Damage Monitoring of Ball Bearing

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Abstract
A simple method and low cost equipment have been developed for monitoring the damage that occurs on rolling surfaces of the ball bearing in machine tool spindle. The monitoring identifies the initiation and the progress of geometrical damage of bearing surfaces and issues a warning prior to the end of bearing life.

Keywords
Spindle, Bearing, Damage Monitoring

1 INTRODUCTION

High speed and high power requirement [1] in machine tool spindles, has been recently possible to accommodate by application of new technologies including the oil-air lubrication of the bearing, improved lubricant delivery to raceway surface and use of ceramic balls [2][3], in line with better understanding of bearing kinematics subject to high rotational speeds [4][5].

The objective of this study is to prevent sudden and fatal arrest of the rotation of such high performance spindles by developing a simple and low cost damage monitoring of the bearing. It should be able to detect the initiation of the damage in the form of a minute cavity, monitor the progress, and issue warning to the user of the machine tool well before the failure occurs.

Bearing technology research has long since focused on the initiation and growth of rolling contact fatigue crack beneath the bearing surfaces [6]. For monitoring the fatigue damage, use of acoustic emission (AE) [7][8], rms(root mean square) value, spectrum analysis, envelope analysis and wavelet transformation [9] of vibration signals have been reported. Practical methods are in use for analyzing the lubrication condition [10] and predicting the remaining life of the bearing in operation.

In the high performance bearing application in machine tool spindles, however, rather than the rolling contact fatigue crack, the loss of fully elasto-hydrodynamic (EHD) lubrication film is the common and essential cause of the bearing damage [2] due to situations such as overloading, loss or deterioration of lubricant, corrosion by foreign reagent such as the coolant penetrated, contamination by dust and chip and sometimes compounded with accidental collision of the spindle end by the mishandling of the machine.

Therefore, the present study is focusing on detecting the initiation and propagation of the geometrical damage of the bearing surfaces.

The damage monitoring reported herewith is based on the analysis of vibration signal emitted by the rolling motion of bearing elements: namely, outer and inner rings and balls.

2 PRINCIPLE OF BEARING DAMAGE MONITORING

2.1 Vibration Signal due to a minute cavity
Suppose an initial damage in the form of a minute cavity has been generated, for example on the inner raceway surface, and a ball rolls over the cavity. The ball first sinks into the cavity, then lifts back on to the rolling surface, generating the acceleration signal analogous to a pulsed sign wave as illustrated in Figure 1. The shape of a single pulse is supposedly close to the sinusoidal wave with a time duration L. Successive passage of the ball train generates acceleration signal consisting of a train of pulsed wave as illustrated in the figure. The pulse repeats with a time period P, due to the passage of the ball train.

2.2 Fourier Transform
Assuming the sinusoidal form with an amplitude R for the pulsed wave, the Fourier transform is mathematically calculated and found to distribute over a wide range of the frequency σ as illustrated in Figure 2. It consists of spectra spaced at the passage frequency (1/P) of balls, whose magnitudes are enveloped in proportion to the

Figure 1 Acceleration signal generated by the passage of ball train over a minute cavity.

following expression:

$$\frac{R}{\sqrt{2\pi L}} \frac{1}{P} \sigma^2 \left[ 1 - \cos(2\pi \sigma) \right]$$  \hspace{1cm} (1)

### 2.3 Power

Power is the sum of the square of the magnitude of Fourier spectrum. In the case of the pulsed sine wave train with the amplitude $R$, duration $L$ and the period of repeat $P$ as noted in Figure 1, the power is found equal to $\left( \frac{R^2 L}{2P} \right)$ when the summation covers up to high enough frequency. As it is proportional to the square of $R$, by monitoring the power of the acceleration signal across a wide range of frequency $\sigma$, it should be possible to detect the size of the minute cavity. Also, since the power is subject to the additive law by definition, it should be possible to detect the increase in number of cavities by monitoring the power.

### 2.4 Time Domain Processing of Power

There are two alternative methods for computing the power of a time signal $f(t)$ according to the Parseval’s (or Schuster’s) equation as noted below:

$$\int_{-\infty}^{\infty} A^2(\sigma)d\sigma = \int_{-\infty}^{\infty} f^2(t)dt$$  \hspace{1cm} (2)

The left hand side of the equation follows the definition of the power given in the above. The computation first needs Fourier transform of the time signal $f(t)$, calculates the squares $A^2(\sigma)$ (commonly known as power spectrum) of the magnitude of the Fourier spectrum and then sums them up. The alternative method, according to the right hand side of the equation, directly squares the time signal $f(t)$ and integrates the result in time domain. This method does not require Fast Fourier Transform analyzer, and can be performed by a much simpler analog electronic circuitry.

### 3 TEST EQUIPMENT

#### 3.1 Bearing Test Bench

In order to test the principle discussed in the previous section, a test bearing is set in a test bench as illustrated in Figure 3. The hydraulic cylinder applies axial load to the test bearing of a variable magnitude regulated by the oil pressure and monitored by a strain gage type load cell. One unit of piezoelectric type accelerometer pickup is attached to an end surface of the spindle housing to sense the acceleration signal. It is attached in the axial direction of the rotating spindle to avoid the influence of the lateral bending vibration of the spindle structure.

#### 3.2 Test Bearing

An angular contact ball bearing with the following specifications has been used:

- Inner diameter of inner ring: 55mm
- Outer diameter of outer ring: 90mm
- Pitch diameter of ball set: 72.5mm
- Ball diameter: 7.1438mm
- Material of balls: ceramics
- Number of balls: 24 pieces
- Contact angle: 20 degree
- Rated load by manufacturer: Cr 13.7 kN, Cor 9.70kN
- Lubrication: grease
- Cooling: no cooling

### 4 SIGNAL PROCESSING SCHEME DEVELOPED

#### 4.1 Damage Signal Conditioner

As illustrated in the upper half of Figure 4, the time signal coming from the accelerometer pickup is converted into the power according to the time domain processing formulated by the right hand side of equation (2). The time signal, after appropriate amplification including high-pass (510Hz) and low-pass (2.2kHz) filtering, first squared by a multiplier, and second integrated, thus giving magnitude of the power as an analog DC voltage signal.

#### 4.2 Failure Prediction Processor

The power signal is then digitally monitored by the Failure Prediction Processor shown in the lower half of the figure. The minimum value of the power signal is first captured during every consecutive time window whose length is set at two seconds. The minimum value thus obtained is the “reading” for every time window and it is removed of unwanted noise that reflects incidental impacts taking
place on the machine such as the impact from tool changing motion. Then following four records are saved in data storage for every day after the bearing is newly commissioned:

1. Date
2. Maximum reading encountered in the day
3. Number of times in the day, when the reading has exceeded a criteria value
4. Number of operating hours of the day

The processor will send out failure prediction alarm when item 3 in the above exceed a reference number (1,000 for example). The saved records are possible to be read out to an externally connected personal computer. The personal computer can visualize the chronological history of the recorded data showing the progress of bearing damage since the beginning of the use of the bearing.

5 EXPERIMENTAL RESULTS

5.1 Initial Damage

An inner raceway surface containing numerous minute cavities is exhibited in Figure 5 as an example bearing on which early stage damage has initiated. When the bearing is rotated at 2,500RPM and 980N axial load, the Fourier transform of the acceleration signal is seen in Figure 6 exhibiting a wide spread distribution of the spectrum conforming to that previously calculated in Figure 2. The power observed in this situation has been 7.90 g². The value is greater than that observed with the same bearing rotated at the same condition before the early stage damage occurred.

5.2 Progress of Damage by Seizure

Seizure is a sudden stop of the rotation caused by the overloading associated with the instability of the temperature distribution among the inner and outer rings.

To observe the seizure condition, a test bearing with no damage is set in the test bench and rotated at 10,000rpm speed. By regulating the oil pressure of the hydraulic cylinder, as the magnitude of axial load is varied from small value to over 10,000N, the power is found staying at a small value as seen in the lower part A of Figure 7. Standard amount of axial pre-loading 441N is practiced when the same bearing is assembled into a spindle system of a machining center rated up to 10,000rpm speed and with fixed position pre-loading. In the case of the fixed position system, the pre-loading starts to increase as soon as the spindle is rotated because the temperature of the inner ring and the spindle itself rises faster than that of the outer ring. Under the regulated axial load on the test bench, when subject to 5,000N axial load or higher, there is a possibility for the seizure to occur in this particular test setup. When 10,700 N axial load was kept, the seizure occurred in nine minutes and the spindle stopped. After cooling off, the spindle could be restarted, but as seen in the upper part B of the figure, the power value was much greater than before, indicating that irreversible damage had occurred.

5.3 Power measured for various levels of damage

Plotted in Figure 8, are the power values measured at variable rotation speeds of following test bearings:

- Shown in green: A test bearing with 1,470N axial load exhibiting the power 3.3 g² and lower.
- Shown in blue: A machining center spindle in service exhibiting the power 70 g² and lower.
- Shown in orange: A machining center spindle with a test bearing having substantial damage but still good for service exhibiting the power 130 g² and lower. Inner raceway surface of the bearing consists of a texture formed through a long period of use as shown in Figure 9.
- Shown in red: A machining center spindle with a test bearing having excessive damage needing replacement exhibiting the power 430 g² and lower. Inner raceway surface of the bearing consists of a rough texture as seen in Figure 10.
As shown in Figure 8, criteria for identifying the initial damage (blue curve) and the necessity for replacement (red curve) have been defined for the test bearing used in the study.

6 SUMMARY

By processing acceleration signal emitted from ball bearing, a simple method and low cost equipment have been developed for monitoring the initiation and progress of the rolling surface damage and predicting the necessity of bearing replacement.

One practical way of using the equipment will be for daily maintenance of many machine tools. In this application, although the overloading test cited in foregoing section is not realistic, in-service tryout is indicating that the equipment allows direct reading of the power indicative of the amount of the damage of each spindle.

Another way will be to dedicate a set of monitoring equipment specific to a unit of machine tool for fully automated predictive monitoring of the main spindle bearing. It has been confirmed that the vibration caused by interrupted cutting increases power reading but not as much as the damage monitoring process is influenced.

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7. REFERENCES


