**Development of Sensor Integrated Bearing Unit for Machine Tool Spindles**

Shohei HASHIZUME*  
Yasuyuki FUKUSHIMA**  
Yusuke SHIBUYA**  
Yohei YAMAMOTO***

Recently, machine tools are required not only high speed, high rigidity and super precision, but also condition monitoring function and the “Connected Industries” related technology strongly for higher reliability. To realize the above mentioned machine tools, NTN has developed the “Sensor Integrated Bearing Unit for Machine Tool Spindles” to detect the various conditions like temperature, heat flux and vibration from the bearings. The unit has the various sensors inside the outer spacer beside the bearings. This report introduces the features, mechanism and performance of the unit.

1. Introduction

Machine tools support manufacturing in different industries including automotive, aircraft, medicine and IT, and their requirements are increasingly diversified. In recent years, various machine tools with new functionality and concepts such as multifunction numerical control and built-in condition monitoring capability have been developed 1), 2).

Recent machine tools, in particular, are required to contribute to unmanned or labor saving operation and improved productivity by using advanced condition monitoring and control technologies as well as IoT, in view of labor shortages due to a decreasing birthrate and aging population. Therefore, early detection of anomalies in main spindles and their supporting bearings in machine tools is highly desirable in order to prevent unexpected damage and the resulting production downtime required for main spindle replacement.

We have newly developed this “sensor integrated bearing unit for machine tool spindles” as a functional product to solve the above mentioned challenges. This unit, applicable to lathes and machining centers shown in Fig. 1, integrates various sensors into the outer ring spacer to enable condition monitoring of nearby bearing raceway surfaces. The following sections introduce the features, configuration and evaluation results of this bearing unit.

2. Damage modes of bearing units for machine tool spindles and features of the developed product

Bearing units for machine tool spindles are used with lighter loads compared with other bearings for industrial machines. Therefore, they rarely experience flaking 3) due to material fatigue, but the main damage
modes are "(a) surface roughness, peeling, and burnout due to poor lubrication" and "(b) indentation due to spindle collision with the workpiece" (Fig. 2).

The developed bearing unit incorporates various sensors in the outer ring spacer adjacent to the bearings. This enables early detection of anomalies compared to conventional measurement on the outer surface of the main spindle. In addition, a heat flow sensor is newly incorporated to improve responsiveness. Damage mode "(a) surface roughness, peeling and burnout" can be detected by temperature sensors, heat flow sensors and vibration sensors, and damage mode "(b) indentation" can be detected by vibration sensors (Table 1).

Table 1 Major damage mode of machine tool spindle bearings and measurement items

<table>
<thead>
<tr>
<th>Detection</th>
<th>Temperature</th>
<th>Heat flow</th>
<th>Vibration</th>
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<td>(a) Detection of surface roughness, peeling and burnout due to poor lubrication</td>
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<tr>
<td>(b) Detection of indentation due to collision of the main spindle and workpiece</td>
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Fig. 3 shows the structure of this bearing unit. Three types of sensors are integrated in the outer ring spacer that is inserted between two back-to-back (DB) angular contact ball bearings. The following sections describe those sensors.

[Temperature sensor]
This sensor detects heat produced within the bearings due to rotation and the spindle’s cutting load. Sensors for measuring bearing temperature during operation are usually installed on the housing’s outer surface due to ease of installation; however, since a cooling path exists between the bearings and the housing’s outer surface, the measured temperature becomes lower than the bearing temperature. In addition, measuring temperature at the housing means that it takes time to detect a rise in temperature when the bearing is suddenly heated, due to the large heat capacity of housing. Therefore, it is difficult to quickly determine a sudden heat-up of the bearings. This bearing unit can measure the temperature of the bearings more accurately compared with measurement on the outer surface of the housing, as it measures the temperature at the outer ring spacer adjacent to the bearings.

[Heat flow sensor]
As the spindle rotates, there will be a difference in temperature between the inner and outer rings (hereafter, inner/outer ring temperature difference) of the bearing unit for spindles. The main reason for this is the difference of heat dissipation between the inner and outer rings. The inner ring with less dissipation shows higher temperature than the outer ring. The inner/outer ring temperature difference becomes larger as the bearing rotates at higher speeds, increasing preload within the bearings and contact surface pressure on the rolling surfaces. In addition,
the inner/outer ring temperature difference also increases when operating with damage and burnout caused by poor lubrication within the bearings. The heat flow sensor adopted in this development catches minor changes better than an ordinary temperature sensor and measures the heat flux going from the inner ring with higher temperature to the outer ring, and is used for anomaly detection due to the inner/outer ring temperature difference.

[Vibration sensor]

Used for anomaly detection of both damage mode "Table 1 (a) surface roughness, peeling and burnout damage" and damage mode "Table 1 (b) indentation." In general, for measuring vibration of bearings in operation, a vibrometer is installed on the outer surface of the housing, for ease of installation, similar to the aforementioned temperature sensor. However, since vibration of the bearing in operation is measured through the housing, the measured vibration levels are reduced from those at the bearing. Therefore, detection is not possible until an anomaly progresses to a sufficiently high level of vibration. The developed bearing unit, on the other hand, integrates the vibration sensor into the outer ring spacer adjacent to bearings, which makes it possible for the sensor to detect small vibrations at the initial stage of anomaly with good sensitivity.

4. Performance evaluation test

4.1 Test conditions, tester configuration

Fig. 4 shows configuration of the tester, modeled after a machine tool main spindle. Condition detection performance was evaluated by integrating the developed bearing unit. Test conditions are shown in Table 2. The test unit, comprised of an ultra-high speed angular contact ball bearing with ceramic balls (HSE Type), was operated under the test conditions. Bearings were arranged in a double-row back-to-back configuration (DB) as is common for machine tool spindles. In addition to the integrated sensors within the developed bearing unit, sensors were also installed at the conventional measurement positions on the outer surface of the housing for comparison purposes. For correlation purposes, the temperature of the bearing outer ring outer diameter surface was also measured (Fig. 4).

![Sensor integrated bearing unit]

<table>
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<tr>
<td>(1) Temperature sensor</td>
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<tr>
<td>(2) Heat flow sensor</td>
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<tr>
<td>(3) Vibration sensor</td>
</tr>
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</table>

[General measurement method]

| (4) Temperature on the outer surface of housing (thermocouple) |
| (5) Vibration on the outer surface of housing                  |
| (6) Temperature on the bearing outer ring outer diameter surface (thermocouple) |
| (7) Temperature on the bearing inner ring inner diameter surface (thermocouple) |

Fig. 4 Test spindles, measurement items and points

4.2 Test results

Outputs of the various sensors in the bearing unit are shown in Fig. 5 for the performance test described in Table 2 and Fig. 4. It was verified that all the sensors performed well from the low speed range to the ultra-high speed range (dmn value: 1.44 million).

Measurements from the developed bearing unit and the conventional measurement method described in Section 4.1 were also compared. Fig. 6 and Fig. 7 show the temperature and vibration measurement results. It was verified that readings from the temperature sensor integrated into the developed bearing unit outer ring spacer were closer to the temperature at the bearing outer ring outer diameter surface than the readings from the outer surface of the main spindle housing. It was also verified that the unit provided higher readings for vibration than measurements from the outer surface of the housing.

In addition, comparisons were also made for an acceleration/deceleration test where the rotational speed was changed at certain cycles. Fig. 8 and
Fig. 9 show the temperature and vibration measurement results. It was verified, in the acceleration/deceleration test also, that readings from the temperature sensor integrated into developed bearing unit outer ring spacer were closer to temperature readings at the bearing outer ring outer diameter surface than the readings from the outer surface of the main spindle housing. The vibration sensor also gave higher readings than the measurements taken on the outer surface of the housing.

Fig. 10 shows the heat flow sensor outputs during the acceleration/deceleration test. The heat flow sensor has good responsiveness versus acceleration/deceleration of the rotational speed and the resulting change of inner/outer ring temperature difference, and improves the accuracy of anomaly detection as well. The inner/outer ring temperature difference is defined as the difference in temperature between the bearing inner ring bore surface and the outer ring outer diameter surface.

※1 Refer to Fig.4 for measurement positions for each item.
4.3 Bearing burn-out simulation test

Bearing burn-out was simulated in order to test symptom detection for this damage mode. Table 3 shows the test conditions. The tester shown in Fig. 4 was used, in a manner similar to the basic performance evaluation test and the acceleration/deceleration test. In this test, only a very small amount of lubricating oil was injected into the bearing when the main spindle was assembled in order to cause the test bearing to burn out easily. In addition, a limiter was set to automatically stop the tester when the motor becomes overloaded due to burn-out of the test bearing.

Fig. 11 shows the relationship between heat flux and temperature, as well as inner/outer ring temperature difference and vibration. The point in time when motor overload was detected is shown by the blue dotted line in Fig. 11. The test results revealed that the heat flux shows an increase of output earlier than temperature, inner/outer ring temperature difference and vibration; therefore, it is considered that this measurement is more effective for early detection of burn-out symptoms.

In Fig. 11, the reason why the vibration value increased even after the tester automatically stopped after detection of overload is because the motor and the main spindle continued rotating by inertia under the burn-out condition.

4.4 Bearing indentation test

In order to test anomaly detection of indentations on the raceway surface produced by spindle collision to the workpiece using a vibration sensor, a simulated indentation was made on the bearing raceway surface, and a test was conducted. Table 4 shows the test conditions. The tester in Fig. 4 was used in a manner similar to the basic performance evaluation test and the acceleration/deceleration test. Fig. 12 shows the simulated indentation made on the bearing raceway surface.

Calculated values of bearing forced vibration frequencies during operation at 1,800 min\(^{-1}\) are shown
5. Summary

Due to diversified market needs and changes in social structure, machine tools are required to evolve with further enhancement of condition monitoring functionality and support of IoT. In order to respond to these needs, we have newly developed this "sensor integrated bearing unit for machine tool spindles."

With this development, we have achieved highly sensitive condition detection compared with the conventional measurement on the main spindle outer surface. In addition, the responsiveness of condition monitoring was improved by adopting heat flow sensors.

We will continue to refine this development for further improvement of performance and commercialization. In addition, we will work on the detection of other conditions such as load, as well as enhancement of condition monitoring functionality.

References

3)  NTN Catalog: Rolling Bearings, Catalog, A-17.