Non-contact acoustic emission measurement for condition monitoring of bearings in rotating machines using laser interferometry

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Abstract: For advanced maintenance and safety in nuclear power plants, it is necessary to combine various technologies that are used to monitor the status of different equipment. Non-contact measurement methods offer technical advantages over contact measurement methods, such as the ability to perform spot measurements, adapt to high-temperature environments, and inspect dynamic parts. The acoustic emission (AE) method can detect earlier abnormal signs in bearings than vibration analysis, which is commonly used in power plants. The AE method is also able to detect various other events such as wear and leakage of materials. However, currently, non-contact AE measurement is not used for condition monitoring in power plants. To verify the feasibility of a non-contact AE measurement method using laser interferometry for condition monitoring technology, laboratory tests were conducted using a rotating machine fitted with bearings that had deliberately been made defective. The AE signals propagating from these defects were measured using a Michelson interferometer on the rotating polished shaft, and a piezoelectric sensor positioned on the bearing housing. This paper demonstrates that the non-contact AE method can detect various stages of deterioration in bearings, and therefore, the method can be considered as a useful future tool for condition monitoring of bearings in rotating machines.

Keyword: acoustic emission; non-contact measurement; laser interferometer; condition monitoring; bearing

1 Introduction

Most issues in rotating machines are closely related to bearing failure. The life of a rolling bearing is determined by progressive flaking that results from rolling contact fatigue. The period of occurrence of flaking is hastened by various bearing defects, such as indentations and smearing, which are caused by external factors [1]. For advanced maintenance, bearing diagnosis utilizing the technologies used to monitor equipment conditions is obviously important for understanding the types and causes of abnormal states and the magnitude of bearing damage as early as possible. The acoustic emission (AE) method [2] is a monitoring technology that uses the elastic waves that are generated in the event of an irreversible release of strain energy such as a fracture, deformation, friction, wear, or leakage. The AE method can detect abnormal behavior and earlier signs of deterioration in bearings than vibration analysis. The characteristics of AEs depend on various phenomena; therefore, it is considered that the AE method offers potential for the detailed diagnosis of bearings by providing information about the types, factors, positions (source locations), and magnitude of abnormal states in machines. Generally, the measurement point in a rotating machine is a bearing housing that is monitored using a piezoelectric sensor. The AE signals obtained during the early to middle stages of bearing deterioration are almost the same level as the background noise. Because the bearing housing is influenced by the increase in noise level in accordance with the rate of shaft revolution, it is very difficult to detect the generated AE signals on the bearing housing. On the other hand, non-contact AE measurement can obtain AE signals directly - extremely close to the AE generation source - in dynamic components. Therefore, by non-contact AE measurement, it is believed that the AE signals emitted by the bearing in the early deterioration stages can be detected at a measurement point, which has a possibility of reducing the background noise. Non-contact AE measurement uses an interferometer, and the measurement object is directly illuminated by a probe laser beam [3-6]. Previous studies using

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interferometers have only been applied to the measurement of static objects. In contrast, in this study, laboratory tests were conducted using a rotating machine fitted with bearings that had deliberately been made defective. AEs propagated on a rotating shaft can be detected by a laser interferometer, and the AE characteristics are compared with those obtained on the bearing housing using a piezoelectric sensor. In this study, the authors of this paper succeeded in identifying the AE parameters that have the highest correlation with the amount of bearing defect.

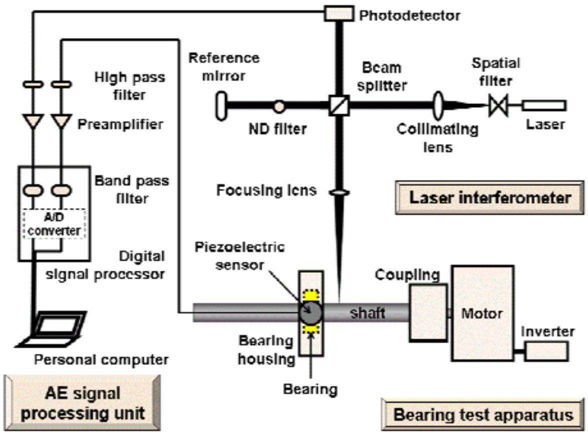

Fig. 1 Configuration of the experimental system.

2 Experimental system

The experimental system consists of three parts: a laser interferometer, a bearing test apparatus, and an AE signal processing unit (Fig. 1). The laser interferometer is configured in a Michelson arrangement. A He–Ne laser (05LHR171, CVI Melles Griot Company) is used as the light source, which emits light of 632.8 **nm** wavelength with a power of 7 **mW**. After the laser beam is spatial-filtered and collimated, it is divided into two beams by a beam splitter. One beam is the reference beam and travels to the reference mirror, while the other is the probe beam that is focused on the shaft, which was polished by lapping to increase its reflectivity. Both beams are reflected back to the beam splitter and recombined to generate interference. The intensity of the reference beam is attenuated by neutral density filters to obtain the highest contrast of the interference fringe. When AEs propagate on the shaft, the relative optical path difference between the reference and probe beams varies as a function of time. As the photodetector converts the interference intensity into corresponding voltage signals, AE signals can be retrieved by frequency analysis of the photodetector output. In the AE signal processing unit, the authors of this paper used a Disp-4 system (Physical Acoustics Corporation), which consists of a high-pass filter (10 **kHz**), a preamplifier (20 **dB**), a band-pass filter (20 **kHz** – 2 **MHz**), and an analog-to-digital converter (A/D resolution 16 bits). The sampling frequency is 5 **MHz**. The main components of the bearing test apparatus are a motor, coupling, shaft, and bearing specimen that are enclosed in a bearing housing. The center of the shaft, which is 30 **mm** in diameter and 300 **mm** in length, is supported by the specimen. The specimens used in this study are 6206 deep-groove ball bearings. The inner diameter, outer diameter, width, and ball diameter are 30 **mm**, 62 **mm**, 16 **mm**, and 9.53 **mm**, respectively. Artificial defects are added to the inner bearing raceways using electric discharge machining. The defect sizes are 0.25 **mm**, 0.50 **mm**, 0.75 **mm**, and 1.00 **mm** in diameter, and all the defects are 0.25 **mm** in depth. The shaft rotation speed is set to 837 **rpm** in all tests, and the total number of rotations during one test is 100,000 (120 **min**). The measurement point on the shaft is located 30 **mm** from the specimen, and the piezoelectric sensor is positioned on the bearing housing. Considering the measured noise signals under suspension, the thresholds of the interferometer and the piezoelectric sensor are set at 62 $\mathbf{dB}_{\mathrm{AE}}$ and 70 $\mathbf{dB}_{\mathrm{AE}}$, respectively. The reference value of $\mathbf{dB}_{\mathrm{AE}}$ is 1 **μV**.

3 Experimental results and discussion

Table 1 shows the AE hit numbers obtained by the laser interferometer and the piezoelectric sensor. The upper line contains the AE hit numbers obtained from the start of the test to 12 **min**, and the lower line contains the AE hit numbers obtained from the start of the test to 120 **min**. For the measurement point on the shaft, the AE hit number increases with defect size. By comparing the AE hit numbers, both lines for each defect size, it is considered that AEs are generated stably because the two AE hit rates have almost the same value. In the case of a defect-free specimen, it is considered that the generated AEs result from wear between the raceways and balls. In

Table 1 AE hit numbers

Measurement method	Measurement point	Time (min)	Defect diameter (mm) -free	0.25	0.50	0.75	1.00
Laser interferometer	Rotating shaft	12	43	609	680	884	1380
		120	1313	5437	6695	8859	13174
Piezoelectric sensor	Bearing housing	12	0	3	3	111	188
		120	0	11	26	815	1771

defect sizes from 0.25 **mm** to 1.00 **mm**, the AE hit numbers are also related to another type of AE, which is generated by the wear phenomenon, resulting from the passage of the balls over a defect in the inner raceway. On the other hand, for the measurement point on the bearing housing, although the AE hit numbers increase with defect size, they are much smaller than those on the measurement point at the shaft. In particular, in a defect size of 0.25 **mm** and 0.50 **mm**, AEs can barely be detected. The cause of the sharp decrease in AE hit numbers is AE amplitude damping on the boundary where the bearing housing and the outer ring of bearings specimen are a state of running fit.

AE peak amplitude and its distribution are usually used for considering AE characteristics. The AE peak amplitude distributions measured on the bearing housing and on the shaft are shown in Fig. 2 and Fig. 3, respectively. On the bearing housing (see Fig. 2), the maximum peak amplitude values change irregularly and are independent of defect size. On the shaft (see Fig. 3), although higher values of peak amplitude are observed to an extent with an increase in defect size, the relation between peak amplitude and defect size is not consistent. Root mean square (RMS) voltage or peak frequency is also widely used for considering bearing damage in bearing fatigue life tests. Fig. 4 shows the distribution of RMS voltage and peak frequency obtained by the piezoelectric sensor on the bearing housing. Basically, the RMS voltage and the peak frequencies have almost the same distribution and cannot show characteristics resulting from a change in defect size. Figure 5 shows the distribution of RMS voltage and peak frequency obtained on the shaft using an interferometer. In defect sizes from 0.50 **mm** to 1.00 **mm**, the maximum RMS voltage and peak frequency increase with defect size. These results suggest that the RMS voltage and peak frequency obtained by measurement of the shaft using the interferometer can recognize defects larger than 0.50 **mm**.

The authors of this paper propose using the frequency centroid and absolute AE energy to monitor the change in defect size. Figure 6 shows the distribution of the frequency centroid and the AE energy measured on the bearing housing by the piezoelectric sensor. In defect sizes of 0.25 **mm** and 0.50 **mm**, the correlation between the distributions and defect sizes is not clear because there are fewer measurements obtained. In defect sizes from 0.25 **mm** to 0.75 **mm**, the correlation between the distributions and defect sizes is also not recognized. In comparison with the distribution in a 0.75-**mm** defect, the distribution in the 1.00-**mm** defect is concentrated in a narrower range. As the piezoelectric sensor has a non-flat frequency response, the distribution is influenced by the effect of the resonance frequency and is associated with the contact surface of piezoelectric sensor. The distributions between the frequency centroid and the AE energy obtained from the shaft measurement are shown in Fig. 7. In all defect sizes, the distributions indicate that the frequency centroid tends to broaden, particularly to a lower frequency, with an increase in defect size. The distribution change with defect size is caused by the phenomenon that an AE is generated by a change in the contact aspect of balls on the defects with an increase in defect size. A comparison of the AE energy distributions indicates that the AE energy reaches higher values with an increase in defect size. This phenomenon suggests that the contact area of balls on a defect surface increases with defect size. The distribution frequency centroid and AE energy can clearly recognize a 0.25-**mm** defect. Thus, analyzing the relationship between defect sizes and the frequency centroid or AE energy in a shaft measurement provides useful information for condition monitoring of bearings.

4 Conclusions

(1) It was demonstrated that the presented non-contact AE measurement method using a laser interferometer can detect AEs on a rotating shaft in a laboratory test.

(2) After analyzing various AE parameters, it was observed that the frequency centroid and absolute AE

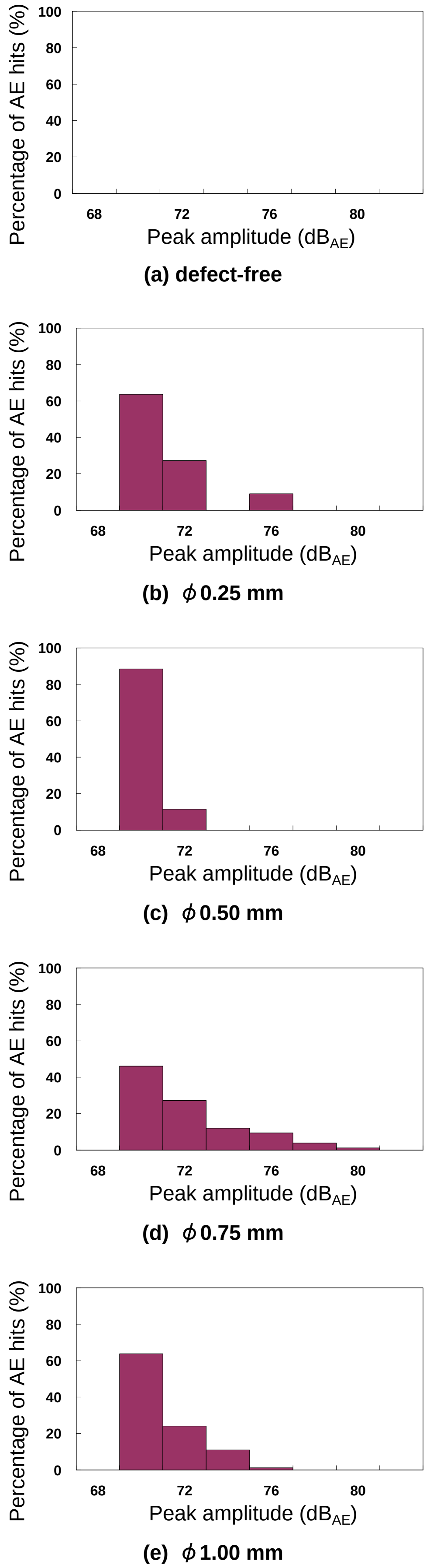

Fig. 2 Peak amplitude distributions measured by piezoelectric sensor on the bearing housing.

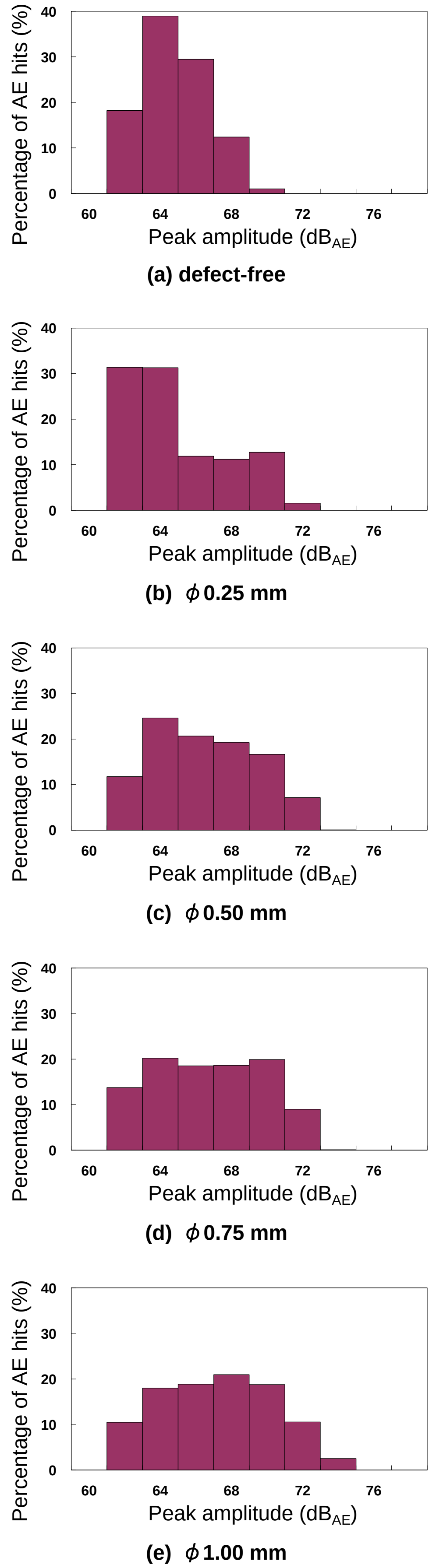

Fig. 3 Peak amplitude distributions measured on the shaft using laser interferometer.

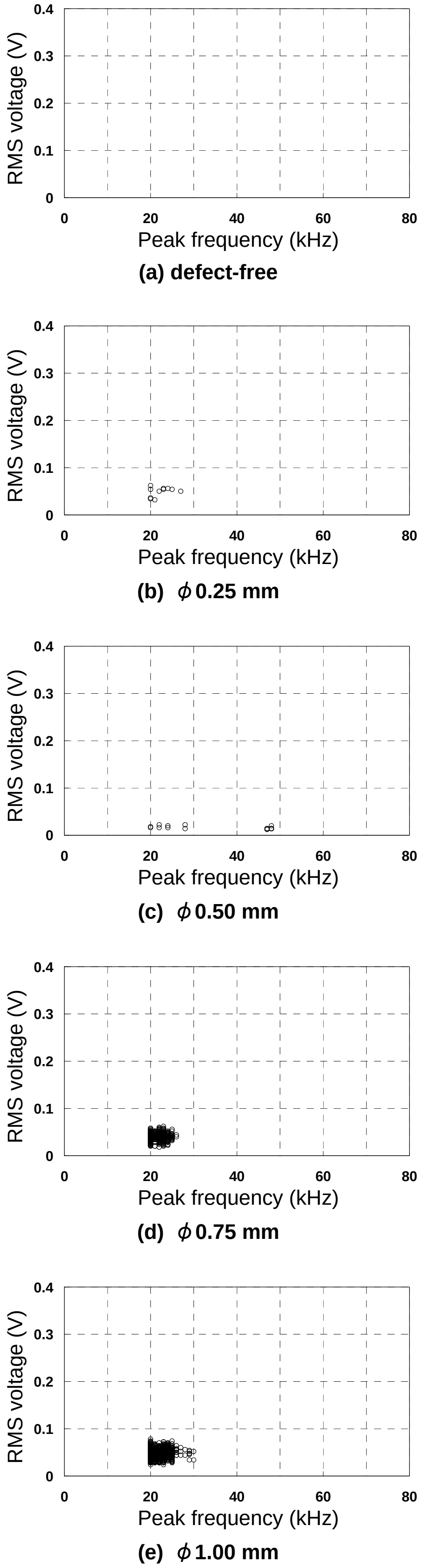

Fig. 4 Distribution of RMS voltage and peak frequency obtained by the piezoelectric sensor on the bearing housing.

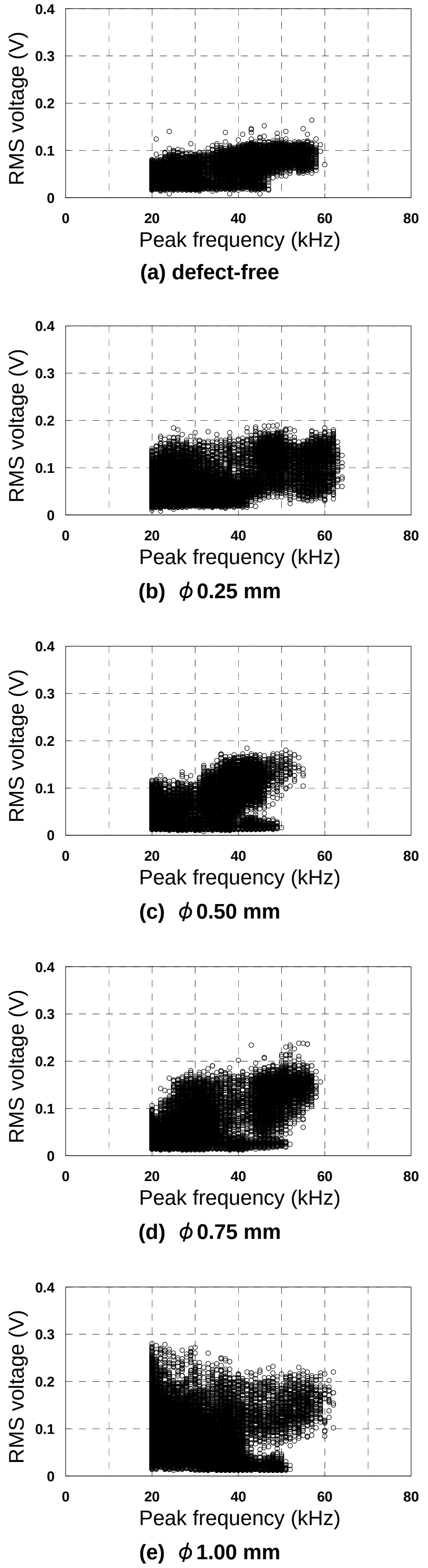

Fig. 5 Distributions of RMS voltage and peak frequency obtained on the shaft using laser interferometer.

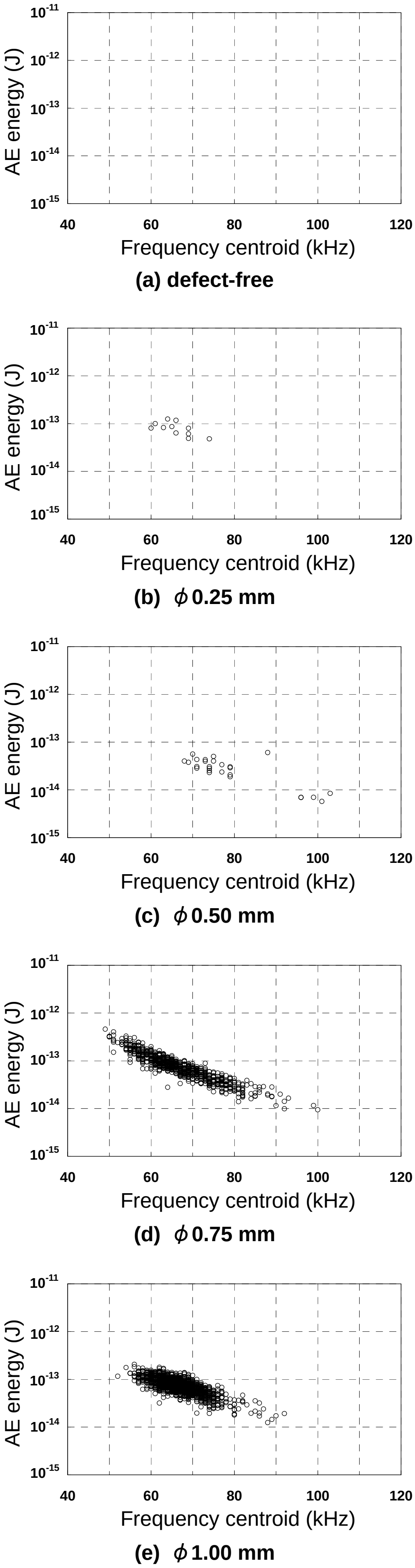

Fig. 6 Distributions of AE energy and frequency centroid obtained by piezoelectric sensor on the bearing housing.

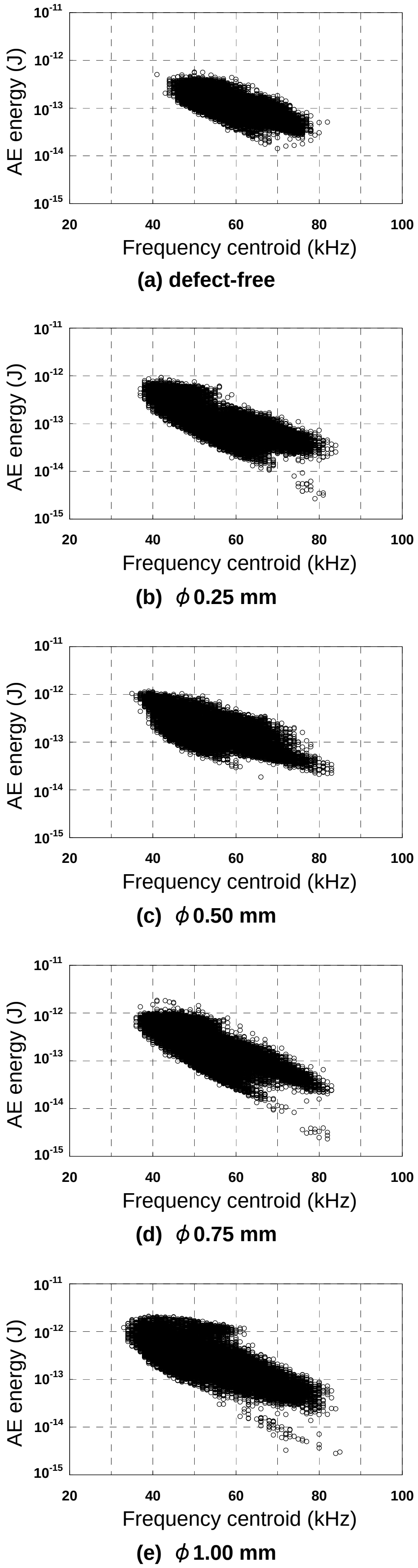

Fig. 7 Distributions of AE energy and frequency centroid obtained on the shaft using laser interferometer.

energy depend on the defect size of the rolling bearing.

(3) The distribution of frequency centroid and absolute AE energy obtained by shaft measurement can clearly detect smaller defects than a bearing housing measurement using the piezoelectric sensor.

The presented non-contact AE method is capable of being used for condition monitoring on rotating machines in actual plants.

References

[1] SKF Group: Bearing Failures and Their Causes. c1994; Product Information 401 (PI 401 E): 1-44. Available from: http://www.skf.com/files/099926.pdf

[2] Condition Monitoring and Diagnostics of Machines–Acoustic Emission: ISO/DIS 22096.

[3] PALMER, C.H., and GREEN, R.E.: Optical Detection of Acoustic Emission Waves," Applied Optics, 1977, 16(9): 2333-2334.

[4] PALMER, C.H.: Sensitive Laser Interferometer for Acoustic Emission and Ultrasonic NDE, Review of Progress in Quantitative Nondestructive Evaluation (NDE), 1986: 5A: 651-658.

[5] BRUTTOMESSO, D.A., JACOBS, L.J., and COSTLEY, R.D.: Development of Interferometer for Acoustic Emission Testing, Journal of Engineering Mechanics, 1993, 119(11): 2303-2316.

[6] WATANABE, M., ENOKI, M., and KISHI, T.: Fracture Behavior of Ceramic Coatings During Thermal Cycling Evaluated by Acoustic Emission Method Using Laser Interferometers, Materials Science and Engineering, 2003, A359(1-2): 368-374.