Initiatives for the High Performance of Machine Tool Spindle Bearings

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The demands regarding machine tool performance requirements are growing more stringent, and in order to satisfy such demands, improving the performance of the bearings used in machine tool spindles is an important issue that must be addressed. This report presents JTEKT's initiatives for the high functionality of machine tool spindle products as an example of spindle bearing and unit product development.

***Key Words**: machine tools, rolling bearing, angular contact ball bearing, cylindrical roller bearing*

1. Introduction

In order to further improve machine tool performance, improving the performance of the spindle unit, one of the major units affecting machine tool performance, is essential and the spindle bearing plays a particularly crucial role. **Figure 1** shows machine tool and bearing needs. Due to the growing need for high-accuracy machining, bearings are being required to offer high-speed, high-rigidity and low-temperature rise performance. Moreover, there are intensifying needs for combined processing machines[1] from the perspective of high-efficiency machining. Bearings are being required to offer both high-speed and high-rigidity performance in order to cover a wide scope of machining, from precision machining of molds, etc. to machining of hard-to-cut titanium alloy, etc. used in aircraft engines, in just a single machine.

Another issue is the reduction of environmental burden. **Figure 2** shows the relationship between "lubrication method" and the "high-speed and rigidity" of spindle bearings. Widely-adopted lubrication methods for spindle bearings are grease lubrication and oil-air lubrication. Grease lubrication is adopted generally due to the fact it is easy to handle and enables simplification of the spindle structure[2], however in high-speed zones exceeding a $d_m n$ value[*1] of 1 million, and in zones where importance is placed on high-rigidity, oil-air lubrication is the preferred method. However, due to requirements for workplace environment improvements and energy-saving stemming from changes in the environment surrounding machine tools, it is predicted that the popularity of grease lubrication will grow due to its minimal oil scatter and lower running costs.

*1 $d_m n$ value: Bearing P.C.D. (mm) × rotational speed (min^{-1})

Moreover, efforts to support IoT are advancing even in regards to machine tools, and these include the monitoring and compensating of thermal displacement, measurement and compensation of geometric error, etc[3]. Furthermore, there is a need to promote monitoring of the spindle unit status through visualization of the bearing status during operation in order to prevent chatter vibration, perform spindle abnormality diagnoses, predict remaining life and so on.

This report will introduce JTEKT's development of a grease-lubricating, high-rigidity, low-temperature rise, double-row cylindrical roller bearing, a grease-lubricating, low-temperature rise angular contact ball bearing as bearings supporting the upcoming needs of machine tools, as well as a dynamic rigidity measurement system.

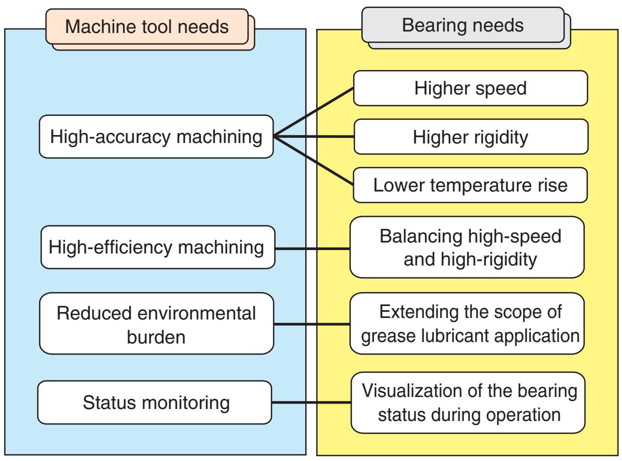


Fig. 1 Machine tool and bearing needs

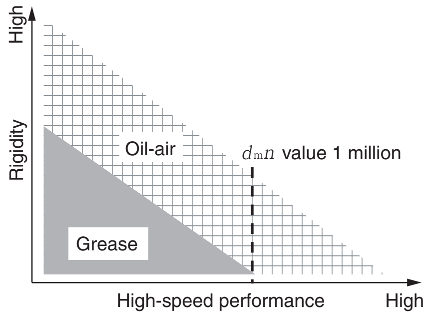


Fig. 2 Relationship between "lubrication method" and "high-speed and rigidity" of spindle bearings

2. Development of a Grease-lubricating, High-rigidity, Low-temperature Rise, Double-row Cylindrical Roller Bearing

2. 1 Issues with Grease-lubricating, Double-row Cylindrical Roller Bearings

Lathes and machining centers are the typical machine tools and while the lathe generally places importance on high rigidity, as described in the preceding paragraph, low-temperature rise and high-speed performances are now also being required. **Figure 3** shows a typical bearing array of a lathe spindle unit. On a lathe spindle, a double-row cylindrical roller bearing is used as the front bearing in order to secure radial rigidity and, commonly, grease lubrication is used here. JTEKT's double-row cylindrical roller bearing adopts a brass retainer[4)] and sometimes contact with the roller during operation can generate metal chips which lower grease performance, therefore it was necessary to use resin cage-type retainers in some high-speed operation applications. In the beginning, we used polyamide resin for this, however, with increasingly tougher spindle operating conditions, the issue of retainer breakages arose. **Figure 4** shows the damaged condition and breakage mechanism of a conventional polyamide resin cage-type retainer.

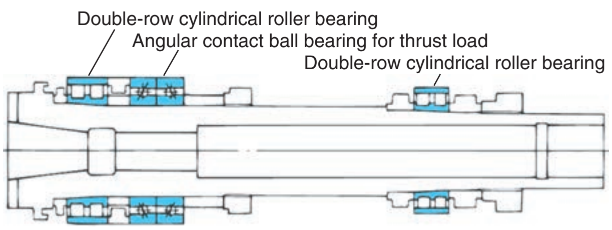


Fig. 3 Typical bearing array of a lathe spindle unit

In order to support the high-efficiency machining demanded for machine tools, rapid acceleration/deceleration of the spindle unit is necessary to shorten non-cutting time. Moreover, there is also a need to support cutting at high loads in order to efficiently machine hard-to-cut materials. Retainer breakage is believed to be caused due to roller lead-lag created from rapid acceleration/deceleration and high load leading to tensile force/compressive load acting on the peripheral direction of the retainer bar.

Due to the above, there was a need to develop a retainer able to withstand rapid acceleration/deceleration operation and high load in order to respond to high-efficiency machining needs.

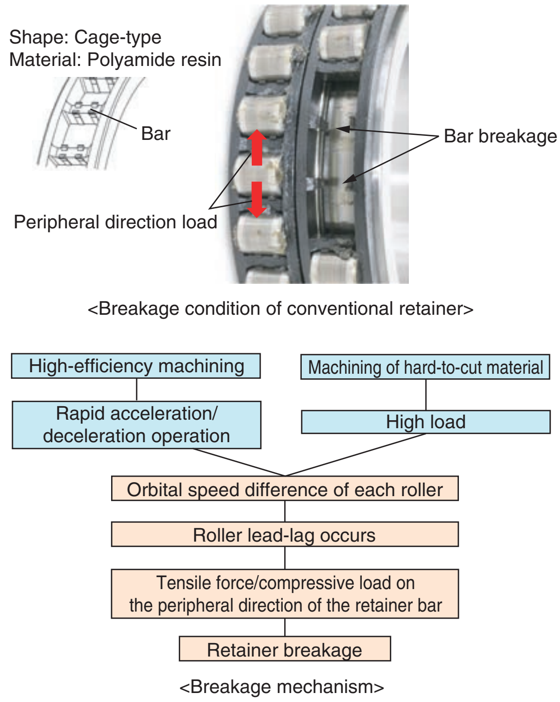


Fig. 4 Damaged condition and breakage mechanism of a conventional cage

2. 2 Features of the Developed Product

(1) Overview of the developed product

Figure 5 is a comparison of the conventional and developed products. In order to respond to rapid acceleration/deceleration operation and high load, we changed the shape and material of the retainer for the newly developed bearing. In regards to the shape, the conventional bearing adopted a cage-type retainer, therefore we used a comb-type on the developed product. Moreover, regarding material, whilst the conventional bearing used polyamide resin, the developed bearing uses super engineering plastic. The roller guide method is adopted in the retainer of both the conventional and developed bearings.

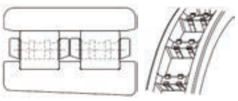
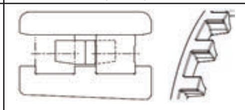
	Conventional product	Developed product
Bearing and retainer shape		
Material	Polyamide resin	Super engineering plastic
Shape	Cage-type	Comb-type
Retainer guide method	Roller guide	Roller guide

Fig. 5 Comparison of conventional and developed product design

Firstly, in regards to retainer material, **Table 1** provides a comparison of retainer property values for the conventional and developed products. Compared to the polyamide resin used for the conventional product, the super engineering plastic used for the developed product has superior mechanical strength; namely 1.6 times greater tensile strength and 3.1 times higher Young's modulus, therefore was adopted on the developed product to countermeasure retainer breakage.

Table 1 Comparison of cage property values

	Conventional product	Developed product
Material	Polyamide resin	Super engineering plastic
Tensile strength, MPa	165	260
Young's modulus, MPa	7 400	23 000
Specific gravity, g/cm^3	1.33	1.4

Furthermore, regarding the retainer's shape, while the conventional product featured a cage-type retainer whereby each side of the bar was annular, the comb-type is characterized by having only one annular-shaped side as per **Fig. 5.** Through adopting this shape, it is possible to reduce the stress generated when tensile force and compressive load in the peripheral direction act on the bar portion.

(2)FEM analysis

In order to confirm the superiority of the developed product related to its shape, we performed an FEM analysis of the maximum principal stress generated on the retainer. **Figure 6** shows the results of a comparison between the conventional and developed products. Compared to the conventional product, the maximum principal stress is around one-third for the developed product when there is peripheral direction load due to roller lead-lag.

(3)Low-temperature rise design

For the developed product, we clarified the heating mechanism in order to achieve low temperature rise. **Figure 7** shows the heating mechanism of the roller guide comb-type retainer, and **Fig. 8** shows the pocket part of the retainer during bearing rotation. For the roller guide comb-type retainer, the rib is distorted (expanded) in the radial direction due to centrifugal force working on it during bearing rotation and retainer movement increases due to the retainer guide clearance becoming larger during rotation. As a result, the contact force of the roller and retainer increases, causing heat generation. Consequently, we believed suppressing the distortion of the retainer rib would be an effective means of achieving low temperature rise.

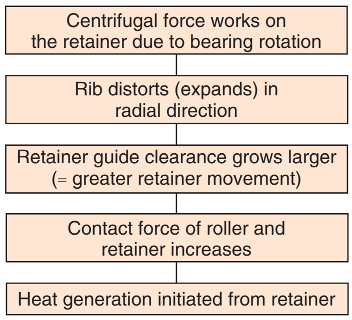


Fig. 7 Heating mechanism of roller guide comb-type cage

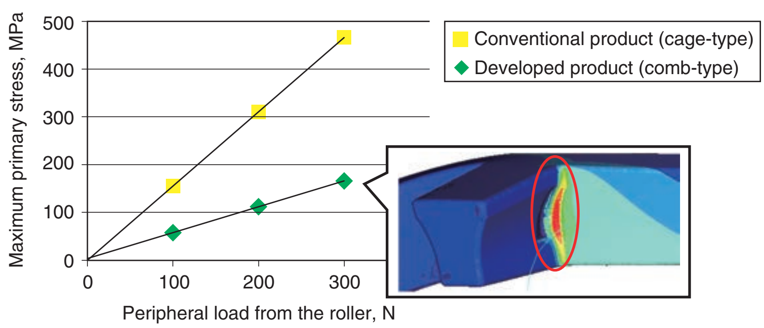


Fig. 6 Analysis result of maximum principal stress

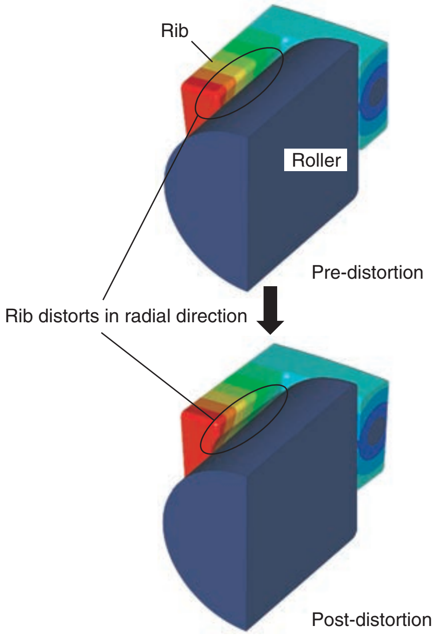


Fig. 8 Pocket part of cage during bearing rotation (conceptual diagram)

In order to suppress rib distortion due to centrifugal force, it would be effective to select a material with superior mechanical strength, and reduce rib weight. Regarding the material, the super engineering plastic selected as a countermeasure to breakage is also effective as a countermeasure to rib distortion. Moreover, in order to reduce rib weight, we shortened the length of the rib. **Figure 9** shows the relationship between rotational speed and guide clearance as a parameter of rib length through the result of FEM analysis. As **Fig. 9** shows, shortening rib length reduces the guide clearance during bearing rotation.

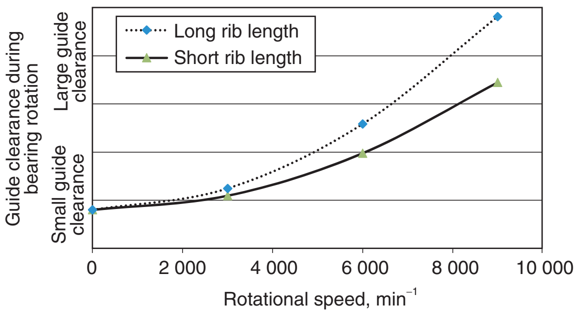


Fig. 9 Relationship between rotational speed and guide clearance (FEM analysis result)

2. 3 Performance of the Developed Product

(1) Durability test

We performed a durability test to confirm the effects of changing the material and shape of the developed product. **Table 2** shows the conditions, and **Fig. 10** shows the results of this durability test. While the conventional product broke after 300 hours, the developed product was capable of over 930 hours of continuous operation, confirming a durability of more than 3 times higher.

Table 2 Durability test conditions

Item	Test conditions
Bearing (I.D. × O.D. × Width)	NN3018 (ϕ90mm × ϕ140mm × 37mm)
Rotational speed	Rapid acceleration/deceleration between 0 ⇔ 6 000 min^{-1}
Lubrication method	Grease lubrication (Filled to 10% of spatial volume)
Radial clearance upon assembly	–30 μm
Spindle orientation	Horizontal
Cooling	Natural heat dissipation

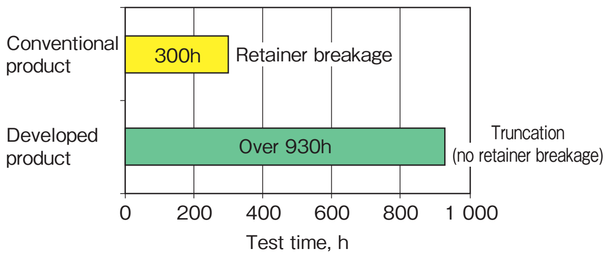


Fig. 10 Durability test result

(2) Temperature rise test

In order to compare the temperature rising tendencies of the conventional and developed products, as well as confirm the effects of a low-temperature rise design with the parameter of rib length, a rotational test was carried out. **Table 3** shows the conditions, and **Fig. 11** shows the results of this test. Developed product 2 (with a short rib length) has 46% lower temperature rise than the conventional product. This is believed to be because, compared to the cage-type retainer of the conventional product, the comb-type retainer of the developed product 2 has good grease discharging efficiency from the race portion, which may have reduced the mixing resistance of grease.

We also observed that, developed product 2, which is designed specifically to have low-temperature rise, has 24% lower temperature rise than developed product 1 (which has a long rib length), confirming that shortening rib length is effective in lowering temperature rise.

Table 3 Temperature rise test conditions

Item	Test conditions
Bearing (I.D. × O.D. × Width)	NN3018 (ϕ90mm × ϕ140mm × 37mm)
Rotational speed	MAX: 9 000 min^{-1} (d_mn value: 1.04 million)
Lubrication method	Grease lubrication (Filled to 10% of spatial volume)
Radial clearance upon assembly	−2 μm
Spindle orientation	Horizontal
Cooling	Natural heat dissipation

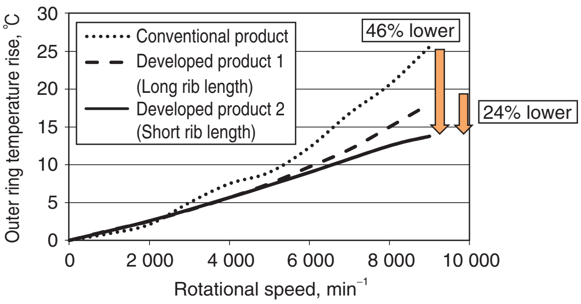


Fig. 11 Temperature rise test results

From the above results, we believe that developed product 2 can contribute to high-speed, low-temperature rise lathe spindles which are generally required to have high-rigidity. We also believe that this product can further contribute to higher rigidity through adoption on machining center spindles, for which importance is placed on high-speed performance.

3. Development of a Grease-lubricating, Low-temperature Rise Angular Contact Ball Bearing

3. 1 Overview of the developed product

As the temperature of a machine tool spindle rises, thermal expansion occurs in the axial direction, which in turn affects the accuracy of the machined parts. As such, in order to respond to the need for machine tools to offer high-accuracy machining, as mentioned in **Section 1** above, there is a need to lower the temperature rise of the bearing, which is the cause of heat generation in the spindle. In regards to this, JTEKT was already selling a series of angular contact ball bearings for machine tool spindles with excellent low-temperature rise and high-speed performance[5)], but we undertook the challenge of lowering temperature rise even further.

To achieve low temperature rise, there is a need to reduce grease mixing resistance and the contact resistance between the retainer and balls, as these cause heat generation, therefore retainer design has a significant influence. As a part of a revised retainer design on the developed product, we optimized the clearance between the retainer and inner ring, as well as the contact points with the balls inside the retainer pocket. **Figure 12** shows a comparison of the conventional and developed products. The clearance between the retainer and inner ring was enlarged compared to the conventional product to improve grease fluidity and reduce mixing resistance. Moreover, compared to three contact points with the balls inside the retainer pocket for the conventional product, the developed product was made to have just one contact point.

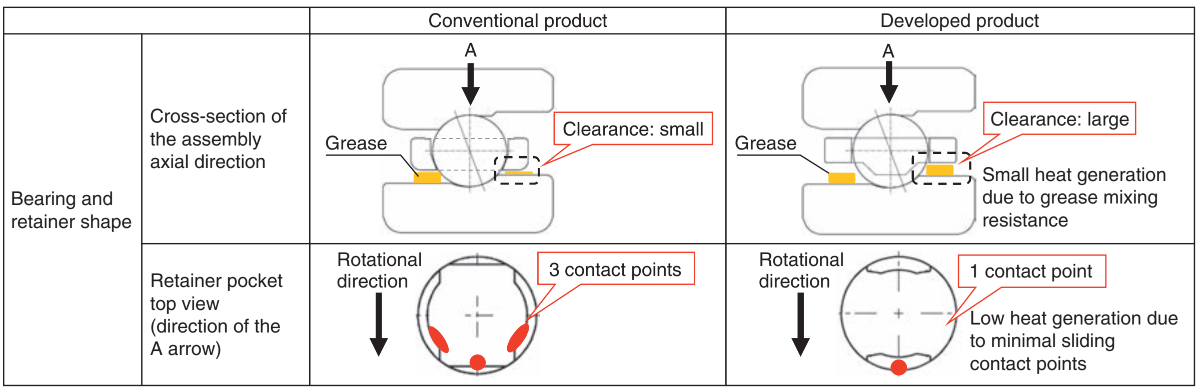


Fig. 12 Comparison of conventional and developed product design

3. 2 Temperature Rise Test

Table 4 shows the conditions and **Fig. 13** shows the results of a temperature rise test. Compared to the conventional product, we confirmed that the developed product had 15% lower temperature rise. Moreover, there is also an expectation that grease life will improve as it is majorly affected by temperature, and we calculated an improvement of over 10%.

Table 4 Temperature rise test conditions

Item	Test conditions
Bearing (I.D. × O.D. × Width)	HAR014CA-5DBB (ϕ70mm × ϕ110mm × 20mm) × 4 rows
Rotational speed	MAX: 10 000min^{-1} ($d_m n$ value: 900 000)
Preload method	Fixed position preload
Lubrication method	Grease lubrication
Cooling	Natural heat dissipation

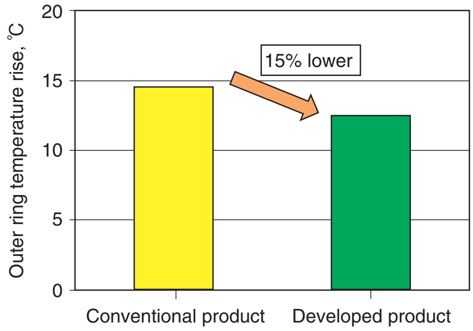


Fig. 13 Temperature rise test results

4. Development of a Dynamic Rigidity Measurement System for Machine Tool Spindles

4. 1 Issues in Conventional Spindle Performance Management

A major factor influencing spindle performance is bearing preload. A higher preload is advantageous for rigidity, however disadvantageous for high-speed, heat generation and life properties. Meanwhile, a smaller preload is advantageous for high-speed, heat generation and life properties, however disadvantageous for rigidity. Moreover, variation of preload creates inconsistency in spindle performance, which in turn impacts workpiece accuracy. As such, one potential approach to obtaining stable spindle performance is appropriate preload management.

Bearing preload is often managed in accordance with either spindle natural frequency, axial static rigidity or start-up torque, and these are generally measured when the spindle is static. However, during machining the spindle is rotating, therefore preload changes as it is affected by centrifugal force and heat. Moreover, in machine tools where the spindle orientation can change, preload can vary due to the weight of the spindle acting on the bearing depending on spindle orientation. Despite these points, there are practically no cases of measuring preload during spindle operation.

The next section will introduce JTEKT's efforts to develop a dynamic rigidity measurement system by adopting magnetic bearing technology[6], to enable measurement of spindle performance in an arbitrary operating status.

4. 2 Features of the Developed Product

Figure 14 is an outline of the dynamic rigidity measurement system. This system comprises of a radial exciter and an axial exciter, and is mounted on the spindle housing. In terms of rigidity measurement, an arbor using the suction force of an electromagnet is mounted to the spindle tip using a non-contact method then vibrated at different frequencies to detect the displacement at such times with a sensor.

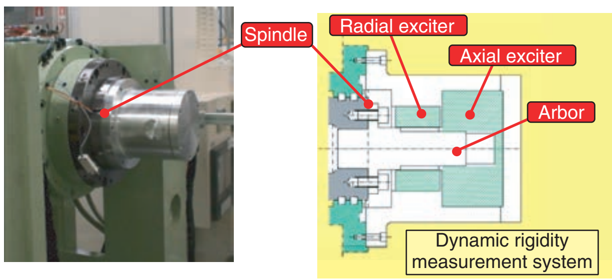


Fig. 14 Schematic of a dynamic rigidity measurement system

4. 3 Measurement Example

Figure 15 shows an example of dynamic rigidity measurement when rotational speed is 5 000 min^{-1} and the spindle is vibrated in the radial direction. It shows the input frequency in the X axis and a dimensionless quantity relative to rigidity in the Y axis. We observed that rigidity decreases when frequency is around 900 Hz and were able to confirm the 1-dimensional natural frequency of the spindle in the radial direction.

Moreover, **Fig. 16** shows the influence of spindle orientation and rotational speed on the measurement of natural frequency. We confirmed that the spindle's natural frequency differed depending on rotational speed, and that the result also changed depending on spindle orientation. This is in good consistency with the theoretical values considering changes in bearing contact angle during operation and the influence of spindle orientation, and indicates that spindle rigidity can be measured during spindle operation.

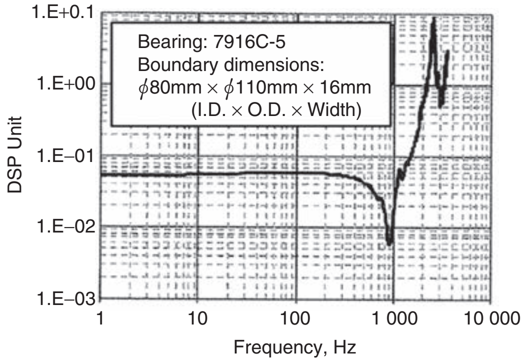


Fig. 15 Example of dynamic rigidity measurement

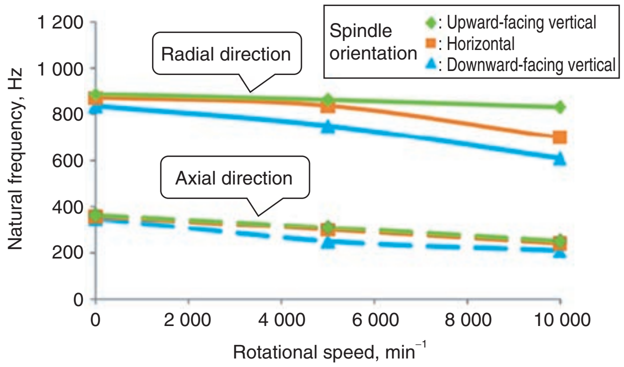


Fig. 16 Influence of spindle orientation and rotational speed in natural frequency measurement

Based on these results, we believe adopting the dynamic rigidity measurement system would make the following possible.

1) Measurement of rigidity and natural frequency when the spindle is static
   ⇒ Apply to preload management in the same way as the conventional method
2) Measurement of rigidity and natural frequency when the spindle is rotating
   ⇒ By ascertaining the natural frequency of the spindle, it is possible to contribute to optimization of machining conditions, such as chatter vibration prevention

Moreover, because it would be possible to measure spindle properties in mid-operation, we believe it would be possible to contribute to monitoring of spindle unit status in the future, such as through spindle abnormality diagnosis, and will continue to promote development in preparation for establishment of a dynamic rigidity measurement system.

5. Conclusion

Higher functionality of bearings for machine tool spindles would lead to higher performance of machine tools. Moreover, it is believed that such needs will continue to diversify, and a need will arise to develop bearings not customized to offer certain limited performances, but rather to meet a variety of demands. Moreover, in order to support the realization of machine tools with autonomic functions of self-diagnosing problems and machining at optimal conditions in response to IoT advancements, JTEKT wishes to promote development of products relating to the monitoring of spindle unit status through the visualization of bearing status during operation.

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