Diagnostic evaluation of rolling behavior in ball bearings by ultrasonic technique

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Abstract. Failures of machines having rotating parts are mostly caused by damage to bearings and there exist increasing demands for detecting damaged bearings at an early stage. However, conventional diagnostic methods, such as measuring temperature and observing vibration, have found difficulties in performing the early detection, so that more advanced diagnosis is necessary. This study therefore applies an ultrasonic technique as an advanced diagnostic method to bearing life tests. Ultrasonic wave pulses (UWP) emitted from a piezoelectric UWP generator can partially reflect from the interfaces of contact zones within the housing and the bearing with regard to the different acoustic impedance between a solid-to-solid contact and a contact dominated by some fluid layers. Hence, the intensity of the resultant UWP echoes can be determined by the real contact area formed at the interfaces. The experimental results of UWP echoes under the different operating conditions have demonstrated that the time intervals between peaks of UWP echoes varied in accordance with the movement of rolling balls and the lubricating phenomena in bearings. This behavior has further suggested the possibility of the early detection of abnormalities in ball bearings by using the variation in UWP echoes.

1. Introduction
Failures of machines having rotating parts are mostly caused by damage to bearings. For this reason, various techniques to monitor temperature, vibration, acoustic emission, lubricant deterioration, change in wear debris and so on have so far been used to detect bearing abnormalities [1]. Among those methods, at present, vibration monitoring and the analysis of its signals could be the most useful and reliable diagnostic tool. A great number of studies on vibration monitoring have therefore been carried out by many researchers and recent investigation has resulted in a simple and precise failure diagnosis method of bearings based on the hypothesis that, if a machine being monitored is in good condition, the probability density function of vibration signals obeys the normal distribution [2]. As an accepted diagnostic tool for the operational conditions of bearings, ferrography has also had much use over the years for sensing a change in ferrous debris particles in lubricating oils, because most parts of bearings are made of steels.

However, those conventional diagnostic methods often find difficulties in detecting damaged bearings at an early stage, so that there exist increasing demands for more advanced diagnostic techniques. For this purpose, current researches have proposed several possible methods, such as online counting of wear debris particles [3], hybrid observation of vibration combined with acoustic
emission [4] and lubricant color analysis [5], and efforts are further made to develop more reliable techniques in practical use. In particular, an ultrasonic technique can be a promising diagnostic tool and provides the possibility of early detection of bearing abnormalities [6]. This study therefore applies the ultrasonic technique as an advanced diagnostic method to bearing life tests. According to the experimental results of ultrasonic wave pulse (UWP) echoes under the different operating conditions, a new parameter of the time intervals between peaks of UWP echoes is introduced as a measure to evaluate the movement of rolling balls and the lubricating phenomena in bearings. An abrupt change in UWP echoes is also taken into account to understand the frictional behavior at the contact surfaces within bearings.

2. Experimental

2.1. Principle and experimental arrangement of ultrasonic technique [7]
In general, transverse ultrasonic waves can only propagate in a solid but not in a liquid or a gas because of the different acoustic impedance between them. At the interfaces of contact zones within a ball bearing and its housing, for instance, the wave pulses emitted from a piezoelectric UWP generator can pass through the areas of real metallic contact and reflect from the areas dominated by some lubricant liquid layers. The lower intensity of the resultant UWP reflection echoes can therefore be obtained under the higher local contact pressure that causes the more real contact area at the interfaces.

Based on the above nature, changes in UWP reflection intensity (URI) with time were experimentally measured under the different operating conditions and the experimental results were used to evaluate the rolling and lubricating behavior in ball bearings. This study used the ultrasonic sensors which could work as both piezoelectric UWP generator and URI receiver. Thus, the sensor was the high speed type UWP generator and, in the tests below, it emitted 5MHz transverse ultrasonic wave pulses with the pulse voltage of 100V. The sensor also received the URI signals at the sampling rate of 100μs with the gain of 77dB through the band-pass filter between 4MHz and 6MHz. Figure 1 illustrates schematically the installation of the sensors and the URI measuring system.

2.2. Experimental methods and conditions of bearing tests

2.2.1. Continuous fatigue test. Using No.6210 single row deep groove ball bearing for the shaft diameter of 50mm, bearing life tests were carried out with lubrication of a commercial VG46 turbine oil and under the constant operating conditions where the radial normal load, the rotational speed and the bearing temperature were 2500kgf, 1000rpm and 60°C, respectively. The change in URI with time was measured every 2 days.
2.2.2. **Measurement under various lubricating conditions.** Bearing life tests were carried out usually under the same constant operating conditions as those of the above continuous fatigue test. En route, at first, in order to prevent any influence caused by remaining bubbles in the lubricating oil, after 2 days from the start of the life test, the change in UWP echo intensity with time was measured under the various operating conditions as shown in Table 1. Please note that the bearing temperature was set to 50°C in all tests here. After such measurements of URI under the various conditions, the tests proceeded again under the constant conditions of 2500kgf, 1000rpm and 60°C. Also en route, then as repeated procedures, the change in URI with time was measured under the various operating conditions of Table 1 every 7 days, and the measurements were succeeded by the tests under the constant conditions.

![Table 1. Operating conditions in measuring URI.](image)

| Operation name | Normal load [kgf] | Rotational speed [rpm] | \( \Lambda \) value |
|---------------|------------------|-----------------------|------------------|
| 1.0-1000      | 1000             | 1000                  | 1.801            |
| 1.5-1000      | 1500             | 1000                  | 1.709            |
| 2.0-1000      | 2000             | 1000                  | 1.646            |
| 1.0-500       | 1000             | 500                   | 1.180            |
| 1.5-500       | 1500             | 500                   | 1.120            |
| 2.0-500       | 2000             | 500                   | 1.078            |

Bearing temperature is set to 50±2°C in all.

The values of oil film parameter \( \Lambda \), which is the ratio of minimum film thickness between the balls and the raceways to composite roughness of their surfaces, were calculated as a measure of the lubricating situations for the operating conditions. If the \( \Lambda \) value is more than 3, the lubrication regime is in favorable fluid lubrication, whereas if the value is less than 1, the regime is in boundary lubrication where some severe metal-to-metal contact occurs. According to the \( \Lambda \) values shown in Table 1, the operating conditions of this study are under the regime of relatively severe mixed lubrication.

3. **Results and discussion**

3.1. **Time interval \( T_i \) between minimum values of URI**

Figure 2 illustrates the typical example of the measured change in URI under the lubricating conditions of operation name [2.0-1000], where the normal load is 2000kgf and the rotational speed is 1000rpm, and after 7 days. Here, the time interval, \( T_i \), is defined as the duration between the two adjacent minimum peaks of URI. \( T_i \) corresponds with the duration between one passing and the next passing of individual balls through the highest loading area in the bearing.

Under the assumption that there exists no slip between the inner ring and balls and between the outer ring and balls in the case of single row deep groove ball bearings, the rotational speed of the cage, \( n_c \), can theoretically be calculated by the following equation:

\[
    n_c = 0.5(1-\frac{D_b}{D_{pb}}) \cdot n_i + 0.5(1+\frac{D_b}{D_{pb}}) \cdot n_o \quad [\text{min}^{-1}]
\]  

(1)

Here, \( D_b \) and \( D_{pb} \) are the diameter of the ball itself and the pitch diameter in the ball bearings, respectively: using the specifications of No.6210 ball bearing, \( D_b \) is 12.7mm and \( D_{pb} \) is 70mm. In addition, \( n_i \) and \( n_o \) are the rotational speeds of the inner ring and the outer ring, respectively, and \( n_o \) is zero because the outer ring is fixed on the housing in the bearing tests of this study. Further, the number
of balls in No.6210 ball bearing is ten. Then the theoretical value of $T_I$ is designated as $T_{I,t}$ and can be estimated by the following equation:

$$T_{I,t} = \frac{60}{n_i \times 10} \times \frac{60}{0.5(1 - \frac{12.7}{70}) \times n_i \times 10} = \frac{14.66}{n_i} \text{ [sec]}$$

(2)

Since the rotational speed $n_i$ is the same as that of shaft revolution, the value of $T_{I,t}$ can be calculated by substituting the rotational speeds shown in Table 1 into Eq. (2).

The experimental values of $T_I$ were measured for operating conditions and dates explained above. Each $T_I$ value was obtained as an average, which was the total duration of succeeding 30 $T_I$ values divided by 30. Figure 3 presents the changes in ratios of $T_I/T_{I,t}$ with time in the case of the measurement under various lubricating conditions. Here, two interesting tendencies can be observed in this figure as follows: (a) the ratios increase with the decrease in $\Lambda$ and (b) the ratios first decrease then increase with time.

![Figure 2. Result of URI measurement (after 7 days, Operation name: 2.0-1000).](image)

![Figure 3. Changes in $T_I/T_{I,t}$ in the case of the measurement under various lubricating conditions.](image)
Regarding the tendency (a), the larger $T_I/T_{11}$ suggests the slower movement of the bearing balls and the lower $\Lambda$ means the poorer lubrication, so that the poor lubrication results in the increased degree of slip in the moving behavior of the bearing balls. Regarding the tendency (b), particularly in the cases of 500 rpm, $T_I/T_{11}$ decreases, i.e. $T_I$ approaches its theoretical value, with time up to the first 14 days. This may be due to the phenomena where the progress of wear leads to the increased contact area, the resultant lowered pressure there and the apparently improved lubricating situations. On the other hand, after 14 days or more, $T_I/T_{11}$ increases, i.e. the rolling behavior of bearing balls becomes unfavorable, with time, probably because of further wear causing severer friction. The evaluation of $T_I/T_{11}$ values can therefore provide the rolling and lubricating behavior in ball bearings, leading to the possibility of early detection of bearing abnormalities.

3.2. Individual values of $T_I$ obtained by extraction method

As above, $T_I$, or $T_I/T_{11}$, increases when the rolling behavior of bearing balls becomes unfavorable. In the same way, the fluctuations of $T_I$ values are expected to become greater in accordance with the lower periodicity of URI varying with time because of the development of the bearing damage and resultant unfavorable rolling behavior. Such fluctuations of $T_I$ values can quantitatively be evaluated by means of the variance of $T_I$ values and it is necessary for the estimation of the variance to obtain individual values of $T_I$ rather than the average of 30 $T_I$ values in the above.

Based on such measured data of URI as those shown in Figure 2, the individual values of $T_I$ can ideally be obtained by identifying each minimum peak of URI as a time point where the difference between succeeding adjacent URI values changes from negative to positive. However, one finds difficulty in extracting the correct time point because there exist obstructive time points where the difference between succeeding adjacent URI values changes from negative to positive but which do not correspond with the minimum peak of URI. In order to eliminate those incorrect points, the extracting procedure to find the correct time point was repeated several times. Figure 4 indicates the representative results obtained by this extraction method in the case of Figure 1 and suggests that each time point corresponds well with each minimum peak of URI.

![Figure 4](image)

**Figure 4.** Individual time points obtained by extraction method (after 7 days, Operation name: 2.0-1000).

Further, Figure 5 shows the results of the Comparison between the values of $T_I$ obtained by the conventional averaging method and the extraction method. Here, $T_I$ of the conventional method is the average calculated as the total duration of succeeding 30 $T_I$ values divided by 30 and $T_I$ of the extraction method is the average calculated as the summation of 30 individual $T_I$ values divided by 30. This figure demonstrates that the values of $T_I$ obtained by the conventional and extraction methods are
very close with each other and provides evidence that the extraction method is a reasonable manner to obtain the individual values of $T_I$.

![Graph showing comparison between conventional and extraction methods](image)

**Figure 5.** Comparison between the values of $T_I$ obtained by conventional and extraction methods (after 2 days under various conditions).

3.3. **Comparison between variance of $T_I$ and half width of first peak obtained by Fourier analysis**

URI varies periodically with time as shown in Figure 2, and the frequency analysis by Fourier transform is also a powerful tool to understand such periodical data. Since the first frequency peaks obtained by Fourier analysis results of the URI data are normally corresponding to $T_I$, if the variance of $T_I$ rises because of greater bearing damage, the half width of the first peak obtained by Fourier analysis is also expected to increase.

Figures 6 and 7 present the changes in the variance of $T_I$ obtained by the extraction method and the half width of the first frequency peak obtained by Fourier analysis with elapsed days, respectively for the continuous fatigue test and the operation name of 2.0-1000. The variance values indicate the increasing tendency with elapsed time, that is, with development of the bearing damage, whereas the half width values provide the opposed trend. This means that there exists no good correlation between the variance and the half width, so that the ultrasonic technique of this study can be useful as a diagnostic evaluation of rolling behavior in ball bearings by utilizing the variance of $T_I$ rather than Fourier analysis of URI measurement data.

4. **CONCLUSIONS**

The experimental results of the bearing life tests under the different operating conditions have demonstrated that the time interval $T_I$, which is defined as the duration between the two adjacent minimum peaks of the ultrasonic wave pulse echo intensity, varied in accordance with the movement of rolling balls and the lubricating phenomena in bearings. The diagnostic methods using $T_I$ values can therefore provide a convenient measure to evaluate the rolling and lubricating behavior in ball bearings, leading to the possibility of early detection of bearing abnormalities.
Figure 6. Changes in variance of $T_1$ obtained by extraction method and half width of maximum peak frequency obtained by Fourier analysis with elapsed days (Continuous fatigue test).

Figure 7. Changes in variance of $T_1$ obtained by extraction method and half width of maximum peak frequency obtained by Fourier analysis with elapsed days (Operation name: 2.0-1000).

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