Development of Sensor Integrated Bearing Unit for Machine Tool Spindles

Shohei HASHIZUME*　Yusuke SHIBUYA**
Daichi KONDO**　Yohei YAMAMOTO***
Hiroyuki IWANAGA****

Machine tools require not only fundamental features like high speed, high rigidity and super precision capabilities, but also condition monitoring and "Connected Industries" related technology. **NTN** developed the "Sensor Integrated Bearing Unit for Machine Tool Spindles" in 2018 and secured many positive responses from the manufacturing industry. **NTN** has recently added load detection function and wireless system to the unit, based on the additional requirements. This report introduces the features, structure, and performance of the unit.

1. Introduction

Machine tools support monozukuri in various types of industry, including automotive, aircraft, medical equipment and IT, and the market demand for them is becoming increasingly sophisticated and diversified[1)2)]. Particularly in recent years, the diminishing working population has created a need to improve production efficiency. There is an increased need to detect abnormalities at an early stage to prevent damage to the spindle and spindle bearing, which are key components within machine tools, and to prevent such factors as downtime and spindle replacement associated with this damage. Generally, a sensor is installed on the outer diameter surface of the spindle to detect any abnormalities as a method to measure the temperature and vibration. However, there is a problem with this method in that the sensor is easy to install but the measuring position is far from the bearing raceway surface, which makes it difficult to detect any abnormalities at an early stage such as sudden temperature rises in the bearing.

To solve this problem **NTN** has integrated sensors in the spacer, a bearing unit component, to perform sensing around the bearing raceway surface. This has allowed us to develop a "Sensor Integrated Bearing Unit" for Machine Tool Spindles[3)] that enables advanced condition monitoring. This product was displayed as a reference exhibit at the 29th Japan International Machine Tool Fair (JIMTOF2018) held in 2018. As a result, we received a great deal of praise from the market for this product and also received many requests to add a load inspection function and wireless technology, and so proceeded with developing these items. The developed product (hereafter, this bearing unit) can be applied to lathes and machining centers as shown in **Fig. 1**, and this bearing unit's features, structure, and performance test results are introduced below.

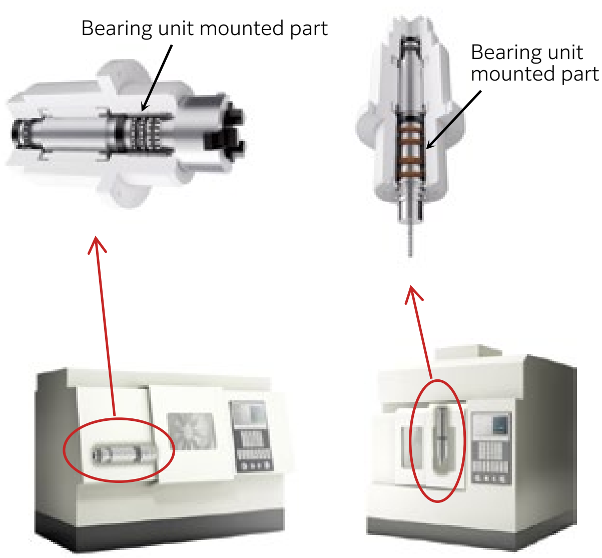

Fig. 1 Machine tools and spindles
(Left : Lathe, Right : Machining center)

*　Application Engineering Dept., Industrial Business Headquarters
**　New Product Development R&D Center
***　Product Design Dept., Industrial Business Headquarters
****　Robotics Sensing Engineering Dept., Industrial Business Headquarters

2. Structure and Function of the Sensor Integrated Bearing Unit

This bearing unit monitors the condition and detects abnormalities at the spindle on machines tools, and the spindle bearing. To achieve this, the bearing unit has 3 types of sensors for load, temperature and vibration built into the outer ring spacer, which is arranged between two rows of back-to-back angular contact ball bearings. Furthermore, the unit has a built-in generator as an independent power source and a wireless module to provide wireless technology. **Fig. 2** shows this bearing unit's structure, **Fig. 3** shows an example of application on a machine tool spindle, and **Table 1** shows the function and purpose.

In addition, when this bearing unit was announced in 2018, it was integrated with 3 types of sensors for temperature, heat flow and vibration. Among these sensors, the heat flow sensor has been replaced with a load sensor.

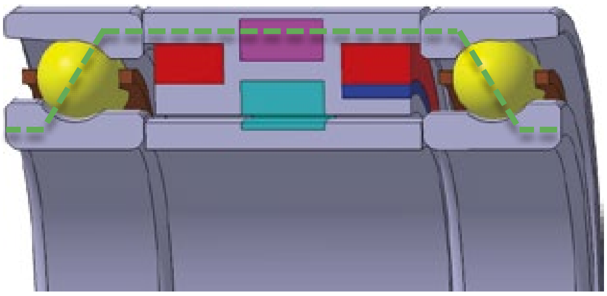

Fig. 2 The sensor integrated bearing unit

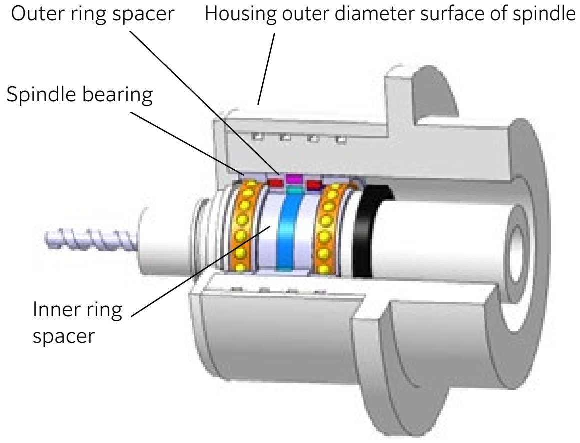

Fig. 3 Application example of the sensor integrated bearing unit to the machine tool spindle

2.1 Sensors

2.1.1 Load Sensor

The load sensor detects loads applied on the bearing, such as bearing pre-load and external loads applied to the spindle.

This bearing unit has a newly developed, compact and high-sensitivity load sensor built into the load path that can detect sudden increases in pre-load that occurs prior to bearing seizure. This contributes to the prevention of such seizure. Furthermore, detecting pre-load for bearings after spindle installation makes it easier to manage the pre-load for such bearings and is expected to reduce the number of man-hours required for assembly in comparison with the conventional method of calculations based on spindle rigidity and the method of calculations based on the spindle's natural vibration frequency. It is also possible to detect the external load applied to the spindle and this can be used to monitor the machining conditions in terms of changes in the cutting load to contribute towards improving the machining quality and productivity. Additionally, there is the potential to also use this to detect collisions between the tool and the workpiece.

2.1.2 Temperature Sensor

The temperature sensor detects heat generated from the bearing as a result of spindle rotation and the cutting load. Generally, when measuring the bearing temperature during operation, the temperature is measured at the housing outer diameter surface of the spindle where the sensor is easy to install, and then the bearing temperature is estimated based on this value. However, fluid cooling channels are provided for the bearing and motor between the bearing and housing outer diameter surface, which means the temperature is lower than when the bearing temperature is measured directly. Furthermore, the housing's heat capacity is large and the sensor requires some time to detect temperature changes. Due to this fact, it was difficult to accurately know the temperature of the bearing.

This bearing unit measures the temperature of the outer ring spacer in close proximity to the bearing. When compared to measuring at the housing outer diameter surface, it provides a more accurate measurement of the bearing temperature and can increase the reliability of condition monitoring.

2.1.3 Vibration Sensor

A vibration sensor is used to detect roughness, peeling, and seizure on the bearing raceway surface due to insufficient lubrication that commonly occurs in machine tool spindle bearings, and to detect abnormal indentations due to collisions between the spindle and the workpiece. Generally, when measuring bearing vibration during operation, the vibration is often measured at the housing outer diameter surface of the spindle because this makes it easier to install the sensor; the same as for the temperature sensor. However, any vibration originating from the bearing is dampened when measured through the housing.

This bearing unit has a vibration sensor built into the outer ring spacer in close proximity to the bearing. Since the vibration is measured at a position close to the bearing raceway surface it is possible to measure the initial stage of an abnormality and even the smallest level of vibration with good sensitivity. Furthermore, there is the potential to also use this to detect collisions between the tool and the workpiece; the same as for the load sensor.

Table 1 Functions & purpose examples of the sensor integrated bearing unit

Function		Purpose
① Load sensor	Detects pre-load for spindle bearing (While spindle is rotating and after spindle installation)	・Early detection for signs of bearing seizure ・Reduces man-hours for spindle assembly
	Detects external loads applied to the spindle	・Detects the machining load applied to the spindle, and monitors machining (Contributes to improving the machining quality and productivity) ・Detects collisions between the tool and the workpiece(Used to reduce spindle damage and investigate the cause of any damage)
② Temperature sensor	Detects temperature changes in the spindle and spindle bearing	・Monitors the condition of the bearing raceway surface
③ Vibration sensor	Detects vibration changes in the spindle and spindle bearing	・Monitors the condition of the bearing raceway surface ・Detects collisions between the tool and the workpiece(Used to reduce spindle damage and investigate the cause of any damage)
④ Independent power source	Supplies power required for the sensors and wireless module	・No need for an externally connected cable or wiring space ・Reduces man-hours to assemble the spindle ・No need to change the spindle structure
⑤ Wireless module	Provides wireless communication to a location outside the spindle for detected data	

2.2 Wireless Technology

This bearing unit has a built-in independent power source and wireless module. This means that there is no need for an externally connected cable and wiring space used to transmit data and to supply power, achieving the same level in handling properties as conventional bearings with spacers that do not have sensor integration. The following sections describe the independent power source and wireless module.

2.2.1 Independent Power Source

The bearing unit uses a compact and high output electromagnetic generator that generates power using the rotation of the spindle. A power-generating rotor is arranged at the inner ring spacer while a power-generating stator is arranged opposing it at the outer ring spacer. This setup supplies the power required for the sensors and wireless module by generating power from the relative rotation of the inner and outer ring.

2.2.2 Wireless Module

A wireless module is built into the outer ring spacer to enable data detected by the sensors to be transmitted wirelessly to a location outside the spindle. The wireless module is compact and consumes only a small amount of power to ensure it can operate using power from the above mentioned independent power source with consideration for communication standards, the frequency used, signal strength, and safety, and to maintain sufficient space required for its antenna even when integrated in the spacer.

3.Evaluation Test

This section introduces the measurement results taken using wireless technology with the load sensor that was newly added to this bearing unit. Evaluation test results are shown for "Detects pre-load for spindle bearing (While spindle is rotating)" and "Detects external loads applied to the spindle" in section ① of **Table 1**.

The test machine used to simulate the machine tool spindle is shown in **Fig. 4.** This bearing unit was set up on this test machine and the evaluation test was performed. A high speed angular contact ball bearing with ceramic balls (HSE type) was used for the test bearing. A two-row back-to-back arrangement was chosen for the bearing to simulate a machine tool spindle. This bearing unit wirelessly transmits data detected by the sensors using the wireless module to a receiver set up at a location external to the test machine.

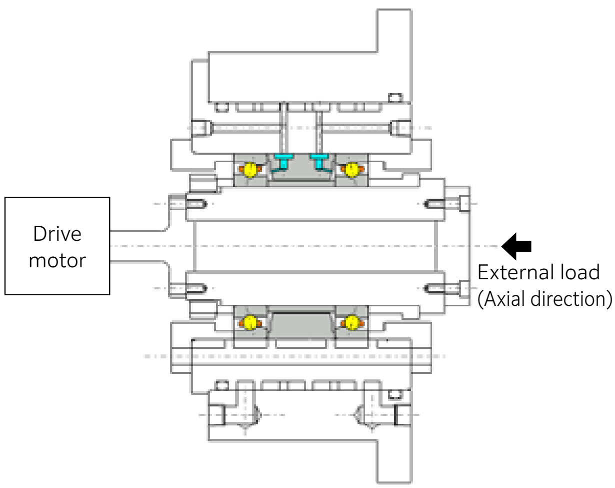

Fig. 4 Structure of test spindle

3.1 Bearing Pre-load Detection Test

A performance test was conducted to detect the pre-load of the bearing while the spindle is rotating. **Table 2** shows the test conditions. **Fig. 5** shows the measurement results from the load sensor using wireless technology that was newly added to this bearing unit. For comparison, the graph also shows the bearing pre-load (theoretical value) obtained from the spindle's rotational speed and the bearing's inner and outer ring temperature which were measured separately form this bearing unit. From the test results we confirmed that it is possible to estimate the pre-load of the bearing while the spindle is rotating using the load sensor on this bearing unit.

Table 2 Test condition of the bearing preload detection

Test bearing	φ 70 × φ 110 × 20 Part equivalent to 5S-2LA-HSE014 (high speed angular contact ball bearing with ceramic balls)
Pre-load method	Fixed position pre-load (pre-load of 750 N after spindle installation)
Rotational speed	0 - 14,000 min^{-1}
Lubrication method	Air oil lubrication
Lubricating amount	0.03 mL/10 min
Lubricating oil	ISO VG32
Lubricating air flow rate	30 NL/min
Fluid cooling channel	Yes, room temperature tuning
Axis position	Horizontal axis
External load	None

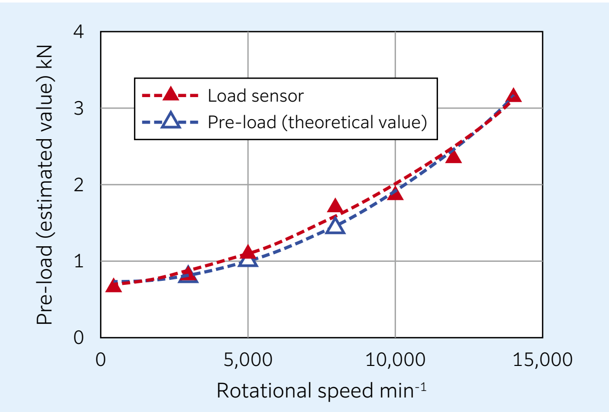

Fig. 5 Test result of the bearing preload detection

3.2 External Load Detection Test

An external load test was conducted to detect the external load applied to the spindle. **Table 3** shows the test conditions. During this test the spindle was rotated at 5,000 min^{-1} and an external load was applied in the axial direction. **Fig. 6** shows the measurement results. From the test results we confirmed that the load sensor on this bearing unit can estimate the external load in the axial direction while the spindle is rotating.

Table 3 Test conditions of the external load detection

Test bearing	φ 70 × φ 110 × 20 Part equivalent to 5S-2LA-HSE014 (high speed angular contact ball bearing with ceramic balls)
Pre-load method	Fixed position pre-load (pre-load of 750 N after spindle installation)
Rotational speed	5,000 min^{-1}
Lubrication method	Air oil lubrication
Lubricating amount	0.03 mL/10 min
Lubricating oil	ISO VG32
Lubricating air flow rate	30 NL/min
Fluid cooling channel	Yes, room temperature tuning
Axis position	Horizontal axis
External load	(Axial direction) 0 - 3 kN

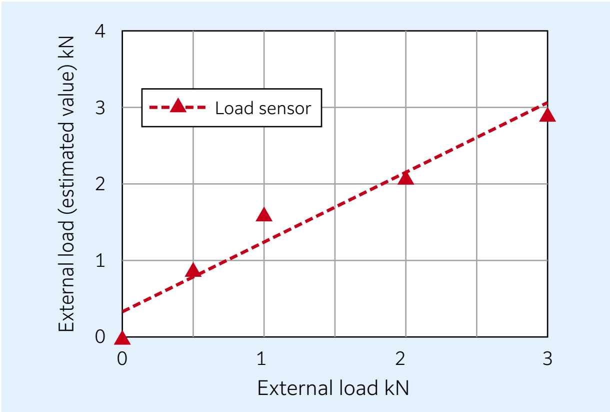

Fig. 6 Test result of the external load detection

4.Collaboration with Industrial IoT Platform

In order to use the data detected by this bearing unit, this bearing unit must be connected to a machine tool and an industrial IoT platform **(Fig. 7)**. When used for machine control that requires high responsiveness, the bearing unit should be connected to the machine tool (data transmission target ①). It is often necessary to develop a dedicated connection program or similar such program in this case. Meanwhile, when monitoring the condition and conducting predictive maintenance that uses measurement data, it is more common to connect to a management system in the form of an industrial IoT platform (data transmission target ②). Since the connection program is provided, the connection can be relatively easily established in this case.

For example, connecting this bearing unit to an industrial IoT platform such as Edgecross[*1] enables information for the load, temperature and vibration to be imported. Utilizing the various measurement data imported into the industrial IoT platform not only enables condition monitoring of the bearing, but it also enables monitoring of the machining conditions. The data can also be stored on a server, which also enables the use of big data.

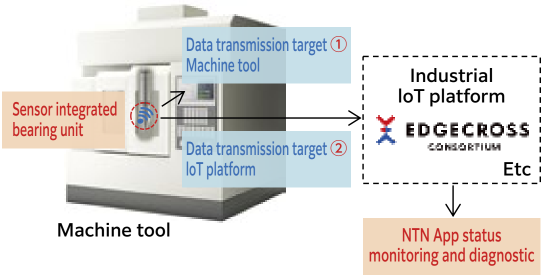

Fig. 7 Communication examples of the sensor integrated bearing unit

This bearing unit uses an independent power source to supply power and send data wirelessly, which can reduce the man-hours required to install sensors and also simplify the move to an IoT environment.

NTN has developed Wind Doctor™, a Condition Monitoring System for wind turbines that fully utilizes bearing analysis and our diagnostic expertise, and provides a monitoring service for power generation companies[4].

Additionally, we are also currently developing a diagnostic application for industrial IoT platforms that incorporates the knowledge and expertise we gained from Wind Doctor™ and plan to propose solutions employing this bearing unit.

*1 : A Japanese-developed open software platform in the field of edge computing to enable FA and IT collaboration. (From Edgecross Consortium official website https://www.edgecross.org/en/)

5.Summary

Further enhancement of condition monitoring functions is required for machine tools against such factors as the backdrop of a diminishing working population.

NTN has developed the “Sensor Integrated Bearing Unit” for Machine Tool Spindles and announced this product at 2018 JIMTOF2018 in response to this need. While promoting proposals to customers, we have received many requests to add a load detection function and wireless technology so have developed a new unit to achieve this purpose.

We will continue to make further improvements in performance and in the practical use of this product into the future. We are also aiming to improve technology for predictive maintenance using AI technology to continue contributing towards more efficient maintenance and operation of equipment, including machine tools.

References

1) Naoki Matsumori, Keiichi Ueda, Technical Trend of the Precision Bearings for Machine Tools, NTN TECHNICAL REVIEW, No.84, (2016) 40-45.
2) Keiichi Ueda, Technical Trend of the Precision Bearings for Machine Tools, Bearing & Motion Tech, No.002, (2016) 33-35.
3) Shohei Hashizume, Yasuyuki Fukushima, Yusuke Shibuya, Yohei Yamamoto, Development of Sensor Integrated Bearing Unit for Machine Tool Spindles, NTN TECHNICAL REVIEW, No.86, (2018) 50-55.
4) Makoto Miyazaki, Wataru Hatakeyama, Application of Condition Monitoring System for wind turbines, NTN TECHNICAL REVIEW, No.86, (2018) 40-44.

Photo of authors





Shohei HASHIZUME
Application Engineering Dept., Industrial Business Headquarters

Yusuke SHIBUYA
New Product Development R&D Center

Daichi KONDO
New Product Development R&D Center

Yohei YAMAMOTO
Product Design Dept., Industrial Business Headquarters

Hiroyuki IWANAGA
Robotics Sensing Engineering Dept., Industrial Business Headquarters