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Detection and Classification of Bearing Flaking Defects by Using Kullback Discrimination Information (KDI)

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Abstract : Kullback Discrimination Information (KDI) is one of the pattern recognition methods. KDI defined as a measure of the mutual dissimilarity computed between two time series was studied for detection and classification of bearing flaking on outer-race and inner-races. To model the damages, the bearings in normal condition, outer-race flaking condition and inner-races flaking condition were provided. The vibration sensor was attached by the bearing housing. This produced the total 25 pieces of data each condition, and we chose the standard data and measure of distance between standard and tested data. It is difficult to detect the flaking because similar pulses come out when balls pass the defection point. The detection and classification method for inner and outer races are defected by KDI and nearest neighbor classification rule is proposed and its high performance is also shown.

Key words : KDI, nearest neighbor classification rule, bearing flaking, detection and classification

1. Introduction

As recent manufacturing facilities become more complex and larger, safety and reliability issues become more critical. Not only the system failure in machinery accompanies with danger but also it increases operational costs. Therefore, the roll of fault detection/diagnosis has become more important. From the point of view, the authors research experimentally on methods of classification by applying pattern recognition theory. The essential requirement to the monitoring system of the bearing damages is not only to detect them but also classify their properties. Until now, diagnosis of various equipments including bearing has been practiced on the basis of various index of vibration (Skewness, Kurtosis, etc.) expressing the statistical character of vibration wave shape. This had the essential limitation, which is unable to detect and diagnose, at early stage of the abnormal conditions because there isn't shown any difference in basic vibration level. Therefore, in case of detecting the defect of an object, it is necessary to detect minute change in the wave shape. This paper constructs the diagnosis system using Kullback Discrimination Information and through experiment. It is considered that this system is suitable in detection this change and tested qualification by applying bearing races flakes defect. Because this method judge on the basis of standard signal like following statement, the choice of standard signal is important. Therefore, this paper is discussed on the selection of standard signal.

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2. Theory

2-1 Kullback Discrimination Information

Kullback Discrimination Information (under here it's KDI) is expressed like the next equation as the measure of incapable degree. Let X_o and X_m to be two d-vector random variables with probability density functions $f_m(x)$ and f_0 (x), respectively [1].

$$I(f_0, f_m) = \int f_0(x) \log[f_0(x)/f_m(x)]dx \tag{1}$$

If X_o and X_m are each normally distributed with n-component mean vectors μ_0, μ_m and $n \times n$ covariance matrices Σ_0, Σ_m respectively, then,

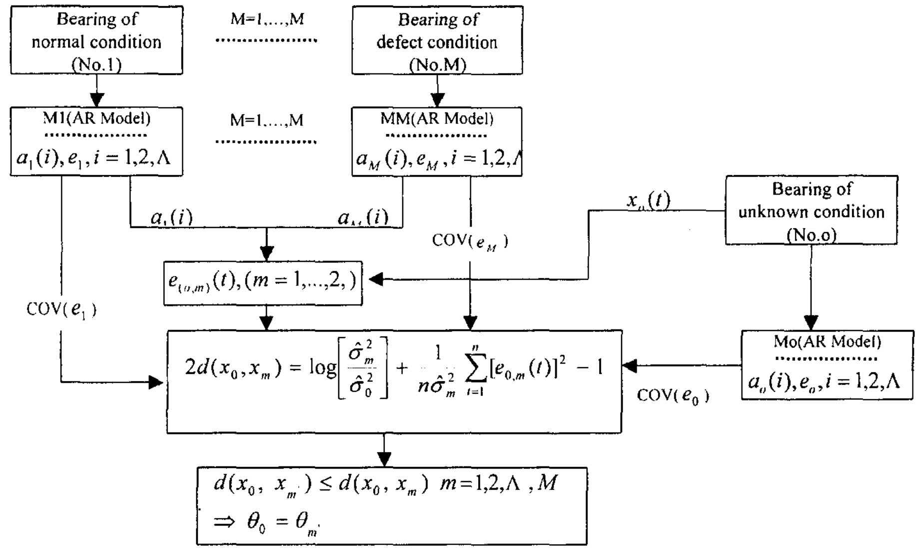

Fig. 1. Bearing defect classification scheme using KDI with the NN rule.

$$2d(x_0, x_m) = \log\frac{\hat{\Sigma}_m}{\hat{\Sigma}_0} + tr\hat{\Sigma}_0(\hat{\Sigma}_m^{-1} - \hat{\Sigma}_0^{-1}) + tr[\hat{\Sigma}_m^{-1}(\hat{\mu}_0 - \hat{\mu}_m)(\hat{\mu}_0 - \hat{\mu}_m)^T] - n \qquad (2)$$

In equation (2) and subsequently, the notation $|A|, tr(A), A^{-1}$ and A^T denotes, respectively, the determinant, trace, inverse and transpose of the matrix A. Here, N-duration sample time series x_0 and x_m. Let, $\hat{\mu}_j = (\hat{\mu}_j(1), \Lambda\hat{\mu}_j(n))$,$\Sigma_j(j = 0$ or $m, m = 1, \Lambda, M)$ be the estimated average and estimated covariance matrices, respectively, of x_j. In case of intending to know a measure of the dissimilarity computed between the sample time series x_0 and x_m. The probability distribution of x_0 and x_m should be regular distribution under the supposition leading out an equality. We can satisfy the regular character of residual series by fitting Auto Regression(AR) Model into the observation data (decide Parametric Model with observation data). Besides, the calculation is simple. The equation (3) is the calculation expression of the distance fitting AR Model.

$$2d(x_0, x_m) = \log\left[\frac{\hat{\sigma}_m^2}{\hat{\sigma}_0^2}\right] + \frac{1}{n\hat{\sigma}_m^2}\sum_{t=1}^{n}[e_{0,m}(t)]^2 - 1 \qquad (3)$$

Here, the mark $\hat{\sigma}_m^2, \hat{\sigma}_0^2$ are variance of time series respectively, and $\{e_{0,m}(t)\}, m = 1, \dots, M$ is the M residual time series generated from filtering time series x_0 for the test from fitting model to the standard time series x_m.

2-2 Nearest Neighbor Classification Rule

Let $x_m(m=1, \dots, M)$ be leveled time sequential data, θ_m level corresponding to that time sequential data, x_0 time series being classified newly, and θ_0 its level. At that time the Nearest Neighbor classification rule (under here it's NN rule) has the following expression [2].

$$d(x_0, x_m) \le d(x_0, x_m); m = 1, \Lambda, M \text{ then } \theta_0 = \theta_m \qquad (4)$$

Namely, NN rule gives level of the nearest neighbor time series to newly classified time series. The flow of defect infection of this paper is shown in Fig. 1.

3. Experiments

Test equipment is shown in Fig. 2. The tested ball bearings are supported at the extremes with ball bearing. The shaft is rotated with 49 rps (=2 940 rpm). The vibration sensor is attached on the bearing housing. The conditions of bearing used in test are all five cases like the following; 1) No defect (normal), 2) outer-race flaking defect; the width of defect is 0.5 mm, the length is 1.6 mm 3) small inner-race defect; the width of defect is 0.5 mm, the length is 1.2 mm, 4) medium inner-race defect; the width of defect is 1.0 mm, the length is 2.0 mm, 5) large inner-race defect; the width of defect is 3.1 mm: the length is 1.2 mm. Acceleration sensor is attached on bearing and the data is saved into transient converter through vibration system with low-pass filter (cut-off frequency 16 kHz). Sampling time is 20 μsec. It has 4096 pieces per 0.082 sec. The data of during four revolutions are obtained and 24 sets of each condition are sampled. One of the experimental data in each condition is set be the labeled time series. The outer-race

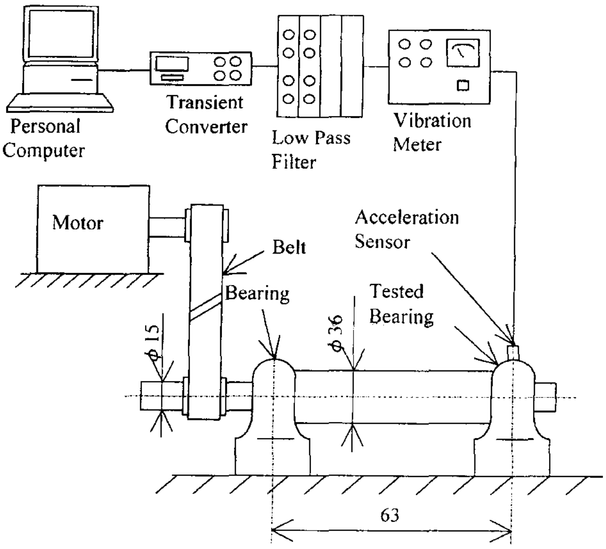

Fig. 2. Schematic diagram of experimental apparatus.

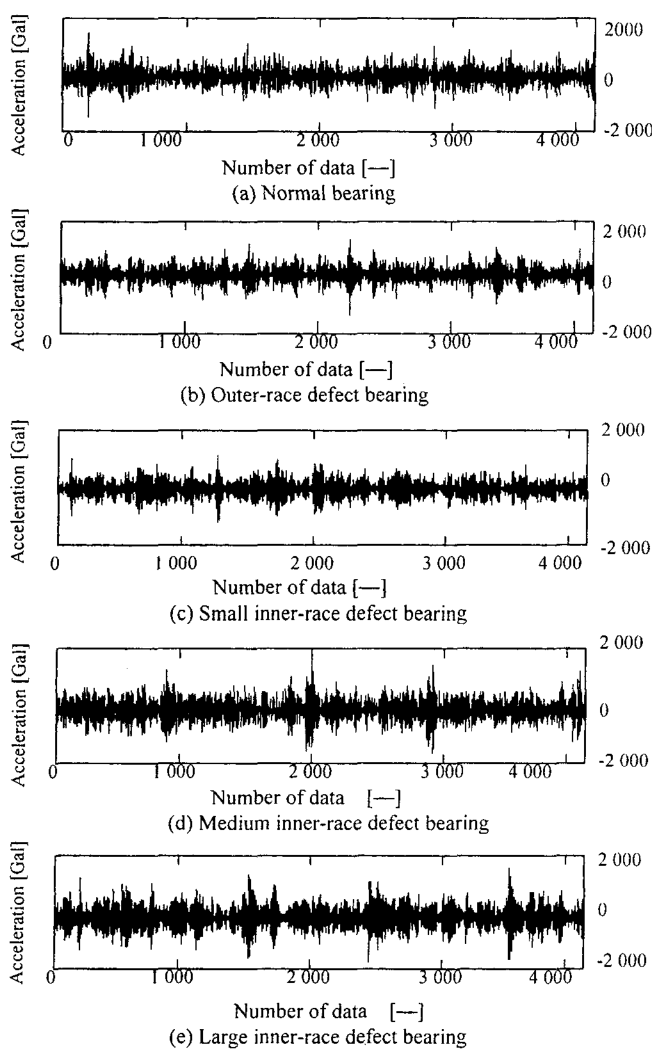

Fig. 3. Acquired signal from each bearing

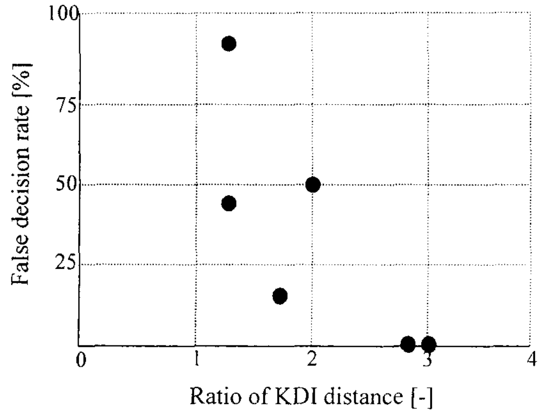

Fig. 4. Relation between ratio of KDI and false decision rate.

and inner-race flaking defect are different according to the size of defect and show similar pulse signal, but pulse interval has different character in time interval passing outer-race flaking, inner-races flaking place. The bearing flaking detected and discriminated in this study is small, it has been impossible to discriminate by using parameter such as Skewness, Kurtosis, etc. of vibration.

4. Experimental Results

The examples of signals gained in above five conditions are shown in Fig. 3, 4 and the result of classification is in Table 1. Normal, outer-race flaking, large inner-race flaking and small inner-race flaking are all classified correctly, but in case of medium inner-race flaking, one is miss classified as outer-race flaking and another one is as small inner-race flaking. The percentage of correct classification is 98%(=118/120).

5. Considerations

This method judges the distance between the labeled time series and the tested time series. Therefore, though the same kind of defect can have different conditions with a standard signal (different size of flakes with different shapes), it is necessary to discriminate between these conditions in practice. There, this research examined whether medium inner-race flaking and large inner-race flaking can be classified as inner-race flaking well or not, in case of letting small inner-race flaking as the standard time series. With the same method, the examination result in case of letting medium inner-race flaking and large inner-race flaking as the standard time

Table 1. Distance between labeled time series and tested time series
(a) Results of normal bearing by KDI, S: Small, M: Medium, L: Large defect size

		Labeled time series				
		Normal	Outer-race Defect	S inner-race defect	M inner-race defect	L inner-race defect
Tested time series	Normal 1	0.0013	0.2354	0.1574	0.0453	0.0992
	2	0.0053	0.2187	0.1459	0.0419	0.1049
	3	0.0052	0.2153	0.1457	0.0415	0.0978
	4	0.0046	0.1725	0.1200	0.0402	0.1256
	5	0.0029	0.2119	0.1491	0.0424	0.1113
	6	0.0046	0.1500	0.1220	0.0394	0.1341
	7	0.0082	0.2358	0.1529	0.0506	0.1156
	8	0	0.1942	0.1249	0.0385	0.1164
	9	0.0020	0.1669	0.1200	0.0357	0.1105
	10	0	0.1687	0.1158	0.0345	0.1292
	11	0.0106	0.2964	0.2106	0.0737	0.1337
	12	0.0070	0.1548	0.1193	0.0357	0.1261
	13	0.0019	0.1983	0.1254	0.0386	0.1072
	14	0.0040	0.1806	0.1300	0.0359	0.1151
	15	0.0072	0.1524	0.1138	0.0391	0.1330
	16	0.0015	0.1966	0.1420	0.0458	0.1237
	17	0.0002	0.1907	0.1417	0.0489	0.1326
	18	0.0018	0.2017	0.1450	0.0435	0.1201
	19	0.0077	0.1594	0.1175	0.0317	0.1161
	20	0.0023	0.1971	0.1516	0.0469	0.1376
	21	0.0056	0.1497	0.1211	0.0444	0.1386
	22	0.0032	0.1965	0.1404	0.0421	0.1205
	23	0.0017	0.1916	0.1418	0.0491	0.1392
	24	0.0030	0.2476	0.1621	0.0506	0.1090

(b) Results of outer-race defect bearing by KDI

		Labeled time series				
		Normal	Outer-race defect	S inner-race defect	M inner-race defect	L inner-race defect
Tested time series	Outer-race 1	0.1171	0.0098	0.0602	0.0689	0.1907
	2	0.0711	0.0138	0.0250	0.0156	0.1012
	3	0.1310	0.0106	0.0671	0.0802	0.2067
	4	0.1319	0.0059	0.0542	0.0706	0.1888
	5	0.1491	0.0075	0.0642	0.0795	0.2032
	6	0.1211	0.0240	0.0792	0.0932	0.2223
	7	0.1141	0.0071	0.0632	0.0704	0.1957
	8	0.0880	0.0040	0.0532	0.0580	0.1765
	9	0.1094	0.0226	0.0519	0.0354	0.1397
	10	0.1067	0.0126	0.0585	0.0571	0.1749
	11	0.0911	0.0119	0.0533	0.0609	0.1840
	12	0.0865	0.0042	0.0565	0.0644	0.2026
	13	0.1050	0.0092	0.0441	0.0455	0.1599
	14	0.1169	0	0.0482	0.0561	0.1724
	15	0.1141	0.0085	0.0620	0.0738	0.1996
	16	0.1114	0.0167	0.0579	0.0611	0.1737
	17	0.1204	0.0017	0.0518	0.0559	0.1701
	18	0.0911	0.0121	0.0581	0.0721	0.1958
	19	0.0911	0.0108	0.0514	0.0508	0.1692
	20	0.0911	0.0077	0.0553	0.0551	0.1801
	21	0.0874	0.0139	0.0336	0.0155	0.1008
	22	0.0971	0.0034	0.0487	0.0531	0.1683
	23	0.1142	0.0124	0.0624	0.0697	0.1940
	24	0.1345	0.0095	0.0669	0.0740	0.1956

Table 1. continued

(c) Results of S inner-race defect bearing by KDI

		Labeled time series				
		Normal	Outer-race defect	S inner-race defect	M inner-race defect	L inner-race defect
Tested time series	Inner-race(1) 1	0.1890	0.0804	0	0.0265	0.0516
	2	0.1587	0.0483	0.0373	0.0689	0.1550
	3	0.1670	0.0586	0.0120	0.0491	0.1090
	4	0.1558	0.0336	0.0204	0.0537	0.1400
	5	0.1430	0.0433	0.0102	0.0405	0.1165
	6	0.1651	0.0966	0.0054	0.0361	0.0717
	7	0.1605	0.0458	0.0214	0.0618	0.1341
	8	0.1828	0.0765	0.0226	0.0600	0.1186
	9	0.1562	0.0377	0.0006	0.0421	0.1103
	10	0.1709	0.0463	0.0130	0.0533	0.1218
	11	0.1376	0.0537	0.0157	0.0455	0.1236
	12	0.1551	0.0377	0.0188	0.0455	0.1188
	13	0.1577	0.0570	0.0086	0.0423	0.1016
	14	0.1833	0.0517	0.0290	0.0711	0.1345
	15	0.1603	0.0474	0.0273	0.0550	0.1321
	16	0.1754	0.0802	0.0124	0.0254	0.0612
	17	0.1713	0.0467	0.0437	0.0744	0.1593
	18	0.1239	0.0398	0.0234	0.0542	0.1470
	19	0.1635	0.0704	0.0180	0.0406	0.0874
	20	0.1671	0.0477	0.0315	0.0568	0.1258
	21	0.1219	0.0334	0.0055	0.0286	0.1044
	22	0.1962	0.0693	0.0229	0.0567	0.1090
	23	0.1670	0.0829	0.0162	0.0475	0.0859
	24	0.1676	0.0495	0.0321	0.0522	0.1172

(d) Results of M inner-race defect bearing by KDI

		Labeled time series				
		Normal	Outer-race defect	S inner-race defect	M inner-race defect	L inner-race defect
Tested time series	Inner- race(2) 1	0.1385	0.0220	0.0532	0.0759	0.1920
	2	0.1054	0.0450	0.0229	0.0117	0.0842
	3	0.1232	0.0370	0.0187	0.0166	0.0823
	4	0.0724	0.0785	0.0357	0.0046	0.0717
	5	0.1185	0.0181	0.0247	0.0291	0.1122
	6	0.1372	0.0546	0.0300	0.0217	0.0715
	7	0.1346	0.1071	0.0440	0.0117	0.0357
	8	0.1096	0.0720	0.0289	0.0106	0.0587
	9	0.1099	0.0532	0.0256	0.0105	0.0646
	10	0.0647	0.0304	0	0	0.0357
	11	0.0644	0.0715	0.0382	0.0032	0.0666
	12	0.0871	0.0859	0.0468	0.0069	0.0540
	13	0.1082	0.0490	0.0368	0.0157	0.0762
	14	0.0866	0.0659	0.0290	0.0059	0.0651
	15	0.0756	0.0991	0.0471	0.0035	0.0593
	16	0.0949	0.0692	0.0381	0.0050	0.0677
	17	0.0701	0.1058	0.0491	0	0.0386
	18	0.0484	0.0282	0.0021	0	0.0417
	19	0.1237	0.1242	0.0603	0.0119	0.0356
	20	0.1046	0.0791	0.0457	0.0123	0.0683
	21	0.1006	0.0859	0.0460	0.0067	0.0606
	22	0.0463	0.1043	0.0637	0.0033	0.0671
	23	0.1005	0.1190	0.0524	0.0050	0.0441
	24	0.0825	0.1546	0.0595	0.0117	0.0348

Table 1. continued
(e) Results of L inner-race defect bearing by KDI

		Labeled time series				
		Normal	Outer-race defect	S inner-race defect	M inner-race defect	L inner-race defect
Tested time series	Inner- race(3)1	0.3704	0.2837	0.0825	0.0986	0
	2	0.3860	0.3118	0.1053	0.1136	0.0202
	3	0.4611	0.3414	0.1238	0.1459	0.0249
	4	0.4687	0.3854	0.1492	0.1473	0.0123
	5	0.4295	0.3929	0.1395	0.1446	0.0230
	6	0.4796	0.4395	0.1736	0.1635	0.0044
	7	0.5346	0.4278	0.1745	0.1885	0.0207
	8	0.4713	0.4627	0.1639	0.1572	0
	9	0.4704	0.4360	0.1696	0.1677	0.0202
	10	0.4060	0.3183	0.0954	0.0995	0
	11	0.3034	0.2557	0.0702	0.0676	0
	12	0.3690	0.3245	0.1011	0.1162	0.0229
	13	0.4823	0.3908	0.1253	0.1333	0
	14	0.4171	0.2958	0.0345	0.1097	0
	15	0.4532	0.4158	0.1390	0.1488	0.0045
	16	0.4093	0.3754	0.1397	0.1342	0.0101
	17	0.4962	0.4921	0.1657	0.1719	0
	18	0.4190	0.3333	0.1171	0.1193	0
	19	0.4676	0.4495	0.1884	0.1597	0.0056
	20	0.4510	0.4121	0.1484	0.1494	0.0085
	21	0.4510	0.3796	0.1458	0.1480	0.0239
	22	0.5128	0.4293	0.1559	0.1613	0.0071
	23	0.5092	0.4097	0.1581	0.1612	0.0164
	24	0.3767	0.3310	0.1053	0.1039	0.0142

Table 2. False decision rate by sample time series

Sample time series	S inner-race defect only	M inner-race defect only	L inner-race defect only
False decision rate(%)	4.2	15.3	43.1

series is the same. It's shown in Table 2. Table 2 shows that the probability of miss classification rate is 43.1% in which the standard time series to inner-race flaking is only large inner-race flaking. If there's only small inner-race flaking, the probability of miss classification rate is 4.2%. The reason of the difference of miss classification probability according to the standard time series is thought to be the following. In order to simplify the theory, only standard time series was gathered and gained mutual distance. It's shown in Table 3. For example, if the standard time series is only in large inner-race flaking, in case small inner-race flaking, if it's classified as large inner-race flaking, the same kinds of flaking, it's classified right. The distance from small inner-race flaking to large inner-race flaking, *d*(small inner-race flaking, outer-race flaking) is 0.066. And the nearest distance with outer-race flaking except for the inner-race flaking, *d*(small inner-race flaking, outer-race

Table 3. KDI between sample time series

	Normal	Outer-race	S inner-race	M inner-race	L inner- race
Normal	0	0.208	0.150	0.052	0.130
Outer-race	0.128	0	0.044	0.051	0.151
S inner ñrace	0.176	0.082	0	0.041	0.066
M inner ñrace	0.072	0.080	0.042	0	0.061
L inner ñrace	0.351	0.333	0.117	0.110	0

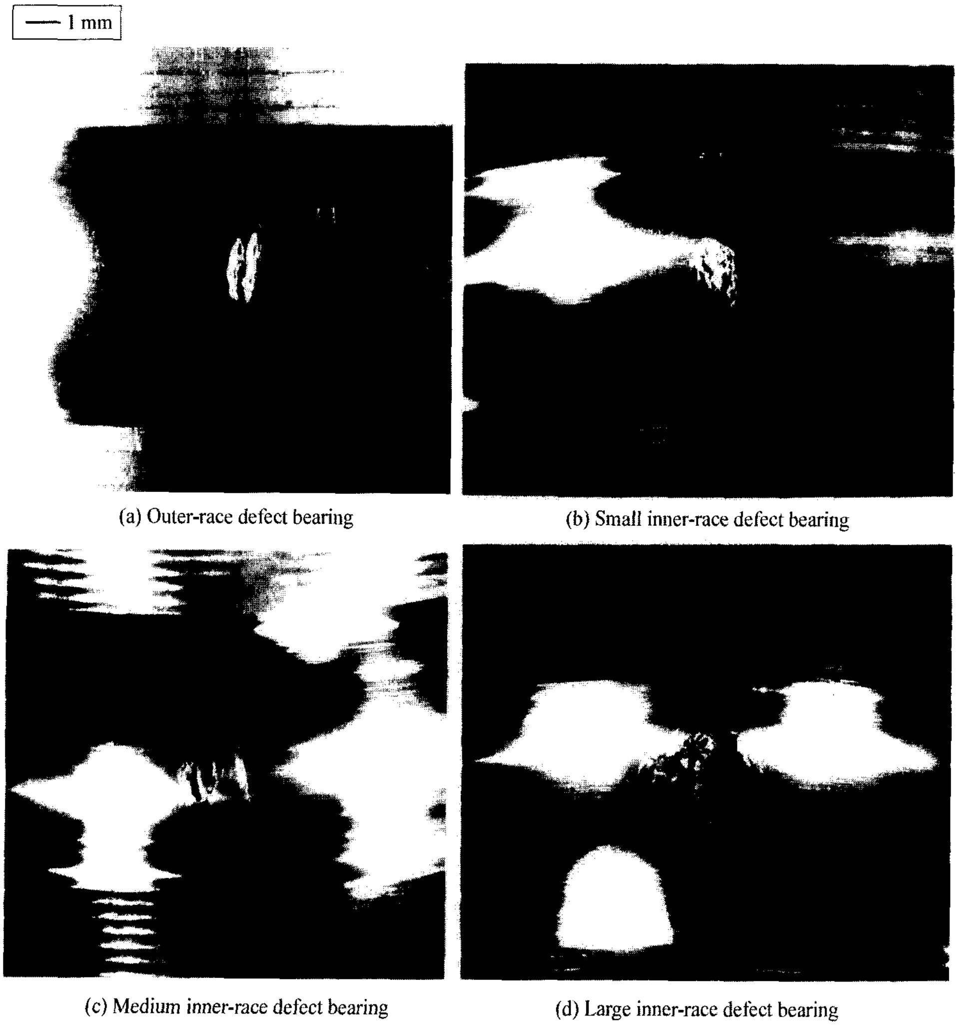

Fig. 5. Defect conditions of bearing (×30).

flaking) is 0.082. The distance rate r is 0.082/0.066, namely 1.25. At miss classifications are row 21 and row 24. In case of the standard time series is in small inner-race flaking, this rate is 1.72 (distance with normal/distance with small inner-race flaking, miss classification row 3/ row 24), and 2.85 (distance with outer-race flaking/distance with small inner-race flaking, miss classification is 0). Including the case making the standard time series as medium inner-race flaking, the rate with distance and probability of miss classification are shown in Fig. 4. It has the trend sliding toward from left to right smaller. Investigating this distance rate on the basis of r, it's right to choose the largest r as the standard time series. Fig. 5 expresses the distance between each test time series and normal standard time series. In order to detect the defect in this figure, one can detect the defect by seeking the distance distribution in normal situation in advance and establishing the standard value.

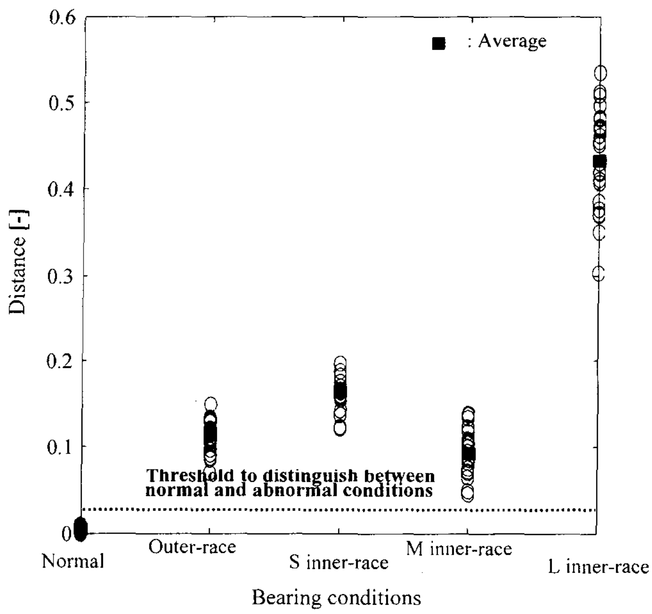

Fig. 6. Distance by normal sample time series.

6. Conclusions

This paper investigated how to apply KDI in classifying and detecting the flakes on bearing race surface. In this study, the method of detecting the object system condition from observation signal data information is tested. The concluding remarks are following;

1) It is possible to classify and detect inner-race and outer-race flaking as small as not being detected with Kurtosis etc. of vibration. The correct classification rate is 98%, including the judge of size of inner-race flaking.

2) The erroneous classification is reduced in the case of the flaking defect, which may have different shapes, if the largest distance ratio, defined as the labeled time series, is determined by detecting several time series.

Acknowledgement

This paper was translated from the Japanese article published in transactions of JSSE [4] and experimental results were inserted.

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