working condition of bearings. When the bearing is undamaged and works well, the vibration signal is subject to a normal distribution and kurtosis is close to 3. When defects emerge and develop, the number of periodic impulses with large amplitude will increase within the vibration signal and kurtosis will increase rapidly. But with the further development of the defect, the level of such periodic impulses increases further and kurtosis will gradually decrease to close to 3 [23]. Thus the state of the bearing system transfers from one normal distribution state to another normal distribution state. Here kurtosis is used to analyze AE signals of the bearing and to investigate its sensitivity to the varying conditions.

Figure 18 shows the change and distribution of the kurtosis of the AE signals are very complicated with varying conditions. By using the physical meaning of Kurtosis, some insight can be drawn from this complicated figure. Al-Ghamd and Mba [19] demonstrated that AE from the bearing without defects is subject to a normal distribution, with a kurtosis close to 3. In our experiment, the AE kurtosis is also close to 3 or a little larger than 3 because of some noise under condition (D0) (see Fig. 18). When the defect emerges and exists, some periodic impulse will be caused and leads the AE kurtosis to increase and highlights that the bearing system has been moved from the normal distribution state. With the increase in the defect size and rotating speed, the number of periodic impulses with large amplitude increases and leads the AE kurtosis to increase greatly, for example, from condition (S1, D1, L0) to condition (S1, D2, L0) in Fig. 18. But with further increases in defect size and rotating speed, more and more such periodic impulses are generated within the AE signal, and the AE kurtosis decreases to close to 3, for example, from condition (S2, D1, L0) to condition (S2, D2, L0), from condition (S1, D1, L1) to condition (S1, D2, L1), and from condition (S1, D1, L2) to condition (S2, D2, L2), in Fig. 18. Thus the bearing system with the defect has switched from a non-normal state to close to another normal state. These results exactly coincide with the results for vibration signals. Furthermore no obvious influence of the constant load on the AE kurtosis can be observed in Fig. 18. Thus applying a constant load does not change the system state.

Table 4 Summary of parameter sensitivity to various conditions

Condition	Counts	Amplitude	Energy	Kurtosis
Load ↑	↑ (not obviously)	-	↑ (higher running parameters)	-
Speed ↑	↑ (greatly)	↑ (greatly)	↑ (greatly)	First ↑ then ↓
Defect size ↑	↑ (greatly)	↑ (when defect emerges)	↑ (not greatly)	First ↑ then ↓

For the parameter analysis, Table 4 gives a summary of the relation and sensitivity of the parameters to the various conditions (load, rotating speed, and defect size). For condition monitoring and defect detection in bearings, increasing the rotating speed will excite strong AE signals and make AE parameters more obvious, so that the defect can be monitored and detected more accuracy and easily.

4 Conclusion

In this experimental study, short-time root-mean-square and autocorrelation functions are used to measure the characteristic frequency of a bearing using AE signals. The results show that the proposed method is very effective in estimating the characteristic frequency from the AE signal. The paper then considers a parameter analysis of the AE signals to explore the relation and sensitivity of various AE parameters to the running conditions of the machine. AE counts, amplitude, energy, and kurtosis are considered for running conditions of radial load, rotating speed, and defect size. The results of AE parameter analysis demonstrate that a constant load applied to the bearing has no obvious influence on the AE parameters. However, the rotating speed has strong influence on the AE parameters for almost every running condition. The defect size has some influence on the AE parameters, but this is not so great. Thus, from the physical meaning of AE parameters, we conclude that the rotating speed has a strong influence on the strain mechanism and deformation mechanism through changing the impact frequency and strength. Thus, varying rotating speed always leads to a great change in the AE parameters under most running conditions of the bearing. The defect itself also has some influence on the generation of AE, but this is not so great. The constant radial load has little obvious influence on the generation of AE. Therefore, in order to excite strong AE for monitoring and detecting defect of the bearing, increasing the rotating speed should be considered first.

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