Prediction of Residual Fatigue Life of Bearings –Part 1: Application of X-Ray Diffraction Method–

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The objective of this study is to predict the residual fatigue life of bearings in operation by a non-destructive procedure. To predict the residual life is almost the same meaning to analyze the fatigue rate of bearing steel. Parameters on the rolling contact surface have been estimated by an X-ray diffraction method. As the results, it was found that half value breadth (HVB) is the most relational parameter changing with the progress of rolling fatigue, and the fatigue rate analysis technique by normalizing the changing quantity of HVB was established. But it will be necessary to take the internal fatigue information in order to precisely estimate the fatigue rate of bearings.

***Key Words**: rolling bearing, non-destruction, fatigue rate, X-ray diffraction, half value breadth*

1. Introduction

Rolling bearings, which have been playing an important role among various mechanical elements in every field, are still an object of active researches. Among such researches, those attracting keen interest include a research for obtaining longer service life and a research for predicting residual fatigue life. The former research typically includes: developing a high-cleanliness steel having less non-metallic inclusions from which flaking occur[1] or heat treatment for surface hardening[2]; or improving anti-fatigue strength by applying residual compression stress to the surface with a shot-peening method[3]. On the other hand, the latter research typically includes: investigating the prebreakdown phenomena of a bearing by monitoring some factors that can be used as prebreakdown phenomena (e.g., acoustic emission) until the bearing breaks[4]. Such research for the residual life prediction is especially important for those bearings used for high-cost or high safety-required facilities.

As described above, the conventional research for bearing service life prediction is directed to monitoring the occurrence of fatigue crack in a passive manner. In recent years, however, there is a growing need to predict bearings' residual service life in an active manner. That is, more and more bearing users want to analyze the fatigue level of a bearing when it has operated for a certain period of time to know the bearing's residual fatigue life as sooner as possible. This need comes from bearing users' desire to know a bearing fatigue level with shorter period of evaluation test so that they can develop new bearing application areas more speedily, to know the safety margin of existing bearing design, and to know the appropriate timing for bearing exchange to provide maintenance more efficiently.

One of widely used methods for evaluating the fatigue level of metal materials is X-ray diffraction method, in which residual stress, half value breadth (hereinafter referred to as HVB) of martensite, and retained austenite are mainly measured as X-ray parameters. Such X-ray parameters have been described in several publications[5)~8)], in which the correlation between the X-ray parameters and the fatigue of rolling bearings was investigated to analyze the bearings' fatigue rate (i.e., the ratio between bearing's service life and bearing's operation time). In these publications, Komura et al. suggested that the combination of HVB and retained austenite was appropriate for fatigue estimation[7], while Hirota et al. suggested that the combination of residual stress and HVB was appropriate for the same purpose[8]. Both of the above methods, however, cannot appropriately evaluate the fatigue of bearings in continuous use, since both of them are not nondestructive approaches to analyze the fatigue, i.e., both of them use electro-polishing pretreatment to break the rolling contact surface of a bearing. Both reports that the best correlation for evaluating the flaking from the inner side of a bearing is the one between the fatigue rate and the X-ray parameter at a depth where the maximum shear stress is occurred.

Due the above needs, Koyo has developed a new method for analyzing in nondestructive manner the fatigue rate of a bearing until it starts flaking from its inner side, so that a bearing for continuous use can be evaluated. This paper describes one aspect of the new method using X-ray diffraction.

2. Preliminary Test

2. 1 Test Method and Conditions

First, a preliminary test was conducted to specify X-ray parameters gained from the rolling contact surface of a rolling bearing which show the correlation with the fatigue rate of the bearing. **Figure 1** shows the test apparatus used in this test. For convenience of X-ray diffraction measurement, cylindrical roller bearings (NU206) were used as test bearings, which are outer-ring-assembly type and are made by through hardening treatment. On both sides of a shaft, cylindrical roller bearings were mounted.

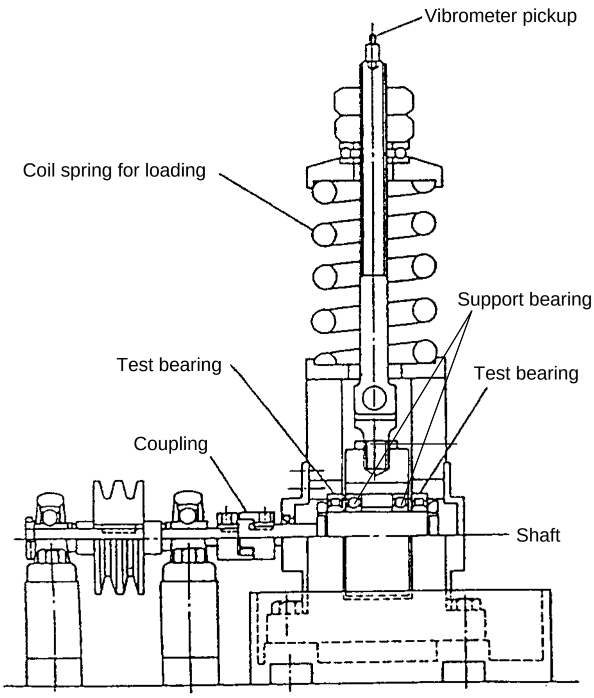

Fig. 1 Test apparatus

Table 1 shows the test conditions. Bearing load is 7.06 kN (0.3Cr) and rotational speed is 2 500 min^{-1}. Turbine oil VG68 was circulated as a lubrication oil and oil temperature was not controlled but was in the range of 70±5℃. Oil film parameter was three or more and was under condition of fluid film lubrication.

Table 1 Test conditions

Test bearing	NU206
Bearing load	7.06 kN(0.3Cr)
Rotational speed	2 500 min^{-1}
Lubrication	Turbine oil VG68 circulated (oil: natural temperature rise)

2. 2 Conditions for Measuring X-Ray Diffraction

X-ray diffraction was measured using an apparatus with a position-sensitive proportional counter (PSPC), measuring conditions of which were shown in **Table 2**. An inner ring of the bearing was measured where the highest load stress generates and three equally-spaced points on three inner race rolling tracks in the axial direction (i.e., total of nine points) were measured. During testing, measurement was intermittently performed until flaking occurred by stopping the test at the predetermined time and measuring the condition of the test bearing whose inner ring was mounted on the shaft with a support bearing.

Table 2 X-ray diffraction measuring conditions

Characteristic X-ray	Cr-Kα
Tube voltage	10 kV
Tube current	30 mA
Irradiation time	100 s
Collimator	1×1mm
Scan method	Inclination method
Incidence method	ψ 0, Constant method
ψ angle	0, 10, 20, 30, and 40 deg.
Measurement range	143~170 deg.
Calculation method of peak	HVB midpoint method
Deflection correction	Filter method
Diffraction face	α : [211], γ : [200]

2. 3 Measurement Result and Determination of Evaluation Parameter

Figure 2 shows the change of X-ray parameters (residual stress, HVB, retained austenite) of the rolling contact surface to the fatigue rate. **Figure 2** also shows the correlation coefficients gained by regression analysis. As **Fig. 2** shows, as fatigue rate increases, compressive stress of residual stress increases and HVB and retained austenite decrease. Comparison among the above three X-ray parameters shows that the combination of the HVB and the fatigue rate has the best correlation coefficient of 0. 943 with regards to the progression of rolling fatigue rate. Thus, the decrease of HVB may be the best evaluation parameter for analyzing the bearings' fatigue rate.

It is noted, however, that the HVB of rolling contact surface differs from bearing to bearing depending on the finishing polish level even when new unused bearings are compared. There is also a report on such a point that the same decrease values in HVB can have different fatigue rate and thus it is difficult to estimate bearing fatigue rate from the rolling contact surface's HVB[8]. The factors that cause such a difference in HVB include the difference in measurement apparatus and measurement conditions. Accordingly, the decrease value of the HVB must be normalized before subjected to evaluation.

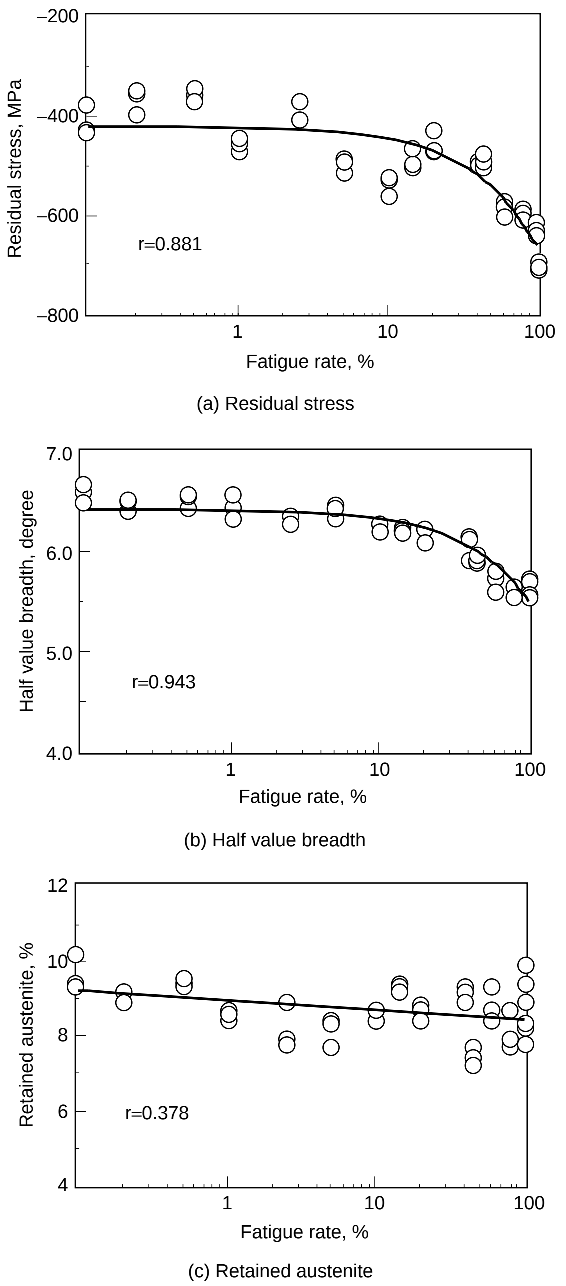

Fig. 2 Change of X-ray parameters to fatigue rate

In view of the above, in this paper, the change of HVB is made dimensionless by using the following formula and the dimensionless change is defined as the decrease rate of HVB.

$$\text{Half value breadth's decrease rate} = \frac{\text{Internal HVB} - \text{Surface HVB}}{\text{Internal HVB}}$$

In the above formula, the internal HVB refers to the HVB of a post-heat treatment material and that is independent of both of rolling fatigue and finishing polish conditions. Since this paper intends to provide a nondestructive method for measuring the bearing's fatigue rate, the measurement of internal HVB was performed on the bearing side face which had no relation with bearing rolling performance and which was electro-polished to the depth of about 50 μ m.

3. Test for Determining Influence of Bearing Load

3. 1 Test Conditions

For practical application of fatigue rate analysis technique, it is desirable to prepare a database by performing tests under various conditions because such an application often requires the analysis of a bearing that is unknown in how it has been operated. For this purpose, tests were conducted with different bearing loads to observe the behavior of the decrease rate of HVB of these bearings. **Table 3** shows the test conditions for these tests. Test for determining the influence on the bearing fatigue rate by bearing rotational speed was omitted because it could be estimated that bearing fatigue rate had no influence on the bearing life as long as the bearing was used with fluid film lubrication.

Table 3 Test conditions

Test bearing	NU206		
Bearing load, kN	4.71	7.06	9.84
Rotational speed, min^{-1}	4 000		
Lubrication	Circulation of turbine oil VG68 (oil temperature: natural temperature rise)		

3. 2 Behavior of Decrease Level of Half Value Breadth (HVB)

Figure 3 shows the result of the above test with three different bearing loads, in which the relation between the fatigue rate and the decrease rate of HVB is shown. It is noted that the calculation of the decrease rate of HVB in this test was performed by measuring, per one test bearing, only those positions of the above-specified nine measurement positions that showed flaking in the inner ring width direction to adjust the measured values with the average of the measurement values in circumference direction. That is, this test was performed on the assumption that any circumference position that shows flaking has the same fatigue rate. As can be seen from **Fig. 3**, the decrease rate of HVB gradually increases within the range of fatigue rate of 20% and subsequently shows further rapid increase. A logarithmic regression analysis was performed on this low fatigue rate range having fatigue rate of 20% or less to obtain the correlation coefficient of 0.732. The same was performed on the high fatigue level range having fatigue rate of 20% or more to obtain the correlation coefficient of 0. 865. This difference in correlation with fatigue rate is presumably attributed to the fact that grain distortion that is accumulated in an inner side of rolling contact region appears on a rolling contact surface when the fatigue rate exceeds 20%. Such a difference is described in a report[7)] that 10% or more increase in fatigue rate during the measurement of the inner side of a rolling contact surface causes the change in evaluation parameters. Therefore, it is estimated that although there is a difference in the increase of fatigue information between bearing inner side and bearing surface, both positions have the same process of fatigue increase.

Based on the above result, it was clarified that the combination of fatigue rate and the decrease level of HVB can provide good correlation with bearing fatigue rate even when different bearing load is applied or when bearings to be tested have different service life.

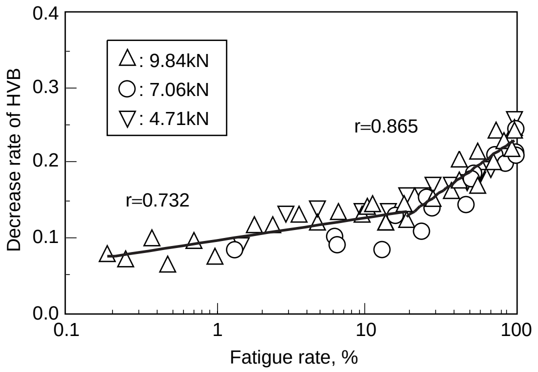

Fig. 3 Relation between fatigue rate and the decrease rate of HVB

3. 3 Reliability Zone

Next, reliability zone is calculated in order to calculate the range in which fatigue rates are dispersed. When **Fig. 3** is used as a database for analyzing fatigue rate, the decrease rate of HVB can be used as a dependent variable from which the fatigue rate can be estimated as an independent variable. In this case, reliability zone can be expressed as 100(1−α)% and can be given by[9]:

$$Y_x - B_{\alpha,x} \leq y \leq Y_x + B_{\alpha,x} \tag{1}$$

wherein Y_x is the decrease rate of HVB that is calculated by the regression curve when fatigue rate is *x*. $B_{\alpha,x}$ in Formula (1) is given by the following Formula (2).

$$B_{\alpha,x} = t_{(n-2);\alpha} S_{Y|X} \sqrt{1 + \frac{1}{n} + \frac{(x-\overline{X})^2}{(n-1)S_X{}^2}} \tag{2}$$

wherein $S_{Y|X}$ is a standard deviation of regression curve, S_X is a sample standard deviation, n is the number of samples, and $\overline{X}$ is the average of samples. The value of $t_{(n-2);\alpha}$ is obtained from distribution table of t.

Figure 4 is the result of using the data of high fatigue level region in **Fig. 3** to obtain 95%-reliability zone (α = 0.05).

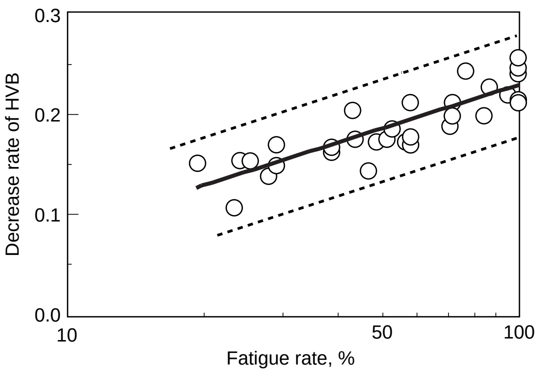

Fig. 4 95% reliability zone of database for fatigue rate analysis

4. Further Application of Database for Fatigue Rate Analysis

4. 1 Application of Database to Point-contact Bearings

As described above, through-hardened cylindrical roller bearings were used to prepare the database for fatigue rate analysis. Such a database needs to be also applicable to point-contact bearings. Thus, fatigue level test was performed on deep-groove ball bearings (No. 6206) to observe the behavior of the decrease rate of HVB to fatigue rate. In this test, bearing load was 8.93kN (0.46 Cr), rotational speed was 4 000min^{-1}, and lubrication conditions were the same as those used in the preliminary test.

Figure 5 is the result of plotting the data regarding the deep-groove ball bearings on 95%-reliability zone of the cylindrical roller bearings shown in **Fig. 4**. As can be seen from **Fig. 5**, the data regarding the point-contact deep groove ball bearings is covered by the line-contact cylindrical roller bearings' 95%-reliability zone. Accordingly, the database shown in **Fig. 4** is verified to be applicable to any bearing contact forms.

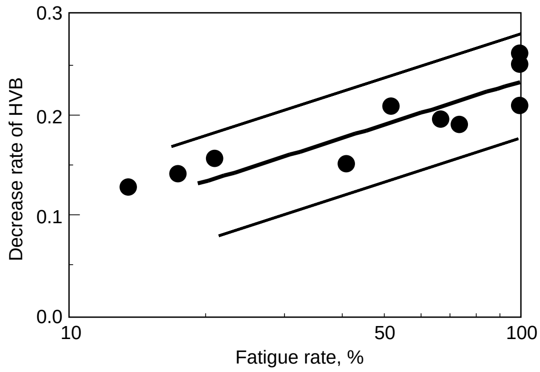

Fig. 5 Behavior of the decrease rate of HVB of deep groove ball bearings in the reliability zone of cylindrical roller bearings

4. 2 Application of Database to Surface-hardened Bearings

Next, application of the database in **Fig. 4** to bearings provided with different heat treatments is discussed. **Figure 6** shows the relation between the fatigue rate and the decrease rate of HVB of the bearing that is provided with surface hardening-heat treatment (i.e., the surface thereof has higher hardness than that of the internal thereof). For comparison, **Fig. 6** includes 95%-reliability zone of through-hardened cylindrical roller bearings shown in **Fig. 4**. Bearings provided with surface hardening-heat treatment in **Fig. 6** include the one gained by subjecting SUJ2 material to carbonitriding-heat treatment, the one gained by subjecting SAE5120 material to carburizing heat treatment, and the one gained by subjecting the SAE5120 material to special carburizing heat treatment. Regression curves of the above differently heat-treated bearings show smaller slopes as compared with those of through-hardened bearings and have too much dispersion to estimate the bearing fatigue rate from the decrease rate of HVB. Therefore, it can be said that the database shown in **Fig. 4** is only applicable to through-hardened bearings and is difficult to be applied to surface-hardened bearings.

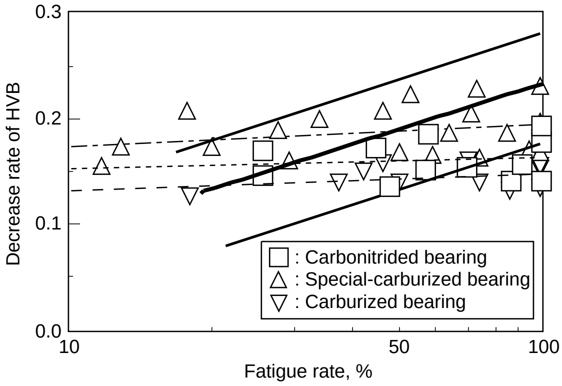

Fig. 6 Relation between fatigue rate and the decrease rate of HVB of surface hardening-heat treatment bearings

Hereinafter, the reason why the decrease rate of HVB of the surface-hardened bearings is small is discussed. **Figure 7** shows the distribution of the internal hardnesses of the above differently heat-treated bearings. As can be seen from **Fig. 7**, the above differently heat-treated bearings have higher surface hardness than that of through-hardened bearing. **Figure 8** shows the distributions of residual stresses in depth direction and HVBs. As can be seem from **Fig. 8**, the above differently surface-hardening-heat-treated bearings have higher surface compressive residual stress and HVB as compared with those of through-hardened bearings, showing the fact that grain distortion has occurred in the former bearings due to the heat treatment. Based on the above result, the small decrease in HVB by rolling fatigue is attributed to large compressive residual stress indicating uniform grain distortion and large HVB indicating un-uniform grain distortion, thereby resulting in small release of the surface layer's grain distortion due to rolling fatigue.

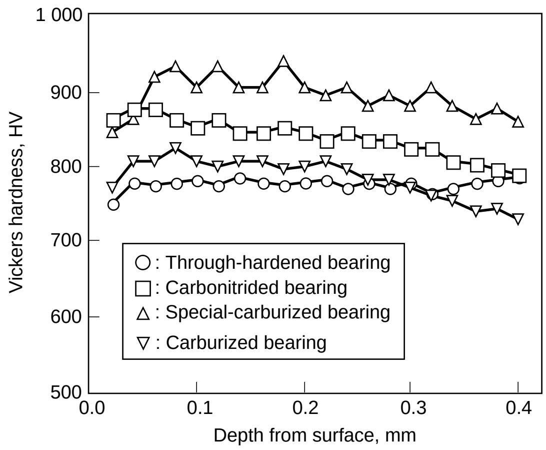

Fig. 7 Distribution of internal hardness of various heat treatment bearings

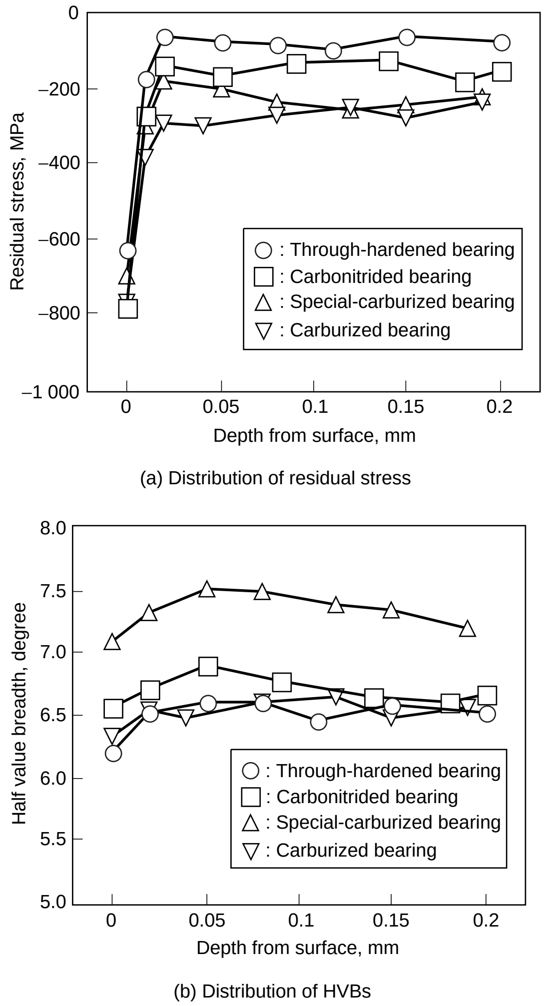

Fig. 8 Distribution of residual stress and HVB of various heat treatment bearings

5. Conclusions

As described above, bearings operated under such conditions that can cause the bearings' flaking from the inside were analyzed using X-ray diffraction method in order to analyze the fatigue rate in non-destructive manner, the results of which are summarized as belows.

(1) From behaviors of X-ray parameters caused by rolling fatigue generated on rolling contact surfaces, compressive residual stresses showed increase and HVBs and retained austenite showed decrease. The combination of the bearing fatigue rate and the change of HVB showed the best correlation for analyzing the bearing residual fatigue life.

(2) The decrease rate of HVB of rolling contact surface is divided by the value of internal HVB to obtain dimensionless decrease rate, thereby preparing fatigue level analysis diagram with regards to through-hardened bearings. In this diagram, the combination of the bearing fatigue rate and the decrease rate of HVB showed good correlation with the bearing residual fatigue life even when different bearing loads are applied or when bearings to be tested have different contact form.

(3) For a surface-hardening-heat-treated bearing, it is difficult to estimate its residual fatigue life because the decrease rate of HVB of the rolling contact surface is small and this causes too much dispersion of fatigue rates to analyze the residual life thereof.

The process by which bearing rolling fatigue leads to the end of the bearing service life is as follows: When rolling fatigue is generated in a bearing operating under normal and clean-oil environment, this fatigue gradually accumulates at the depth from which the maximum shear stress is generated to result in flaking, thereby the bearing's service life is ended. In view of the above basic process, it can be said that the HVB measurement by X-ray diffraction method does not provide enough accuracy for the estimation of the bearings' residual fatigue life because it only provides the fatigue information of rolling contact surface. It was also observed that the X-ray diffraction method is difficult to be applied to surface-hardened bearings. Thus, in order to increase the analysis accuracy and the applicability, it is necessary to provide the method for obtaining bearing's internal fatigue information in a nondestructive manner. For this purpose, the next report of this series will provide an approach for analyzing the bearing fatigue rate using an ultrasonic method.

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