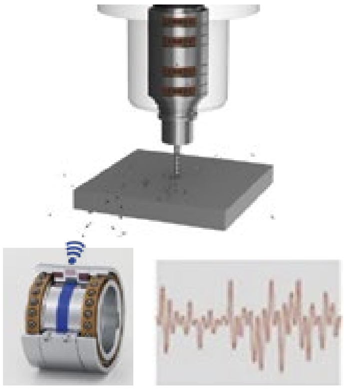
Prospects

Development of Sensor Integrated Bearing Unit for Machine Tool Spindles



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Machine tools are sometimes called the “Mother Machine” or “Mother of Industry” and have been supporting manufacturing all over the world. They are required for not only fundamental features like high speed, high rigidity, and super precision, but also condition monitoring and “Connected Industries” related technology. In 2018, **NTN** developed the “Sensor Integrated Bearing Unit for Machine Tool Spindles”, and additionally, applied the load detection function and wireless system to the unit in 2020. **NTN** has recently added the data receiver unit which collects the data from the “Sensor Integrated Bearing Unit” in machine tool spindles and the software for data communication. This report introduces the features, structure, and performance of the unit, and offers communication examples between the unit and machine tools.

1. Introduction

Amid significant changes in the global environment and social structure, the industrial world has been tackling various social challenges, such as achieving carbon neutrality to slow down global warming, achieving sustainable development goals (SDGs), and improving production to further enrich people’s lives, by integrating new technology created in the 4th industrial revolution (Industry 4.0) into core technologies developed over many years.

Among these technologies, machine tools[1) 2)] that support manufacturing in various industries, including the automotive, aircraft, medical and IT sectors, are being promoted to further improve basic performance in terms of “high speed, high durability and high accuracy” as a response to energy loss reduction and work force reduction. Productivity improvements and manpower reductions using IoT technology are underway.

NTN has developed the “Sensor Integrated Bearing Unit” for Machine Tool Spindles (hereafter, this bearing unit)[3)], which has sensors built into the spacer, a component of a bearing unit. This enables sensing of the temperature and vibration around the bearing raceway surface, making it possible for advanced condition monitoring of machine tools. **NTN** showcased a reference exhibit of this at the 29th Japan International Machine Tool Fair (JIMTOF 2018) held in 2018. A load detection function was also added to this bearing unit together with wireless operation[4)] in 2020.

We have also added a data receiving unit that acquires data detected by the sensors on this bearing unit at the exterior of the spindle as well as communication software to send and receive the data with the aim of further improving the usefulness of this bearing unit. This bearing unit’s characteristics, structure, performance test results for load and other sensors, and how to connect it to machine tools are described below.

2. Functions and purpose of the sensor integrated bearing unit

Table 1 shows the functions and purpose of this bearing unit. When a bearing that supports the rotation of the spindle (hereafter, spindle bearing), a key component on machine tools, is damaged, operation at the machine tool stops and the spindle must be replaced; this significantly lowers productivity. Due to this fact, there is a growing need to detect this damage early on. Furthermore, it will be even more necessary in the future to increase the productivity of machine tools and to minimize the dependence on individual expertise in machining monitoring in response to the aging of skilled personnel and the decline in the working-age population ratio. This bearing unit is expected to contribute towards these needs while also contributing towards achieving sustainable development goals (SDGs).

For example, if we detect the machine load applied on the spindle, and use this information for machining monitoring, we can optimize the machine conditions such as cutting depth, feed, and rotational speed. This is expected to provide increased machining quality and productivity. Furthermore, this bearing unit detects tool and workpiece collision to reduce

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Table 1 Functions & purpose of the sensor integrated bearing unit

	Function	Implementation method	Purpose	Connection to SDGs
(1)	Detects **preload** for spindle bearing (While spindle is rotating and after spindle has been installed)	Load Sensor	• To see sudden rises in preload that occurs before bearing seizure, and to detect signs of bearing seizure early on • To make it easier to manage preload on bearings after the spindle has been installed, and to reduce assembly manhours for the spindle	• Improve productivity, and reduce energy loss through optimized production • Reduce defective workpieces (waste) • Contribute towards automation and manpower reduction
(2)	Detects **external loads** applied to the spindle		• To detect machining load applied to the spindle, and contribute towards improved machining quality and productivity using machining monitoring • To detect collisions between the tool and workpiece, reduce damage to the spindle bearing, and use it to investigate the cause of the damage	
(3)	Monitors temperature changes in the spindle bearing	Temperature Sensor	• To monitor the bearing raceway surface and lubrication conditions	
(4)	Monitors vibration changes in the spindle bearing	Vibration Sensor	• To monitor the bearing raceway surface • To detect collisions between the tool and workpiece, reduce damage to the spindle bearing, and use it to investigate the cause of the damage	
(5)	No need for an externally connected cable or wiring space for power supply	Independent Power supply	• To reduce man-hours to assemble the spindle • To eliminate the need to change the structure of the spindle	• Reduce energy loss with independent power supply and improved productivity
(6)	External connection for data transmission No need for cable or wiring space	Wireless Module		

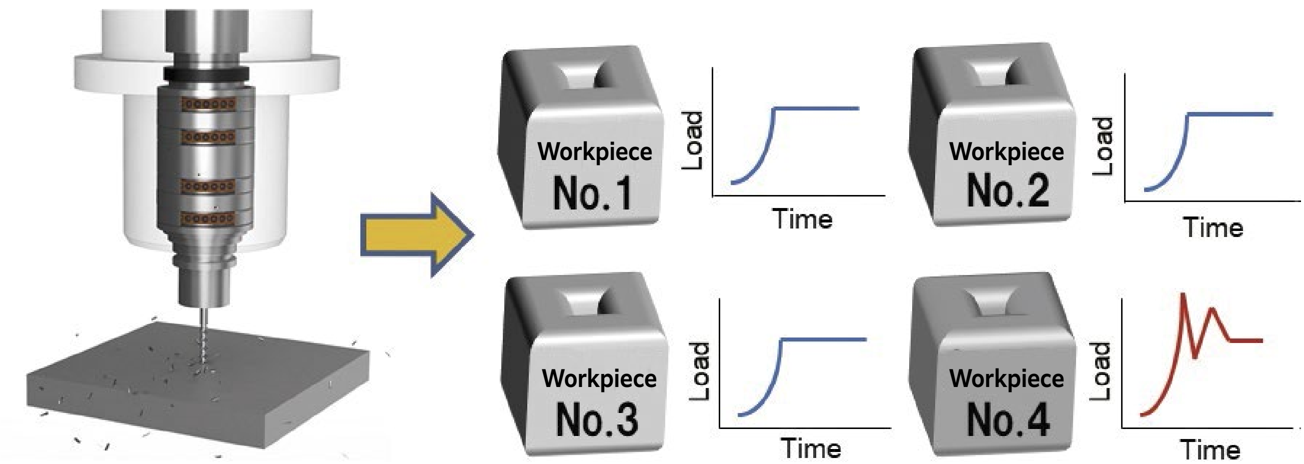

Fig. 1 Illustration of sensor integrated bearing unit application
Example of improving machining quality by linking machining data to each product of a machine tool

damage to the spindle bearing, uses real-time information to determine the cause of the damage, and as shown in **Fig. 1**, links machining data for each manufactured product to both improve machining quality and promptly investigate the reason why a defect occurred.

3. Structure and specifications of the sensor integrated bearing unit

3.1 Structure

Fig. 2 shows a structural illustration of this bearing unit. This bearing unit comprises a set of angular contact ball bearings arranged back-to-back with an outer ring spacer and inner ring spacer provided between the angular contact ball bearings. The outer ring spacer and inner ring spacer are equipped with sensors, circuits to process data detected by the sensors, a wireless module, and an independent power supply.

The independent power supply uses an electromagnetic induction generator. A stator consisting of a coil and yoke is built into the outer ring spacer, and a rotor with alternately magnetized N and S-poles is attached to the inner ring spacer. Electromagnetic induction is generated by the relative rotation of the outer ring spacer and inner ring spacer which generates the power required to run the sensors and circuits.

Fig. 3 shows an example of application for this bearing unit on a machine tool spindle. Factors such as the internal clearance and the difference between the width of the inner ring spacer and outer ring spacer are adjusted to apply preload on the bearing. This maintains high rigidity at the bearing which ultimately improves machining quality. With this structure, bearing preload and the load applied to the tool during machining act on the outer ring spacer so a load sensor is provided on the outer ring spacer of this bearing unit.

The sensors, circuits, and an independent power supply are built into this bearing unit in a compact way;this enables it to achieve the same dimensions as a conventional outer ring spacer without sensors.

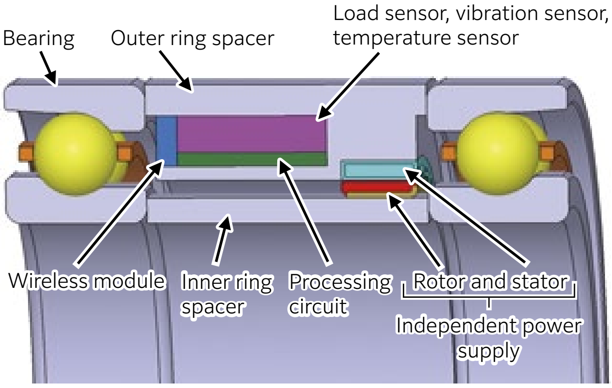

Fig. 2 Structural illustration of sensor integrated bearing unit

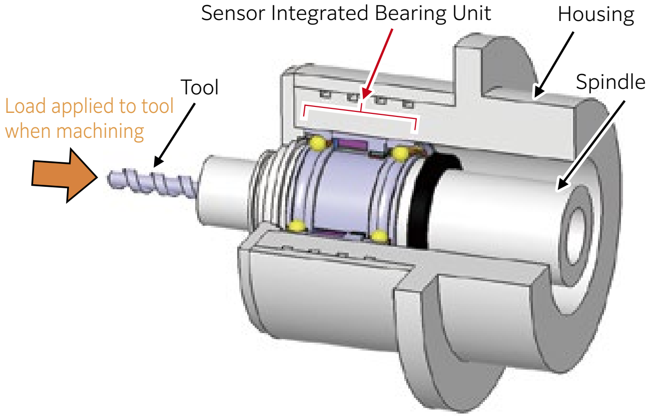

Fig. 3 Example of application for the sensor integrated bearing unit on a machine tool spindle

3.2 Specifications

Table 2 shows the specifications for this bearing unit. It lists load, temperature, and vibration acceleration for sensing items. Bluetooth Low Energy (2.4 GHz) is used for the telecommunication standards to allow for a lower power consumption at the wireless module and to make it more compact. The operating temperature range is set to -20 to 70 ℃ with consideration for the allowable temperature of electronic components mounted on the module.

Table 2 Specifications for the sensor integrated bearing unit

Bearing	Type	Ultra-high speed angular contact ball bearings with ceramic balls (Equivalent to 5S-2LA-HSE014) Double row back-to-back arrangement
	Bore diameter × outer diameter × width	ϕ70 × ϕ110 × 20 (per row) mm
Spacer	Inner ring spacer bore diameter × outer ring spacer outer diameter × width	ϕ70 × ϕ110 × 40 mm
Sensing	Load	Maximum detection load: 45 kN
	Temperature	Detection range: - 40 to 125 ℃
	Vibrational acceleration	Detection range: ± 50 G Response frequency band: up to 11 kHz
Independent power supply		Electromagnetic induction generator
Communication standard		Bluetooth Low Energy (2.4 GHz)
Operating temperature range		- 20 to 70 ℃

4. Connecting to equipment

Fig. 4 shows an schematic example of using the data communication capabilities of this bearing unit. Data detected by the sensors is transmitted wirelessly from the wireless module built into the outer ring spacer to the data receiving unit provided with a USB antenna for data reception. The data receiving unit, the customer's machine tool and server are connected by a LAN cable so that data can be verified.

Data transmitted from the wireless module consists of 3 types of data; these are load, temperature, and vibration detected by each sensor. Since each data type is constantly transmitted to the connected equipment, it is expected that it will be used to control, monitor conditions as the spindle bearing, and provide predictive maintenance to machine tools that require a high level of response.

A separate connection program is required to connect the data receiving unit to dedicated equipment. However, if the system uses an IoT platform, it has the advantage of making the system more versatile and easier to connect. **NTN** provides "Bearing Diagnostic Edge Application" for Industrial IoT Platforms[5] to support efforts in this area.

This bearing unit has an independent power supply to feed power to the unit and can transmit data wirelessly, which makes it easy to use in an IoT environment.

5. Evaluation test

This section introduces the test results for the load, temperature, and vibration sensor built into this bearing unit.

Fig. 5 shows the evaluated spindle that simulated the machine tool spindle. This bearing unit was assembled onto this evaluated spindle and then the evaluation test was carried out. This bearing unit wirelessly transmitted data detected by the sensors to a receiver installed externally on the spindle using the wireless module.

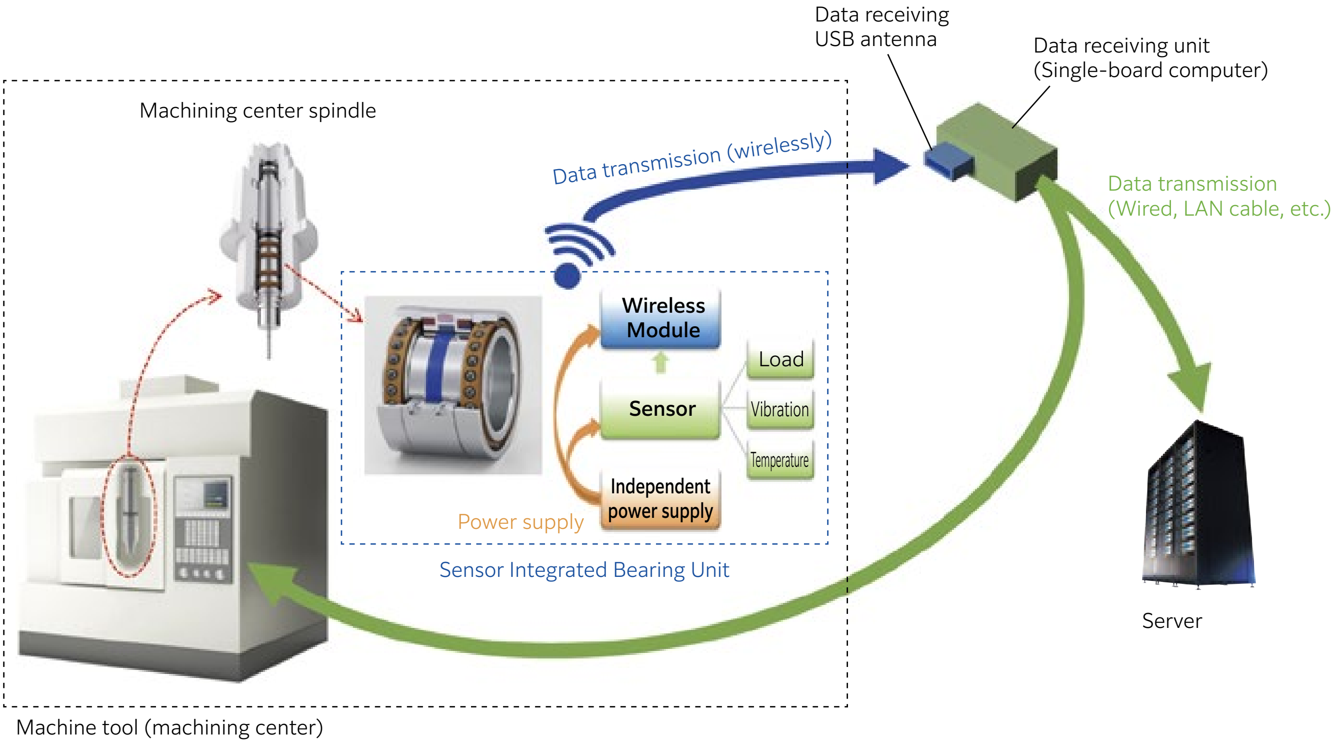

Fig. 4 Example of using the sensor integrated bearing unit

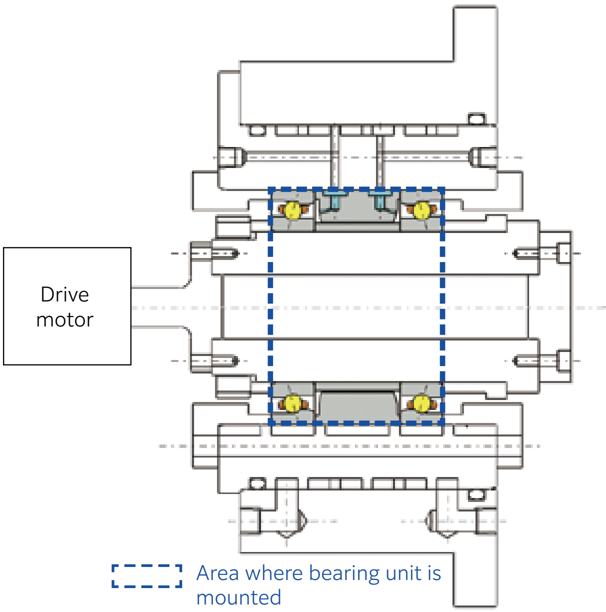

Fig. 5 Structure of evaluated spindle

5.1 Verifying load and temperature responsiveness during an acceleration/deceleration test

An acceleration/deceleration test was carried out in which the rotational speed was changed, assuming the actual operation conditions of a machine tool. **Table 3** shows the test conditions and **Fig 6** shows the test results for load and temperature. It was confirmed that this bearing unit can detect changes in bearing preload and temperature for fluctuations in the rotational speed. It was also confirmed that it has a higher temperature sensitivity than an external sensor.

Table 3 Acceleration/deceleration test conditions

Test bearing	$\phi 70 \times \phi 110 \times 20$ Equivalent to 5S-2LA-HSE014 (Ultra-high speed angular contact ball bearing with ceramic balls)
Preload method	Fixed position preload (preload of 750 N after spindle installation)
Rotational speed	6 000→10 000→6 000→8 000 min^{-1}
Lubrication method	Air-oil lubrication
Lubricating amount	0.03 mL/10 min
Lubricating oil	ISO VG32
Lubricating airflow rate	30 NL/min
Fluid cooling channel	Yes, room temperature tuning
Axis position	Horizontal axis

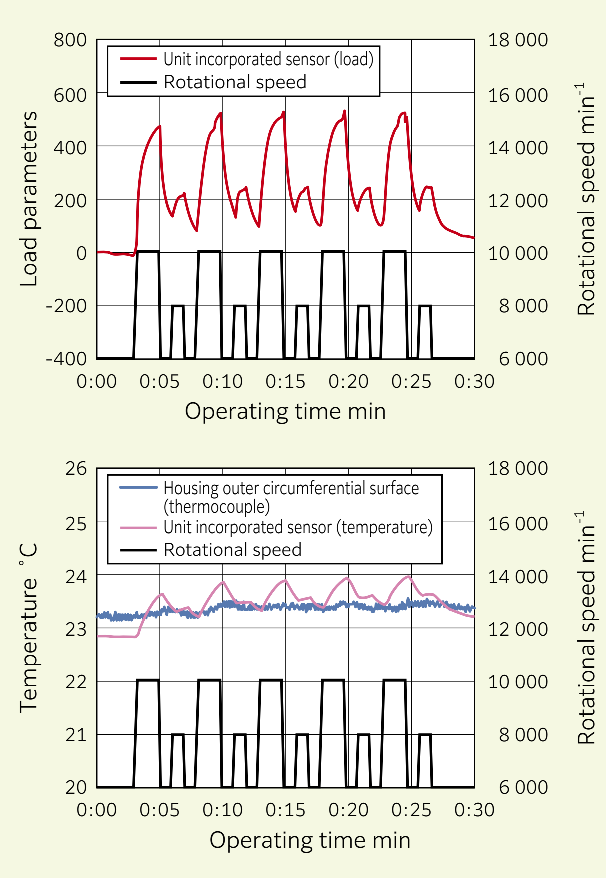

Fig. 6 Acceleration/deceleration test results

5.2 Indentation bearing vibration verification test

To tackle the detection of an abnormality on a bearing that uses a vibration sensor, damage (an indentation) was simulated on the bearing raceway surface. Then a vibration verification test was carried out on the evaluated spindle in **Fig. 5** with the same condition as for the acceleration/deceleration test. **Table 4** shows the test conditions and **Fig. 7** shows a 3D illustration of the simulated damage (indentation) created on the bearing raceway surface. During the test, the vibration on the outer circumferential surface of the evaluated spindle housing was measured at the same time together with the vibration detected by the vibration sensor built into the outer ring spacer, and both measurements were compared. For a vibration of 5 000 min^{-1} at the test bearing, while checking components with frequency that matches the inner ring damage, feature quantities of the sensor built into the outer ring spacer were greater than at the housing outer circumferential surface, showing that the signal to noise ratio improved **(Fig. 8)**. The vibration sensor built into the outer ring spacer is considered to be able to detect damage on the bearing with better accuracy.

Table 4 Vibration verification test conditions

Test bearing	Equivalent to $\phi70 \times \phi110 \times 20$ 5S-2LA-HSE014 (Ultra-high speed angular contact ball bearing with ceramic balls)
Preload method	Fixed position preload (preload of 750 N after spindle installation)
Rotational speed	5 000 min^{-1}
Lubrication method	Air-oil lubrication
Simulated damage (Indentation)	1 location on inner ring raceway surface
	Depth of 6 μm

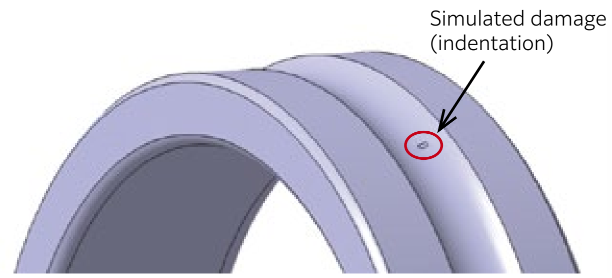

Fig. 7 3D illustration of the simulated damage (indentation) created on the bearing raceway surface

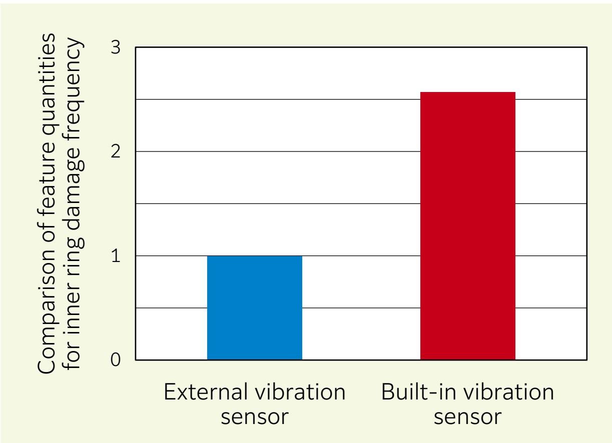

Fig. 8 Indentation bearing vibration verification test results

6. Summary

Trials are underway to use and introduce sensing technology on machine tools, against the backdrop of the rising demand for condition monitoring and machining monitoring.

To meet this demand, **NTN** is making progress with developing the "Sensor Integrated Bearing Unit for Machine Tool Spindles", which has a built-in wireless function and can detect load, temperature, and vibration. **NTN** has also made proposals for new methods to connect developed products and machine tools.

We will continue to repeatedly evaluate this bearing unit through operation tests for its practical use and promote further improvements and refinements to its function. Furthermore, we will also work on establishing more advanced condition monitoring and predictive maintenance technology by combining this bearing unit with AI technology. These efforts will support the efficient operation of machine tools.

We intend to work on developing technology that will enrich the lives of people and be ecologically friendly in support of sustainable development goals (SDGs) for the future.

References

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