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The United Nations adopted the Sustainable Development Goals (SDGs) in 2015, a set of targets that demand the pursuit of economic development and affluence as well as protection of the global environment, elimination of poverty and disparity, and assurance of a safe life for people. In response to such social requirements, and in addition to the rapid development of ICT, IoT, and AI, the industrial world is evolving dramatically. Involved in industrial machinery on a large scale, NSK will contribute to the Earth, society, and industry through the development of new products and technology. Here in this Special Issue of Products and Technology for Industrial Machinery we introduce these technologies.

In this era of transition from tangible goods to intangible goods ("Mono Kara Koto" in Japanese), NSK will start a business of condition monitoring for bearings. We have developed unique technology for diagnosing bearing abnormalities through our long-standing service for customers. These articles present our work of commercializing this technology, the product of simple diagnosis equipment BD-2, and new diagnosis technology.

This issue introduces the technological trends in the areas of bearings and direct-acting products used in robots, for which there is ever-growing demand; wind power generators coming to receive much attention in Japan, spurred by rapid changes in the global business world to achieve a decarbonized society; machine tools with ever-increasing performance involving the recent trends of IoT and robots; and railroad vehicles, which are being expanded particularly in developing countries. In addition, we will introduce NSK technology and products that are being used in a variety of industries, such as the motor industry, mining, and steel industries. Furthermore, we will introduce guidance robots, omni-directional mobile wheel units, and vibration control actuators for train cars, creating new product regimes.

With four core technologies (material, tribology, analysis, and mechatronics) as our foundation, our company will add new core technologies (organic functional material and sensing technology) while continuing to contribute to the development of society and industry as well as protection of the global environment.
Approach of Condition Monitoring in Industrial Machinery

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Abstract
In industrial machinery fields, IoT (Internet of Things) based solutions are expected to improve O&M (Operation and Maintenance) efficiency. Condition Monitoring, one of applications leading the realization of IoT concept, enables a predictive maintenance to optimize O&M. In this article, we will introduce NSK’s latest approaches for condition monitoring by taking an example in wind turbine application.

1. Introduction
Keywords such as IoT (Internet of Things) have become widespread among the general public, indicating a rapid shift to a society where everything is connected to the Internet. Proposals made in many countries (e.g., Industry 4.0, Industrial Internet, Made in China 2025), and Connected Industries) place great importance on the application of IoT. Condition monitoring is regarded as the field that will play a leading role in the realization of IoT, and it is in progress from various aspects.

In the fields of IT and ICT, the predecessors of IoT, NSK has provided technical services of health diagnosis for rotating machines including bearings through providing a diagnostic device NSK Bearing Monitor and the unique analysis system NSK ACous NAVI™, which connects global worksites and NSK technical representatives via the Internet. Bearing Monitor has been replaced with Bearing Doctor BD-2 (to be described later in an article on new products). NSK is making progress in the condition monitoring field through upgrading various products on the basis of analysis and diagnostic technology of ACous NAVI™. The present article describes technical research content developed through a research and development project of the National Research and Development Agency, New Energy and Industrial Technology Development Organization (NEDO), as part of the approach to condition monitoring for wind turbines.

2. Condition Monitoring of Industrial Machinery
In the field of industrial machinery, various types of data are gathered from sensor devices installed on equipment (sent via the Internet to be stored on databases and in the cloud) and then analyzed with large-scale data analysis. This leads to benefits in various fields, including design support, production optimization, operation optimization, and preventive maintenance. In the field of condition monitoring, optimization of Operation & Maintenance (O&M) is expected by promoting preventive maintenance through real-time monitoring of the operating conditions and malfunctions of the facilities and system, including infrastructure such as power generators, railway vehicles, and machine tools.

Before the advent of condition monitoring, O&M was carried out with Time Based Maintenance (TBM), assuring proper machine performance by periodic inspection. It consists of the inspection and replacement of parts after such prescribed period with the objective of preventing malfunctions of facilities. Although its planning is easy, excessive maintenance cannot be avoided. Besides, responding to sudden machine failure is difficult. Moreover, measurement devices for periodic inspection are designed with a priority on portability and easy installation, limiting the capability. Furthermore, the judgment of a machine fault highly relies on knowhow and the experience of maintenance staff.

In contrast, facility maintenance based on condition monitoring uses condition monitoring devices while taking full advantage of IoT. It continuously evaluates the condition of the facility and predicts the machine fault before it happens. It is Condition Based Maintenance (CBM) that maintains the facilities more reasonably. The monitoring devices installed on the facilities continuously transmit the measurement data to the server through the network. The server analyzes various evaluation values, detects the changes in time sequence, and reports the result to the maintenance staff. That enables the maintenance staff to make a timely and appropriate maintenance plan based on the result. Extension of the period between maintenance along with adequate arrangement of spare parts reduce cost.

3. Condition Monitoring of Wind Turbines
Due to a recent increase of the momentum of renewable energy, more wind turbines are expected to be installed over the medium and long term. Further reduction of power generation cost requires an improvement of the capacity factor (facility availability). Figure 1 shows the failure frequency for subcomponents part of a wind turbine and the associated repair downtime (period of non-operation & maintenance period). The downtime of the rotor parts near the drive train of the item on the bottom row exceeds 20 days on average. Some repairs can be done inside the nacelle, but in case the failed part should be moved out of the nacelle, heavy machinery such as a crane must be arranged. In Japan, where more than 70% of the land area is mountainous, the land available for installation is limited. Consequently, it is expected that offshore wind turbines will increase but become more difficult to access. In such a circumstance, operation optimization with condition monitoring would provide a great advantage.

3.1 Objective of condition monitoring
When a large component such as a gearbox needs to be replaced, in addition to the parts for replacement, heavy machinery such as a crane has to be arranged for the purpose of lifting the component to the nacelle and taking down the old part. With a weak wind duration, summer in Japan is suitable for maintenance work. The lack of power generation during maintenance work in a weak wind duration makes for a small disadvantage for power generation. Requirements for condition monitoring are the early detection of a machine fault and estimation of the life time before the wind turbine plunges into a major failure. In general, wind turbines power generators are operated in a wind farm where there are multiple wind turbines. Early detection of a machine fault and life time estimation would enable an efficient maintenance plan, such as a crane, which can be arranged for maintenance work for multiple wind turbines.

![Fig. 1 Failure frequency and repair downtime]
3.2 Issues of condition monitoring

Figure 2 shows the structure of a standard wind turbine. The main object of condition monitoring is the drive train, which comprises a generator, and the main shaft bearing, which supports the main shaft connected to the gearbox and the blade. The main shaft of an MW class wind turbine rotates at 10–30 rpm by the wind. The gearbox amplifies the rotation speed by 80–100 times, driving the generator. Detecting a fault of the main shaft bearing is quite difficult because the SN ratio is extremely low. The signal level from the damage source is low due to a small vibration energy load by slowly rotation. Moreover, there is a variety of noise sources, such as the gearbox, the generator connected to it, the yaw control system rotating the nacelle, and the pitch control system adjusting the blade angle. The fault detection of the main shaft bearing was addressed in the NEDO project. Measuring real wind turbines clarified the issues and proposed its solution. The next chapter describes its content.

4. Damage Detection of the Main Shaft Bearing for Wind Turbines

As the first task in the fault detection of the main shaft bearing, a damage simulation test was carried out with the aim of investigating the relationship between the extent of the bearing damage and vibration. Then, vibration of a real wind turbine was measured, and vibration data up to the point of damage and replacement was obtained. On the basis of comparisons of these sets of data, some issues are described. Some solutions are proposed for them.

4.1 Damage simulation test

A damage simulation test was carried out with main shaft bearings for a 2 MW class wind turbine. As shown in Figures 3, bearings with four levels of artificial defects were prepared, ranging from extremely minor damage to serious damage prohibiting continued operation. The numbers in parentheses are the ratios of the damage area, the fraction of the damaged area to the bearing raceway surface as indication of the extent of the damage. The testing conditions set were the load equivalent to a real machine and three conditions of rotating speed.

Figure 4 shows the test result, with $d_{m,n}$ (roller pitch radius of the bearing) and $n_{m}$ (rotation speed) as the horizontal axis and the ratio of effective values of vibration acceleration (absolute value) to normal values (relative value) as the vertical axis. In tests with no vibration source in the environment, the vibration levels increased with higher rotation speeds and are further enhanced uniformly with higher damage levels.

4.2 Measurement in the real wind turbine

A measurement of vibration has been carried out on 4 wind turbines at a standard power output of 1 MW.

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Fig. 3 Artificial defect on rolling bearings

Fig. 4 Experimental results using artificial defected rolling bearings
in the same wind farm. Figure 5 shows the outline of the measurement. The measurement data was sampled simultaneously at 25 kHz with a monitoring system installed in the nacelle.

Measurements were carried out continuously from November 2016 to October 2017, during which period a failure was found in the main shaft bearing in one of the wind turbines, which was replaced in May 2017. As shown in Figure 6, a bearing with a damage area ratio of about 8% occurred in one place on the outer ring raceway surface and the vibration acceleration measured on the main shaft bearing, on which the bearing occurred, is shown in Figure 7. It shows the average and the standard deviation of RMS value in the selected three months (December 2016 to May 2017). Before replacement, April 2017, immediately after replacement and September 2017, immediately after exchange. As demonstrated in the damage simulation test, the vibration depends on the rotation speed. Therefore, only the data with a rotation speed of 25.4-25.8 rpm was the control rotation speed of this wind turbine was taken. The average value actually moved up and down before and after the damage replacement. However, the vibration represented by the standard deviation is too large. The comparison with the test results are shown in Figure 4 (real wind turbine, $a = 0.34$ m/s²). The absolute value of April 2017 shows a similar damage level, however, relative value (ratio of values before the replacement to those after) are within the range of minor damage.

Figure 8 shows the time waveform of the main shaft bearing vibration during the damage simulation test (medium damage) and the real turbine measurement (immediately after the damage replacement). In the test result, an interval of impact vibration 0.51 second matches a specific bearing defect frequency from artificial defect. In contrast, the real wind turbine measurement result of a normal condition immediately after replacement is equivalent to the impact vibration of the test. Impact vibration of a much larger amplitude also occurred. Figure 9 is a schematic of the vibration transfer path around the main shaft bearing of a wind turbine. Blade's hub vibration driven by the wind is transmitted to the main shaft bearing through the main shaft. Similarly, generator vibration is transmitted to the main shaft bearing too. The structural vibration of the tower supporting the nacelle including the drive train is also transmitted. Therefore, the aim is to ensure an appropriate SN ratio for damage detection of the main shaft bearing by reducing the influence of these disturbance vibration.

4.3 Damage detection at the real wind turbine

In this section, to obtain an appropriate SN ratio for damage detection of the main shaft bearing, the environmental vibration should be adequately processed as an external disturbance. Accordingly, each vibration signal from the surrounding structure shown in Figure 9 was analyzed. Here all the data used was the wind turbine without any damage detected on the main shaft bearing and from operation at the nominal rotation speed.

(1) Gearbox

Figure 10 shows a frequency analysis result of the vibration at the gearbox planetary part and the main shaft bearing, measured synchronously. The gearbox of this wind turbine has one planetary stage and two parallel stages. Table 1 shows the vibration characteristics such as gear mesh frequency measured by gearbox components. In the spectrum of the gearbox planetary part, gear mesh frequency of second parallel stage can be seen up to 4th harmonic frequency (5.9 kHz). On the other hand, at the main shaft bearing, up to the third harmonic (3.4 kHz) is visible. The spectrum of the main shaft bearing is lower than 3 kHz. However, the vibration level of medium and higher frequency are largely decrease.

(2) Blade / Hub

The high level impact vibration shown in Figure 8(b) can be detected inside and outside the nacelle by human ears. The source can be identified inside the hub, and the occurrence, frequency, and amplitude depend on each wind turbine. The cause was found to be frequency analysis results of the main shaft bearing vibration for a case in which impact vibration occurred significantly. The impact vibration occurred at an interval of about 0.3 seconds, and the main shaft rotation period is 0.01 seconds, to have an influence on the spectrum range from 1 kHz to 6 kHz.

(3) Tower / Nacelle

Figure 12 shows a frequency analysis result of the vibration at the nacelle floor and the main shaft bearing measured synchronously. Both show approximately similar result in the frequency range up to 10 kHz, where the structural vibration occurs. The peaks at 4-6 kHz is the
fundamental frequency of the characteristic vibration of the tower. This spectrum range covers the main shaft rotation frequency of about 0.33 Hz and the blade pass frequency of about 1 Hz = 3 x 0.33 Hz. However, these levels are low compared to the characteristic vibration of the tower including higher harmonics.

The vibration signal measured at the main shaft bearing is superimposed by these external disturbances and the main shaft bearing internal vibration. Based on these results, the data before and after the damage replacement is analyzed, and an appropriate damage detection method is proposed. Figure 13 shows the time wave form of the main shaft bearing vibration before and after the damage replacement. The impact vibration occurring before the replacement has an interval of about 0.2 s, which is different from the impact vibration of the blade/hub described above. In contrast, this impact vibration disappeared after the damage replacement.

The frequency analysis result of the time wave form in Figure 13 is shown in Figure 14. Before the replacement, vibration level in the frequency range from 2 kHz to 6 kHz is strongly excited, and the level of near 100 Hz is also high. The result of envelope analysis applying to the each excited frequency range is shown in Figure 15. Although it is more obvious for 2 kHz to 6 kHz before replacement, shown in figure 15 (b), the spectrum peak 6.0 Hz is visible up to the higher harmonics. These results indicate that the outer ring of the main shaft bearing is damaged. This peak frequency of 4.9 Hz is consistent with the interval of 0.2 s of the impact vibration confirmed by the time wave form mentioned above. Here, 50 Hz to 200 Hz is the frequency range of the influenced gearbox vibration, and 2 kHz to 6 kHz is that of the impact vibration from the blade/hub, hence the SN ratio at each frequency range is reduced. However, the influence of the gear vibration component of the second harmonic or higher is small. From these results, the frequency range of 50 Hz to 150 Hz is the most adequate for the bearing detection of this wind turbine main shaft bearing.

Figure 16 shows the result after having applied a band pass filter of the frequency range of 50 Hz to 150 Hz to the same data shown in Figure 7. For bearing damage detection, the sensitivity indicated by the difference in the vibration level can be improved and the variation can also be significantly reduced. A comparison with the result of the similar filtering on the damage simulation test data is shown in Figure 17. (a) In the absolute value evaluation, the damage level is not evaluated correctly. This means that because the vibration transfer path between the vibration source and the sensor position is different between the real wind turbine and the test rig, it is difficult to perform an evaluation with the absolute...
value. In contrast, (b) in the relative value evaluation, damage level is similar to the serious damage level (damage area ratio = 1.2%). The vibration transfer path involves nonlinearity such as the bearing gap and temperature change, etc. However, it regards that the taking of a ratio largely cancels out the difference in the vibration transfer paths and leads to this result. This evaluation methods mentioned above require the setting of filtering on each type of wind turbine, which presupposes the understanding of the wind turbine mechanism. In contrast, the trends in IoT, such as machine learning and big data analysis, are expected to contribute to the evaluation.

5. Postscript

This report introduces the technical research content regarding NSK projects on condition monitoring of industrial machinery, taking the wind power field as a subject. NSK continues to grapple with the development of condition monitoring, not only with wind power generators but also in a variety of fields covering NSK products. NSK proposes new technologies and develops new products on the basis of the market needs obtained through measurement data as well as through condition monitoring.

6. Acknowledgments

This article describes technical research content on condition monitoring of wind turbines developed through a research and development contract of the National Research and Development Agency, New Energy and Industrial Technology Development Organization (NEDO). We would like to express our sincere gratitude to NEDO, other research collaborators, and wind power companies for their cooperation in the measurement on real machines.
Technical Trend of Industrial Machinery Bearings

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Abstract
In recent years, industrial machine tool demand has remained fairly stable and it will continue to grow at a good rate in the future. In the global market, efforts to solve universal problems such as sustainable consumption, production, and climate change are being coordinated by all countries. The industrial machinery industry has greatly contributed to sustainable development by daily technological innovation. This paper introduces the latest technology of bearings used in these industrial machines such as Robot reducer, Servomotor, Mining machinery, and Steel-gear related machines.

1. Introduction
Over the past few years, the decrease in the working-age population and increases in labor costs have spurred rapid increases in demand for industrial robots. In addition, increases in the global population and the economic growth of developing countries are prompting the mining of iron ore, copper, and other minerals as well as natural gas.
On the other hand, the United Nations has implemented the Sustainable Development Goals (SDGs), including materials for consumption, production, and climate change for all countries, adopting a resolution to address these issues with the aim of realizing them. A variety of industrial machinery fields are deeply involved in the SDGs and are contributing greatly to a sustainable society through daily technological innovation. This article describes the state-of-the-art technology of the bearings used in these industrial machines.

2. Technology of a Reduction Gear for Robots and Servomotor Bearings
The main drive source of the robot was an electric servomotor with high controllability and easy handling. Moreover, during the motor output, high-speed rotation and low torque, a reducer is needed to convert the output to low-speed rotation and high torque. This article describes the technology of the bearings used in servomotors and reducers.

2.1 Technology for servomotor bearings
Servo-motor mounted servomotors are operated in harsh environments where they are subjected to significant variations in speed, and temperature, and between start-stop and shutdown. They are also operated in harsh environments with external forces and vibrations due to high-speed rotation at the start and with high temperature in the area. The required functions are a precise control of rotation, stopping, and positioning, which are achieved by brake and encoder attached to the motor shaft. Technological issues include brake slipage and feed error due to dust contamination on the surface of the brake plates and encoder plates.

NGK performed simulation experiments to confirm the relationship between the brake and encoder inside the bearing, and the contamination of the encoder. Figures 1-4 show the outline and the result of contamination. These results have confirmed the effectiveness of the technologies developed, such as low-friction grease and light contact DW seals, and earned a reputation for high reliability.
2.2 Technology of bearing for robot’s reduction gear

Since reduction gears for robots are used in arm joints, the requirements include compactness, lightweight, low backlash, high rigidity, and long life. Since the output shaft is exposed to heavy external weight and moment loads, NSK takes full advantage of its analysis technology to provide special bearings compatible with both high rigidity in a limited space and long life. Figure 5 shows a specific example. Here, the optimized internal design such as the number of balls, and contact angles and operation preload are set to achieve both high rigidity and long life.

Also, the input shaft and intermediate shaft are exposed to heavy weight loads, leading to the adoption of small needle bearings and tapered roller bearings with low volume and high load capacities.

Fig. 5 Design examples of robot reducer bearings

3. Technology of Bearings for Mining Machinery and Shale Gas Industry

This section describes the long lifespan technology of the bearings for mining machinery and the technology of bearings for thermal power generation by natural gas, with the lowest amount of CO₂ emission among fossil fuel thermal power generation.

3.1 Technology for bearings used in mining machinery

The pulleys for mining conveyors that have a total length of several kilometers or more use self-aligning roller bearings that can absorb shaft deflection with high load capacity. The bearing replacement work requires precise control of internal clearance, leading to the adoption of the seal-less type bearing. NSK developed a “high sealing and self-aligning roller bearing” (Photo 1, Figure 6), which adopts a unique sealing seal, enabling precise control of clearance during bearing installation with high sealing performance. It has a good reputation in the market. The design of this new bearing is optimized so that the width remains the same as the conventional bearing even after high performance seals installed. Furthermore, Hi-TF technology with long life makes the load capacity of the bearing similar or superior to conventional products. Consequently, this new bearing achieves long life even in a harsh environment with a high weight load and where there is a lot of dust.

Figure 7 shows the test operation result at a mining site of the conventional products and the new product. While the conventional product showed flaking after being operated for about one year, the new bearing showed no abnormalities such as flaking. The amount of contaminants in the grease was about 1/10 of the amount in the conventional product, proving high sealing performance.
8.2 Technology of bearing for liquefied gas pump

Liquefied gas pumps are specialized pumps (Figure 8) for accepting, transporting, and feeding a variety of liquefied gases to a tank or an onboard plant. Representative liquefied gases include liquefied natural gas (LNG, ~-162°C), liquefied petroleum gas (LPG, about -40°C), and liquid nitrogen (LN₂, ~-196°C). The impeller of this pump is supported by a bearing lubricated by liquefied gas. Rust inhibitors for bearings cannot be used due to the cryogenic environment. Therefore, stainless steel with high corrosion resistance is adopted for the bearing. The cage material is a low-temperature, highly self-lubricating fluorosilicon resin, which is fastened with special rivets (Figure 9).

In recent years, adoption of silicon nitride ceramic ball bearings has been increasing as a measure to prevent electrolytic corrosion due to ionization of the pump matrix. Since these balls have excellent performance against wear, they are expected to have longer lifespan and improved reliability. However, since the coefficient of linear expansion of this ceramic ball is extremely small compared to the stainless steel of the inner and outer rings, there is a problem that the radial internal clearance changes in the range from room temperature to extremely low temperature (~-196°C). As a countermeasure, we are promoting the development of the high-performance new ceramic ball bearing, spaceCR60™ (Photo 8) using a new ceramic material with a linear expansion coefficient (due to that of stainless steel in the inner and outer rings).
3.8 Technology of bearings for a shale gas mining drill head

Recently, the mining of oil and natural gas has become possible from the shale layer at around 2,000 m below the surface of the ground, resulting in a rapid increase in the mining output, mainly in North America. The drill motors for drilling a hole reaching the shale layer have a large load, with a structure where the internal bearing is lubricated by muddy water (the structure of a drill motor is shown in Figure 12). The main requirements for the bearing are the least amount of raceway wear possible even with muddy water lubrication and no fracture of raceway rings and rolling elements during operation. The specifications of the bearing satisfying the requirements above are 4 point contact ball bearings (multi-row ball, plane and outer rings made of carbonized steel, and balls made of 440C tool steel (ASTM A500)).

NSK has completed a field evaluation of the new bearings, adapting unique materials for the inner and outer rings. As a result, it was confirmed that there was no fracture in the bearing, and the wear characteristics were also equal to or better than the current carbonized material (Photo 1). NSK continues to collaborate with drill manufacturers with the goal of establishing the specifications of optimized bearings.

4. Postscript

This article describes the technology of the bearings used in industrial machinery. In recent years, "smart" technology has been introduced, which focuses on efficiency, energy saving, and waste reduction. This technology is being used to improve the performance of industrial machinery. "Smart" technology has also been adopted in the field of machinery, where it is being used to increase productivity and reduce costs. The development of "smart" technology has been driven by the need to reduce energy consumption and improve efficiency. This technology has been used in many industries, including the construction and mining industries. In conclusion, the development of "smart" technology is a key factor in the success of industrial machinery.
2. Technological Trend of Wind Turbines

Recently, in order to improve power generation efficiency and reduce the cost of power generation, there has been a shift to create bigger wind turbines and install them offshore. At present, the mass-produced offshore wind turbine of the largest power generation capability is produced by MHI Vestas, and it generates 8.0 MW. MHI Vestas has announced that they developed a successor with a capacity of 9.5 MW. Furthermore, GE announced in March 2018 that they will develop a 12 MW offshore wind turbine. The shift is creating bigger wind turbines and installing them offshore is picking up speed.

There are two types of wind turbines, one with a speed-up gear and the other without one (Figure 2). In the current top ten list (Table 1) of large capacity wind turbines, both types exist. Elimination of the speed-up gear would diminish the number of mechanical elements that may fail, thus improving reliability. However, the wind turbine would become larger and more complex, making it more expensive and heavier. The mass-produced MHI Vestas turbine (8.0 MW) and the new 9.5 MW model both have a speed-up gear, and it is thought that future offshore large wind turbines will utilize this gear as well.

3. Bearings for Wind Turbines

Figure 3 shows the equipment constituting the drivetrain of a general wind turbine with a speed-up gear, and the typical bearings used in the drivetrain. In the main shaft, the speed-up gear and generator of the drivetrain of a wind turbine, bearings of different types and sizes are used. One or two bearings with an outer diameter of 1−2 m are used in the main shaft, depending on the support type. Many bearings with an outer diameter of 0.2−0.3 m are used to support several gear shafts in the speed-up gear. The generator uses bearings with an outer diameter of 0.4−0.6 m to support the rotor shaft.

As wind turbines get bigger, market demand for larger bearings and bearings with high load capacity will increase. The next section describes bearings for the wind turbines that NSK developed in response to these demands.

Table 1 Ten of the biggest wind turbine

<table>
<thead>
<tr>
<th>Order</th>
<th>Type</th>
<th>Power Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MHI Vestas V154 / 8.0MW</td>
<td>Gear</td>
</tr>
<tr>
<td>2</td>
<td>Adwen AD-180 / 8.0MW</td>
<td>Gear</td>
</tr>
<tr>
<td>3</td>
<td>Siemens-Gamesa Renewable Energy SWT-8.0-154</td>
<td>Gearless</td>
</tr>
<tr>
<td>4</td>
<td>Enercon E-126 7.5MW</td>
<td>Gearless</td>
</tr>
<tr>
<td>5</td>
<td>Siemens 6.0 154 / 7.0 154</td>
<td>Gearless</td>
</tr>
<tr>
<td>6</td>
<td>Ming Yang SCD 6.0MW</td>
<td>Gear</td>
</tr>
<tr>
<td>7</td>
<td>Saionie 6.2M152</td>
<td>Gear</td>
</tr>
<tr>
<td>8</td>
<td>GE Halides 8MW</td>
<td>Gearless</td>
</tr>
<tr>
<td>9</td>
<td>Sinow 6.0 900</td>
<td>Gear</td>
</tr>
<tr>
<td>10</td>
<td>Dongfang-Hyundai Heavy Industries 5.6MW</td>
<td>Gear</td>
</tr>
</tbody>
</table>

3.1 Main shaft bearings

Since the bearings supporting the main shaft bear the large radial and axial loads transmitted from the wind-facing blades to the main shaft, they require high rigidity. One of the main shaft structures of typical wind turbines is a three-point-support type supported by a single bearing (Figure 2). This type uses spherical roller bearings for the main shaft bearing.

As wind turbines get bigger, the load on the bearings becomes larger. A big wind turbine supports the main shaft with two bearings (Figure 2). This type uses single-row or double-row tapered roller bearings, single-row cylindrical roller bearings, and spherical roller bearings.
The main shaft rotates at a very slow rotation speed of 8–15 rpm, so the lubrication condition inside the grease-lubricated bearing is poor. Moreover, in a spherical roller bearing, a specific differential slippage occurs, which often wears out and damages the bearing (Figure 4). NSK, considering that the coating of Diamond-Like Carbon (DLC) on the spherical roller bearing is effective against that wear, is carrying out the evaluation.

### 3.2 Bearings for speed-up gears

A speed-up gear is used to increase the extremely slow rotation speed of the main shaft to the high rotation speed of the generator. Many gears are used for a high-speed-up ratio. The gear shafts use 10–20 bearings for support. The main shaft of the 4 MW class rotates at around 11 rpm, while the 4-pole generator rotates at 1 500–1 800 rpm, requiring a speed-up ratio of over 150. On the other hand, since the blade edge speed is restricted due to the wind noise issue, the main shaft rotation speed must be lowered as the wind turbines become larger (blades become longer). For the case of speed up the low main shaft rotation speed to the rotation speed of a 4-pole generator, a speed-up ratio of over 150 is required. Therefore, a system adopts a generator having more than 4 poles and a speed-up gear of a low speed-up ratio (around 50) (Medium Speed Type) is also used.

As Figure 5 shows, 1 planetary + 2 helical speed-up gears are used for up to 2.5 MW, but for a higher speed-up ratio, 2 planetary + 1 helical type is used. Some medium speed types with a low main shaft rotation speed adopts 2 or 3 planetary gears$^5$.

As the size of a wind turbine becomes bigger, the input torque from the wind is increased, intensifying the load on the bearing. A planetary gear uses a bearing supporting the carrier shaft and a bearing supporting the planetary gear shaft. As the torque is increased, the drive shaft thickness, making the carrier bearing bigger and the bearing load capacity larger. However, as the shift to more compact and lighter-weight planetary gears continues, there will be an especially high demand for a planetary gear bearing with a high load capacity. Consequently, in more cases the outer ring is eliminated, the bearing bore of the planetary gear is made of the raceway surface of the outer ring and the bearing load capacity is made
Larger with a larger roller diameter (Figure 9). The speed-up gear bearing for a wind turbine often becomes damaged at an early stage due to a small grinding or white surface etching. This type of grinding is called white structure etching. The white structure etching can be reproduced in a rolling contact fatigue test with a high speed-charge specimen. Accordingly, the white structure etching of a speed-up gear bearing of a wind turbine is estimated to be also caused by hydrogen. The white structure etching is considered to occur through the four steps shown in Figure 4. Step 1: Due to addition of an oil lubricant and influence of slippage, vibration, and electricity, the lubricant is decomposed, generating hydrogen, and the generated hydrogen penetrates into the steel of the bearing. Step 2: Decomposed hydrogen impairs the formation of a white structure in the steel. Step 3: Creepage occurs along the boundary surface of the white structure. Step 4: Creepage propagates, leading to etching.

There is a measure to apply a black acids coating on the surface of the bearing. Hydrogen is generated through the decomposition of the lubricant due to a chemical reaction with a fresh metal surface formed by metal contact. Black acids coating suppresses the formation of a fresh metal surface, stopping the hydrogen generation. However, wear of the black acids coating leads to shortened bearing lifespan. Therefore, use in an environment with sufficient oil is desirable.

The research that has been carried out thus far has demonstrated that improvement of the steel alloy components suppresses the white structure etching, resulting in increased lifespan. Adequate addition of alloy elements is considered to delay the progress of microstructural change. Also, the creepage grinding treatment is effective for prolonging the lifespan limited by white structure etching. The compressive residual stress over the surface can delay creep propagation, and the increase in the residual stress amount can delay the concentration of hydrogen at the position of high shear stress.

Consequently, NSK has developed anti-white structure-grounding steel (AWS-TF™) through the optimization of an alloy composition and special heat treatment. AWS-TF™ achieved a lifespan, limited by white structure etching, of over seven times longer than standard steel (SU35) (Figure 9). Our unique steel for the measure against surface etching grinding, Super-TP™, is also effective against white structure etching and has a lifespan that is four times longer than that of standard steel (SU35).

8.8 Bearings for generators

Deep groove ball bearings and cylindrical roller bearings are generally used for generators. In a generator bearing, a voltage difference occurs between the inner and outer rings, often causing electrical erosion (burning metal by current passing across). As a countermeasure against this electrical erosion, although the periphery of the generator cannot be insulated, the standard bearing can be replaced with an insulated bearing of the same size as a countermeasure. An insulated bearing is either an insulated deep groove ball bearing with ceramic balls or an insulated bearing with the outer ring of stainless steel processed with ceramic thermal spraying (Figure 11).

Fig. 7 White structure etching and observed white structure in material cross section.

Fig. 8 Creepage mechanism of white structure etching.

Fig. 9 Comparison of service life between AWS-TF™ and other materials.

Fig. 10 Electrical erosion on the outer surface of a deep groove ball bearing.

Fig. 11 Ceramic-coated insulated bearing.
4. Quality with High Reliability

Wind turbines generate electricity onshore and offshore under harsh conditions where wind conditions are constantly changing. Power generation requires high performance in all parts used in the drivetrain and generator.

In particular, regarding the recent increase in size of offshore wind turbines, there is demand for reliability that is higher than that of land-based wind turbines due to the rise in repair costs of the main shaft, speed-up gear, and generator. In order to meet these requirements, NSK manages the quality history of bearings and improves quality stability. It also produces and delivers bearings that have undergone special quality control with a higher degree of assurance.

5. Design Assistance by Analysis

Increasing the size of wind turbines requires bearings with a high load capacity. In addition, since the cost increases, including the construction cost, the weight of the speed-up gear is kept low and the rigidity is also lowered. Therefore, a bearing design that takes into account deformation of the entire speed-up gear is in demand. To increase the bearing's load capacity, FEM analysis is used to optimize the cage shape (Figure 13).

FEM analysis is carried out for the entire speed-up gear, including the housing and planetary carrier, as a means of investigating the influence of speed-up gear deformation. In addition, this type of analysis is used to estimate the load of each roller inside the bearing, estimate the lifetime, and examine the bearing specifications (Figure 13).

Looking ahead, analysis technology will play an increasingly important role, and NSK is working on the application and improvements in the efficiency of analysis technology.

6. Summary

Wind turbines shift from onshore installations to offshore installations, where wind conditions are better. In addition, offshore wind turbines are increasing in size in areas with medium and low wind conditions. Accordingly, market demand is growing for larger bearings that are capable of bearing high loads and bearing with high load capacity and high reliability. To address these needs, NSK will continue to develop bearings with high reliability and high load capacity while also contributing to advancements in the wind turbine industry and to the protection of the global environment.

References


The Technical Trend of Machine Tool Components

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Abstract
In recent years, machine tools have been under the condition of rapid change due to the increase of electric vehicle production, expansion of IoT/Industry 4.0 and rising labor cost due to decrease of engineering workforce. Under the circumstances, machine tool manufacturers have to achieve higher productivity and accuracy. Machine elements that contribute to performance increase of machine tools need to be adaptable to the needs and technologies of machine tool for greater sophistication.

In this article, we will explain trends of machine tool technologies in recent years and latest technologies of machine elements such as spindle, ball screw and linear guide based on the trends of IoT/Industry 4.0 for machine tool and machine tool exhibition.

1. Introduction

The conditions surrounding machine tool manufacturing have recently been changing rapidly. These include the electric vehicle production, expansion of IoT, and rising labor costs due to the global decrease of the working population. To respond to these changes, manufacturers of machine tools across the world are aiming for further improvement of productivity and precision, and they continue to develop machine tool technology to achieve that goal. The machine element parts contributing to performance improvement also need to adjust to the needs of sophistication of manufactures of machine tool and end users.

NSK has an extensive lineup of important machine element parts, including spindles, bearings for spindles, ball screws and their support bearings, and linear guides, which determine the performance of machine tools. NSK has been developing products that meet the changing needs of machine tools.

This article describes recent technological trends of machine tools and the state-of-the-art technology of NSK in response to them.

2. Trends of Machine Tool Technologies

2.1 Trend of IoT/Industry 4.0 in machine tools

One recent trend in manufacturing is Industry 4.0 with the background of expanding IoT. Industry 4.0 is a manufacturing revolution promoted by the German government under industry-academia-government collaboration, also called the fourth industrial revolution, and it aims for the mass-production of customized products (mass-customization) at a cost that is equivalent to mass-produced products of the same specification. This strategy is for the survival of the German manufacturing industry with high wages compared to those in Asian countries. Under these circumstances, machine tools are required to be more efficient.

Figure 1 shows the findings on the exhibition related to IoT/Industry 4.0 at the 28th Japan International Machine Tool Fair (JIMTOF) in 2016. Examination of exhibitions from 150 companies shows that 90% of the exhibitions are related to IoT. More than half of the exhibitions aimed to improve operation rates, such as operation monitoring and the visualization of the whole factory. The percentage of exhibitions dealing with condition monitoring systems (CMS), with a focus on failure prediction and diagnosis, was only about 17%.

In the future, it is expected that further development will be made in each company towards practical realization of CMS, which will boost the percentage of exhibitions related to CMS.

2.2 Technology trend of spindles

Figure 2 shows the findings of an independent examination performed by NSK for over 50 years since the 11th JIMTOF held in 1982 on the number of high speed spindles over 10,000 rpm exhibited at JIMTOF. This indicates that since the 20th JIMTOF held in 2000, the number of high speed spindles over 10,000 rpm on exhibition has increased at a high number.

Until then, the practical utilization of high-speed and high-performance spindles was largely limited due to the lack of high-speed bearing and high-speed spindle, and the implementation of the conical spindles was limited due to the constraint of heat generation and heat generation by the heat generated by the spindle. Accelerating the development of high-speed operation, spindle performance, and improved manufacturing efficiency.

In recent years, the technology for improving efficiency by increasing the cut depth, guided by a stability limit diagram from rigidity characteristics of the machine tools to avoid reproducible chatter vibration has been applied to practical use.

Also, progress in small-volume production of many various products has raised the issue of improving cost production efficiency. Streamlining the time-consuming final polishing process requires refining the quality of the finished surface by improving the precision of spindle rotation.

These efficiency-related trends are in accord with the demands from Industry 4.0 mentioned in the previous section.

In addition, in the production site, not only the improvement of the production efficiency but also care for the environment are in demand. Therefore, the needs regarding the spindle lubrication method are shifting from oil-air lubrication using a huge amount of energy-consuming compressed air to grease lubrication.

In light of these spindle technology trends, NSK has developed a single ball bearing while adopting the new SURSAVE™ cage and ultra-high speed high frequency spindle with grease lubrication, which will be explained in the next chapter.

Fig. 1 Findings of an exhibition related to IoT/Industry 4.0 in JIMTOF 2016

Fig. 2 Findings of the number of machine tools with a spindle speed of 10,000 rpm or more in JIMTOF
2.3 Technology trends of the feed system

2.3.1 Rapid traverse speed of the machining center

Figure 3 shows data from independent research performed by NSK in regard to the trend of JIMTOF exhibitions and the rate of ball screw-type machining centers. This result indicates an annual increase at the rate of 50-60 m/min, but leveling off at 60 m/min.

In contrast, Figure 4 shows data from independent research carried out by NSK in regard to the rapid traverse speed of ball screw-type machining centers exhibited in the European Exhibition of Machine Tools (EMO). EMO is one of the world’s four largest exhibitions of machine tools together with JIMTOF (Japan), CIMT (China), and JIMTOF (Japan). The research was centered on European manufacturers. The percentage of high velocity machines over 60 m/min exhibited at EMO 2017 was 14%, significantly exceeding the 5% of JIMTOF 2015.

With this in mind, the rapid progress of higher traverse speed, especially in Europe, is one aspect of the promotion of streamlining machine tools required by Industry 4.0, as mentioned in 2.1.

Japanese manufacturers limit the ball screw speed up to 20 m/min and set the rotation speed to 3,000 rpm, achieving a traverse speed of 60 m/min with a tendency to aim for both high precision and high efficiency. In contrast, European manufacturers seem to have achieved a speed exceeding 60 m/min by using high lead ball screws with a load of 30 mm at a rotation speed of 3,000 rpm. As a measure against degradation of positioning accuracy associated with high ball screw leads, they adopt fully closed loop control, directly detecting the machine position in the linear scale.

NSK has developed a high-speed, low-noise deflection-type ball screw, compatible with the German industrial standard (DIN) for the European market, where speed enhancement is more advanced, and gave a press release in 2017. The details are explained in the next chapter.

2.3.2 Guide-way type on the machining center

Figure 5 shows the result of independent research carried out by NSK in regard to the guide-way type on machining centers exhibited at JIMTOF. The rate of roller guide adoption is on the rise, reaching 60% in 2015. Behind this development, roller guides with a high load capacity and rigidity, the reliability of the machining center is recognized as an appealing aspect. This trend of adopting roller guides originated from Europe. Figure 6 shows the research result regarding the guide-way type on machining centers exhibited at EMO. In Europe, the roller guide is established in the standard specification, with its adoption rate reaching 87% in 2017. Moving forward, we will keep a close eye on the trends of the roller guide adoption rate in Japan to find out whether it will boost to a level similar to that in Europe.

NSK is working on performance improvement of roller guides in response to this shift to the roller-type guide-way, described in the next chapter.


NSK has been developing new products in response to the changes in the environment surrounding machine tools as described above. In the following, state-of-the-art technology of spindles and guide-ways will be introduced.

3.1 State-of-the-art technology of spindles

3.1.1 Angular ball bearing adopting the new SURSAVEugged

High quality appearance is in demand for the mold used in the injection molding of plastic products. Accordingly, the conventional standard was machining the cavity surface of a mold into the designated shape, followed by the final polishing of the surface. In recent years, the progress of control technology of NC machines and speeding up of spindles have enabled machining up to the final finishing process as much as possible, with the aim of improving the efficiency of mold manufacturing.

The issue here concerns the spindle rotation precision, particularly the lowering of non-repetitive run out (NRO). As Figure 7 shows, the cutting work as typified by end mills, unlike the grinding work with a whetstone, is an intermittent process. With end mills, processing is carried out by transferring a spindle while intermittently cutting the work with multiple blades with each rotation of the axis. At this time, the depth at which the blade cuts again after cutting the workpiece once and rotating must be as similar as the previous cut as possible. In case of spindle rotation precision, especially NRO, it is degraded and the blade does not come back to the same position after one axis rotation. Moreover, a slight difference in each cut depth occurs.

Repeated machining of the whole workpiece in this manner would create random roughness on the work surface, deteriorate the appearance quality, and require extra time for polishing.

Spindle rotation precision is roughly divided into repetitive run out (RRO), affected by rotational balance and component accuracy, and non-repetitive run out (NRO) mentioned previously. While RRO is largely determined by the setting of the spindle, NRO, which influences the machined surface quality, is mostly dictated by the rotation precision of the bearing.
3.1.3 Ultra-high speed high frequency spindle with grease lubrication

The lubrication methods of bearings for spindles of machine tools are mainly divided into all-air lubrication and grease lubrication. Table 1 shows the characteristics of both methods.

Spindles for grinding, where lighter weight loads than spindles for cutting, but are required to allow higher rotation speeds. Accordingly, they generally adopt small radius bearings rotated at a high speed with all-air lubrication.

With all-air lubrication, a nozzle is used to spray compressed air mixed with lubrication oil inside the bearing at high speed. As only a small amount of oil is needed, it is possible to lower the dynamic friction torque.

In addition, a large amount of compressed air delivers lubrication oil to the inside of the bearing without fail, making the bearing highly reliable. As a result, all-air lubrication has been used for a long time in high-speed machining tools and automobile part processing machines requiring reliability.

However, all-air lubrication consumes 30–60 [L/min] of compressed air for one row of bearings. For a spindle with 4–6 rows of bearings, the amount of compressed air consumption is 100 [L/min] or more.

At production sites with many machines, like automobile part processing lines, protection of this compressed air consumption is an important topic.

In addition, maintenance work such as periodic feeding of lubrication oil and filter replacement is needed. NSK, in response to these needs, has developed "Ultra high speed high frequency spindle with grease lubrication" for the grinding process (Photo 3).

Grease lubrication needs to maintain the lubrication condition only with the grease initially included in the bearing. Unlike all-air lubrication, grease lubrication has a finite lifespan, so physical deterioration by changing the bearing and chemical deterioration.

![Figure 7](image1.png)

Fig. 7: Mechanism in which the appearance quality of the processing surface decreases due to NRRO

For the new SURSAFE™, super engineering plastic developed by NSK was selected for the material. This material has characteristics superior to conventional materials in strength, elasticity, and dimensional stability, maintaining the design freedom and enabling the optimization of internal design. This has allowed for a decrease in cage deflection to a minimum and suppressing NRRO by about 60% compared to conventional products (Figure 8).

In addition, by not only enhancing the spindle rotation precision but also by eliminating unnecessary cage motion, the dynamic friction torque during high speed operation has been reduced by about 20% (Figure 9).

Adoption of this bearing would allow for a reduction in the overall operating time, which is considered to contribute to improvement of production efficiency.
of base oil by heat are unavoidable. In addition, increase of grinding dust for processing into the spindle would significantly lowers lubrication performance due to mixing of water into grease. In some cases, grease may flow out of the bearing. Improvement of reliability was a priority. Prevention of these problems required installation of an air purge by compressed air on the tool side of the spindle.

The optimised grease selection, improvement of grease inclusion method and optimization of internal design have enabled the ultra-high-speed high-frequency spindle to achieve a 20% increase in speed compared with conventional grease lubrication spindles. As for grease lubrication, it has achieved 79,000 rpm (250 x 10^8), which used to be the range of application of oil-air lubrication (Qw = m is a measure of bearing rotation speed, expressed by the product of rolling element pitch diameter d.e. and the speed of rotation n.).

In addition, to respond to the need of reducing the amount of compressed air used, a larger cooler has been installed on the tool side of the spindle (Figure 10). That has reduced the risk of grinding work ingestion with air purge. Adoption of this spindle would lower compressed air consumption in grinding process and contribute to mitigation of environmental loads.

3.2 State-of-the-art technology of element parts of the feed system

3.2.1 High speed low noise deflector-type ball screw

As mentioned in the previous chapter, feed systems of machine tools have made progress in speeding up with the goal of productivity improvement. To respond to this demand, NSK has been working on increasing the speed of ball screw. Especially, improvement of the parts for ball nut as well as the deflector has achieved the high-speed performance of the ball screw without sacrificing the noise performance. The deflector-type ball screw has been developed to meet the requirements of high-speed and low-noise. As for the high-speed low noise series, the NSK has developed a new deflector-type ball screw with high-stiffness in the industry.

Ball screw characteristics, such as high-speed, low-noise, and good smoothness, are greatly influenced by the ball nut. In order to improve these characteristics, it is important to reduce the ball nut directly by ball nut machining. Also, for high-speed low noise series, the unique design of the ball nut has been realized. Realization of smooth ball nut realization has improved the performance.

Development of the High Speed Low Noise Deflector-Type Ball Screw was based on this ball nut design. The technology for performing a three-dimensional analysis of the ball motion and the deflector was established, and an optimal deflector package was identified to be effective for a high-speed and low-noise series. In addition, modification of the fixture method of the deflector on the ball screw nut and the material of the deflector has realized the following advantages.
3.2.2 Roller guide with highly dustproof seals

As mentioned in the previous chapter, for roller guides with high load capacity and rigidity, the reliability of machine tools is the appeal, and adoption rates have reached 80% in Japan and 87% in Europe for machining centers. Under these circumstances, especially in recent years, diversification of machining objects and the popularization of high-pressure coolant enabling high-speed, high-efficiency processing of difficult-to-machine materials have boosted the number of cases in which machine element parts are used in environments where the complete prevention of ingress of chips and coolant is impossible. Ingress of foreign objects inside the bearings of roller guides would deteriorate the lubricating agent and cause failure of the roller recirculation, and, as a result, there is a risk of damage occurring within a short time.

With this in mind, NSK has developed a highly dustproof V1 seal and V1 bottom seal and achieved long operation life of roller guides in an environment surrounded by foreign objects, aiming at improvement of dustproof performance of the roller guide.

(1) Highly Dustproof V1 Seal (Side Seal)
Side seals are installed to make the bearing edge dustproof. In prolonged operation in a harsh environment, lip damage due to contact with foreign objects and lubricant removal due to foreign objects cause tears and erosion of the seal lips. The highly dustproof V1 seal, with optimized seal lip shapes and materials with high anti-erosion performance, has reduced the foreign object ingress to about half compared to conventional standard seals. Furthermore, the occurrence of damage such as tears is reduced even in a degraded lubricating condition, enabling sustainment of high dustproof performance for a long time (Figures 13 and 14).

Photo 5 Highly dustproof V1 seal

Fig. 13 Test results of the amount of foreign matter incursion for the V1 seal

(2) Highly Dustproof V1 Bottom Seal
In the automobile part processing machines, as shown in Figure 15, the structure of a roller guide used in an underside arrangement with fixed bearings and rail-guided movement of the main shaft is shown. This structure allows arrangement of x, y, and z axes in the back of the machine, enabling a system adaptable to a variety of production modes. However, as rails in the processing room are exposed, the dustproof performance against the coolant and cutting chip ingress from the bearing bottom is required more than ever. To meet such needs, by adoption of the lip shape and material similar to the highly dustproof V1 seal (side seal), the highly dustproof V1 bottom seal has been developed, with dramatically improved dustproof performance against foreign objects ingressing from the bearing bottom. By making a double seal by installing it on the outer side of the conventional bottom seal, coolant ingress has been suppressed to 1/10 of the conventional standard seal. In the same manner as the highly dustproof V1 seal (side seal), anti-erosion performance of the seal has been improved, and it is capable of maintaining high dustproof performance for a long time.

Fig. 14 Test results of wear resistance for the V1 seal

Photo 6 Highly dustproof V1 bottom seal
4. Postscript

In light of the trends expressed in the exhibition of machine tools, this article describes the technology trends of machine tools and the state of the art technology of spindle, ball screw, and linear guides, all essential parts of machine tools.

For those in next-generation manufacturing, such work is an essential foundation for realizing highly productive and efficient manufacturing. In this context, NSK will continue to develop high-performance, high-quality products capable of contributing to the progress of machine tools.

References


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Technical Trends of Railway Products

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Abstract

Train travel, and will remain one of the most important modes of transportation in the world, especially from the point of view of the trend toward a more stable and economical travel. Safety always comes first in the operation, and we have kept proceeding the train through our history. This article focuses on the technology trend of railway bearings for safety, ease of use, and traction, noting how they can realize reliability and contribute to safety operation. This article also includes technical information on relevant products of the source, condition monitoring systems, and access to safety compensation, which are gaining their positions especially in the higher speed train for more safety and comfortability. We are responsible for contributing to railway operations, from various points of view, with our technical solutions, now and in the future.

1. Introduction

Railroads are a very economical means of mass transportation that support people's daily lives. Railroads have a long history, which were pulled over the track by horses. In steam engine railways, the beginning of the 19th century, locomotives were pulled over the track. Steam locomotive railways were put to practical use at the beginning of the 18th century, first in Great Britain, and then in Europe and the U.S. In Japan, the first railroad started to operate in 1825 between Shinagawa and Takaido, 30 years behind Great Britain. The Japanese railroad technology developed into the present Shinkansen, and the commercial operation of the linear Shinkansen is nearing dream. Overseas, especially in developing countries, installing the infrastructure for railway and high-speed railroads is in progress. This is an effective countermeasure against chronic traffic jams due to the increasing usage of population concentration in metropolitan areas and environmental problems. This article describes the technology trend of bearings supporting railroad transportation and related technology development in NSK.

2. Technology Trends

2.1 Railroad Vehicles

Since the advent of the zero series Shinkansen, railroad vehicles are becoming faster. In recent years, China has made rapid progress in high-speed railway technology and already operates railroad vehicles with a maximum speed of 380 km/h. Great Britain has plans to implement vehicles capable of reaching a speed of 400 km/h. On the other hand, in Europe and Asia, many countries have introduced high-speed trains, which make up the skeleton of the transportation system. In addition, standardization of various specifications has been progressing overseas. Particularly in Europe, in view of mutual trade sharing and the aim to expand the European specifications all over the world, the movement of further standardization is evident.
2.2 Bearings for railroad vehicles

Bearings being used around the axle are shown in Figure 1. Bearings are classified into three types: axle bearing, gear unit bearing, and traction motor bearing. Therefore, there is growing demand for higher bearing reliability. NSK is responding to this by optimizing internal specifications, adopting high cleanliness steel, and applying a non-destructive inspection of materials.

2.2.1 Bearings for axle

Bearings for axle are important because they directly support the vehicle. Damaged bearings could have a serious impact on the axle operation of the vehicle. Moreover, in the event of a failure, the reverse bearing does not work, leading to reduced performance and efficiency. NSK has developed various types of bearings to meet these requirements. These bearings are categorized in terms of quality categories. According to the evaluation results, the bearings are used in the bogie and actual vehicle in EN 12063.

In addition, from the viewpoint of grease leakage and foreign object ingress from outside, a grease-packed bearing must be sealed. Seals are classified typically into two types: contact type and labyrinth type. Both of these seal cases are fitted to the bearing outer ring. The seal lip contacts with rotating parts for contact type seal and keeps optimal clearance for the labyrinth type seal. The sealing method and material are selected in consideration of the sliding surface speed and environmental conditions. On the other hand, for oil lubrication adopted for the Shinkansen, while the countermeasures against oil leakage from the axle box are important, it is easy to monitor the bearing conditions by oil level, buse, and metallic debris, which is collected on the magnetic plug. Oil lubrication is considered to be a stable way to lubricate the bearing. Extension of the period between maintenance is in strong demand by the market from the LCC viewpoint. Especially to respond to the need of no disassembly of the bearing over a long period, suppression of grease degradation is the key. Adoption of plastic cages instead of the conventional steel press cages is one countermeasure. In addition, the bearing monitoring system, described later, is now expected to be a new method of extending the maintenance period, as shown at InnoTrans 2018.

In Europe, in accordance with the “Mandate on Mutual Operation of European High-Speed Rail Network,” the standard on the axle bearing for railroad vehicles was established as EN 12085, EN 12081, and EN 12082 (Table 1). These standards have standardized the bearing specifications, grease packed and evaluation methods of performance and durability. This enables the axle bearing to be used in the international trains, especially in Europe, keeping a certain level of quality performance. Moreover, the standard for RAMS (Reliability, Availability, Maintainability, and Safety) has also been established. To meet the requirements for globalization, NSK is also developing products based on the standards mentioned above.

### Table 1 EN standards for railway bearings

<table>
<thead>
<tr>
<th>Standard</th>
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<tbody>
<tr>
<td>EN 12060</td>
<td>Roller bearing Basic specifications of the axle bearing: Specifying the material purity, hardness, marking, and test level, also specifying the ultrasonic probing method, magnetic powder test method, eddy current flow detection method, and strength test method of the plastic cage.</td>
</tr>
<tr>
<td>EN 12061</td>
<td>Lubrication grease Grease qualities specifications: Grease types are categorized according to the speed up of a vehicle to a maximum speed of 200 km/h. Evaluation will be made by various tests on the grease itself as well as tests on the bogie and actual vehicle by EN 12082.</td>
</tr>
<tr>
<td>EN 12062</td>
<td>Endurance test Specifications of the endurance test method of the grease-including bearing: Includes both tests on the bogie and on the actual vehicle. Specified are test conditions such as the simultaneous test evaluation of the two bearings in the test on the bogie. The judgment is evaluated by the bearing temperature during the test and the abnormalities of the bearing and grease after the test.</td>
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Almost all the axle bearings are lubricated by grease packed inside the bearing (Photo 1). For grease lubrication, it is important to know the grease behavior inside the bearing especially at high speed operation. In high speed rotation, grease is easily sputtered out to the seal case side by centrifugal force until it is finally settled at stable positions. So, it is important to control grease distribution inside the bearing by paying extreme care to the initial grease distribution and each grease amount.

In addition, from the viewpoint of grease leakage and foreign object ingress from outside, a grease-packed bearing must be sealed. Seals are classified typically into two types: contact type and labyrinth type. Both of these seal cases are fitted to the bearing outer ring. The seal lip contacts with rotating parts for contact type seal and keeps optimal clearance for the labyrinth type seal. The sealing method and material are selected in consideration of the sliding surface speed and environmental conditions. On the other hand, for oil lubrication adopted for the Shinkansen, while the countermeasures against oil leakage from the axle box are important, it is easy to monitor the bearing conditions by oil level, buse, and metallic debris, which is collected on the magnetic plug. Oil lubrication is considered to be a stable way to lubricate the bearing. Extension of the period between maintenance is in strong demand by the market from the LCC viewpoint. Especially to respond to the need of no disassembly of the bearing over a long period, suppression of grease degradation is the key. Adoption of plastic cages instead of the conventional steel press cages is one countermeasure. In addition, the bearing monitoring system, described later, is now expected to be a new method of extending the maintenance period, as shown at InnoTrans 2018.

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The gear box, which transmits the driving force from traction motor to axle, is equipped with bearings on a pinion shaft and large gear axle. These bearing types are mostly tapered roller bearings in Japan. The possible concerns about bearing failure could be fatigue failure and wear of the cage due to engaged vibration. In response to these issues, NSK has adopted a reinforced cage. The bearing on the pinion shaft is in a severe condition due to high speed rotation and vibration from coupling which is connected with traction motor. Because of this, NSK applied the surface treatment of soft nitriding to the cage if necessary.

On the other hand, for high speed vehicles overseas (especially in Europe), pinion shafts adopting cylindrical roller and ball bearings are typically used. It is necessary to adjust axial clearance in case of tapered roller bearings on installation of the bearings. However, ball bearings of that type can fix the clearance on their own, resulting in eliminating the need for this clearance adjustment. However, the increased number of bearing which leads to gain weight and total bearing width can be disadvantageous. Furthermore, in recent years, driving mechanisms are being developed in Japan with the use of double helical gears for Shinkansen trains. This type of gear reduces the axial load to the bearings, allowing for the adoption of cylindrical roller bearings. Nevertheless, it requires optimization of the specifications of the roller end and rib face on which positive sliding contact can occur.
3. Efforts for Related Technology

3.1 Sensing of bearings and bearing condition monitoring

To contribute to further safety and improvement of reliability for railroad vehicles and to transition from time-based to condition-based maintenance intervals, development of various sensors and a bearing damage prediction diagnosis system for early detection of bearing damage is underway.

The axle sensors (Photos 3 and 4) developed in 2004 were applied to the M250 series limited express container vehicle “Super Rail Cargo” (maximum speed 120 km/h). Japan Freight Railway Company started the operation of this series on March 13, 2004, and has been using it for more than 15 years. This sensor has a multi-sensor structure, with multiple sensing functions in a single sensor. A single sensor can contain internal sensors for temperature and vibration, or temperature and rotation velocity. There are several types of combinations. In addition, in 2012, axle box (Photo 5) containing a rotation speed sensor were developed and adopted in the 501 series and 502 series trains of West Japan Railway Company.

In recent years, progress has been made not only in regard to the development of the various sensors mentioned above but also for the development of a bearing damage prediction diagnosis system for the early detection of bearing damage with full utilization of information from the sensors. The feature of this diagnosis system is its ability to detect early symptoms of bearing damage. Information regarding bearing damage gained over a long time as a bearing manufacturer is indispensable for the construction of the diagnosis logic.

In the future, and in accordance with the various activities utilizing IoT in the railroad industry, we will contribute to the improvement of safety and reliability for vehicle operations through the continued development of products with integrated sensing technology and diagnosis technology.

3.2 Improvement of vehicle comfortability

3.2.1 Installation of active suspension

Railroad vehicles are expected to meet the technological demands for safety and reliability and, in the case of luxury trains, are expected to provide high comfort. In particular, suppression of vehicle vibration has gained prominent attention as an issue for assuring comfortability. Vehicle vibration stems from a variety of causes, including rail waviness, gradient changes, and vehicle curves transmitted indirectly from the bogie to the vehicle body, and the surrounding air pressure directly shaking the vehicle body from side to side. To suppress these vehicle body vibrations, passive suspensions, as shown in Figure 2, such as axle springs, bolster springs, and lateral moving dampers, are installed on railroad vehicles.

To further improve comfortability, installation of active suspension is in progress, enabling active control of car body vibration. Active suspensions are broadly classified into semi-active suspension and full active suspension. Semi-active suspension controls the damping force of dampers, and full active suspension actively eliminates the car body vibration through the use of pneumatic, hydraulic, and electric actuators through generating force in the opposite direction of the vibration force.
4. Future Technology Tasks

The products introduced herein are important parts supporting the safety, reliability, and comfort of railroad vehicles. Further improvement of their performance and reliability is our ongoing task. In addition, from an economical viewpoint, improvement of maintainability and reduction of maintenance (ultimately maintenance-free) are growing demands. For that task, development of material technology of each part, including heat treatment, residual life diagnosis technology, and new technology on conditioning monitoring, introduced in this article, is of growing importance. However, just fulfilling the demand for high-end technology will not satisfy the market needs, which are expected to be even more demanding in the future. Taking full advantage of the present technology supported by long-standing achievement, the development of more precise and accurate analysis/simulation technology and the continued provision of high performance and high system reliability are our ongoing tasks as a supplier.

5. Postscript

NSK products introduced in this article are installed on railroad vehicles used by many people as a means of transportation in everyday life, playing a significant role for many people. Even a minor malfunction could have a major impact on the lives of the general public. Being fully aware of our huge responsibility, we will continue contributing to the progress of railroad vehicles in the future.

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ISO 13482 certificated and practical application of Guidance Robot LIGHTBOT
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New Field Products Development Center, Technology Development Department 1
Yusuke Fukushima
New Field Products Development Center, Technology Development Department 2

Abstract
We have developed a robot that guides visually impaired and elderly people to their destination at hospital. In this report, we introduce practical application and the approach of social implementation of this robot. Practical application is our ultimate goal. In order for robots to be accepted by society, we acquired the safety standard ISO 13482 for personal care robots. We also implemented a mechanism to disseminate sales forms, insurance, maintenance, subsidies, etc. The robot was introduced to Kanagawa Rehabilitation Center.

1. Introduction
In light of the low birthrate, aging population, and dwindling working population, a variety of approaches are ongoing in regard to personal care robots. Particularly, the number of visually impaired people who require support by seeing-eye dogs and helpers is estimated to be 316 thousand21 in Japan and 252 million5 around the world. Visually impaired people state the following as the most serious problems they face when they are in public: crowds and traffic are scary is an inconvenience. Other problems include public places are hard to use and building facilities are inadequate, highlighting complaints about facility inconvenience22. In addition, in wide spaces such as homes without any characteristic objects, it is especially difficult to find the way to a particular destination23. We have heard similar opinions in our independent interviews with those affected by vision loss. There is strong demand for assistance guiding visually impaired people inside big facilities (hospitals, public places, administrative institutions, etc.). We have therefore set a target to realize transportation assistance robots that are mainly capable of guiding inside a building. Within Japan, research on transportation assistance robots for visually impaired people, including obstacle avoidance and point-to-point motion, is underway. Current research includes MELDIO24 by the Tsukuba team and the walking guide robot25 by the Mori team. In other countries, assistance equipment such as The GuideCane26 of the Ulrich team, a walking stick with wheels using transportation robot technology, and the indoor navigation equipment27 of the Kulkarni team are being developed. However, they are still at the research stage and have not yet been put to practical use in a facility. On the other hand, there have been many practical applications and implementations of many autonomous mobile robots in recent years. These include Amazon Robotics and butler robots, for example, robots for delivery in the warehouse, robots for delivery outside the warehouse, and security robots. However, robots with a human interface and ability to move to a destination with a human have not been realized yet. We have been working on the development of guidance robots capable of guiding visually impaired people to destinations without them getting lost inside a hospital (even a big hospital), other public places, and administrative buildings. First, we have developed a robot with an emphasis on intuitive operation that moves smoothly in response to human input and avoids obstacles on the way28. Next, we installed map information along with self-localization and path generating functions on the robot. Then we developed a robot for guiding a user, carried out demonstration experiments and long-term monitoring tests, and made repetitive improvements in response to advice29-32. In addition, responding to demand from hospital operators, we have developed a robot with an intended user base expanded to include sighted people, specifically elderly people. Demonstration experiments have proven that there has been no reduction in its ability to be effectively used by visually impaired people. Those affected by vision impairment have made passionate requests for its early realization33-34.

In this manuscript, on the basis of experience developed through the development and demonstration experiments made as far, we discuss the results of our work on the condition of realization and social implementation, acquisition of safety certificate ISO 13482, and the framework for social implementation.

2. Approach for Realization and Social Implementation
Realization and social implementation of personal care robots will be beneficial for both users and managers as well as expanding the safety standard of third parties. For that purpose, we think that the following three conditions need to be satisfied.
1. (1) assurance of safety for social acceptace
(2) high cost efficiency
(3) scheme for promotion including sales methods, insurance, maintenance, and subsidies

This section describes the outline of (1) and (2). Section 3 explains the acquisition of safety certificate ISO 13482, and section 4 explains details of the scheme construction.

2.1. Safety standard
In response to a comment from a hospital operator requesting safety certification from a third party, we obtained the only international standard on the safety of personal care robots, ISO 13482, issued in February 2014. That marked the 11th acquisition in Japan35, following Boepepe of Panasonic and HAL of Cyberdyne. In addition, it is the first acquisition for a robot with an intuitive interface, moving together with the user.

2.2. Cost efficiency
Cost efficiency is, in other words, the operating ratio. From interviews with hospital operators, it was estimated that a guiding robot specialized for visually impaired people would need about once or twice a month in a big hospital. It was pointed out that if a robot is specialized for visually impaired people, only the cost efficiency would be low. On the other hand, it is common for even sighted people to get lost in a big hospital. In response to the comment that a robot guiding elderly people also would improve patient satisfaction, the target users have been expanded based on the fact that people who are unfamiliar with the layout in the hospital, in particular elderly people. The numbers of new patients per day estimated on the basis of information made available on the Internet by hospitals are about 152 at Tokyo Metropolitan Tama General Medical Center (as of 2016)36, about 202 at Juntendo University Medical Department Urayasu Hospital (as of 2016)3, about 320 at Jichi Medical School Hospital (as of 2014)38, about 382 at the Hospital of the University of Occupational and Environmental Health (as of 2014)39, and about 111 at Yokohama Municipal Citizen’s Hospital (as of 2016)40. There is an average range of about 100–200 new patients per day. With an assumption of a guiding time of 3 minutes per patient, it would take 8–10 hours to guide every new patient, indicating that a transportation assistance robot capable of guiding patients would alleviate the workload of receptionists, providing a big benefit to the hospital.

3. Acquisition of ISO 13482
3.1. Risk assessment
ISO 13482 was issued in February 2014 as the only international standard on the safety of personal care robots. It is a safety standard on the basis of risk assessment (RA) (Figure 1)41. Through RA, hazard sources and hazardous events are identified and then the risks are analyzed, and processes that minimize the risk to an acceptable level are evaluated. As there is no test method clearly defined or standard values such as conventional standards for industrial products, we have independently optimized evaluation standards on the basis of the design philosophy of the manufacturer and concepts of the equipment developed in addition to RA. To obtain ISO 13482, it is recommended to cooperate with the certification organization from the design phase. We proceeded with authentication with confirmation of the Certification System Development Promotion Office, Japan Quality Assurance Organization (JQA).

Figure 2 shows the authentication process. In Phase 1, the development flow of a specification declaration and design, as well as the design control system, are audited. In Phase 2, the systems of evaluation, validation, production, and production control are audited.

RA was carried out on the devices42 that had already been developed for demonstration experiments, and design changes were made where necessary. The scheme43 developed by the National Institute of Occupational Safety and Health, in a project with the New Energy and Industrial Technology Development Organization (NEDO) Incorporated Administrative Agency, was adopted as the RA sheet. Visually impaired people, who do not have any difficulty in walking by themselves, and elderly people were present as the users, and a handheld equipped accessible坡 was used in the environment.

Hazard sources were identified in accordance with ISO 13482 Appendix A. With additional hazard sources identified on the basis of hazardous events identified through our demonstration experiments in the past, we have identified and performed risk assessment on a total of 102 hazard sources. Table 1 shows an excerpt of the RA sheet.

For hazard sources with high scores as the result of the initial risk assessment, risk mitigation measures were carried out on each of them. Falling down on a step was the hazardous event with the highest risk score, which was reduced by careful operation and reinforcement of the safety device.
Fig. 1 Overview of the ISO 13482 safety requirements (source: JQA document)

Fig. 2 Process of ISO 13482 certification (source: JQA document)

Table 1 EN standards for railway bearings

(a) Risk matrix

<table>
<thead>
<tr>
<th>Severity of damage</th>
<th>Damage occurrence (probability)</th>
<th>Frequency of exposure/time</th>
<th>Hazardous event occurrence probability: P</th>
<th>Hazard avoidance/mitigation probability: A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serious injury (long-term medical treatment)</td>
<td>4 12 19 20 24 28 32 39 40 44</td>
<td>Continuous/ steady</td>
<td>4 Very probable</td>
<td>4</td>
</tr>
<tr>
<td>Medical treatment (short-term medical treatment)</td>
<td>3 9 12 15 18 21 24 27 30 33</td>
<td>Frequent/ long time</td>
<td>3 Highly possible</td>
<td>3 Impossible</td>
</tr>
<tr>
<td>Recovery by first aid treatment</td>
<td>2 6 8 10 12 14 16 18 20 22</td>
<td>Sometimes/ short time</td>
<td>2 Possible</td>
<td>2 Possible</td>
</tr>
<tr>
<td>No injury/temporary pain</td>
<td>1 3 4 5 6 7 8 9 10 11</td>
<td>Rare/ instantaneous</td>
<td>1 Rare</td>
<td>1 Easy</td>
</tr>
</tbody>
</table>

(b) Initial risk assessment

<table>
<thead>
<tr>
<th>Hazard source category</th>
<th>Hazard source</th>
<th>Hazardous event (hazardous situation)</th>
<th>Risk matrix</th>
<th>Engineering method by the manufacturer</th>
<th>Risk mark</th>
<th>Risk mark</th>
<th>Appropriate item number of the requirement summary sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical shock due to an error of the position confirmation or navigation</td>
<td>Electric shock, burn</td>
<td>Due to many navigation errors, the user mistakenly enters into a hazardous area (descending stairs, and the car and the hatch)</td>
<td>24</td>
<td>Avoid any such descending stairs as much as possible. A warning on the ceiling warns the descending stairs to prevent the user from falling. No special provisions to prevent and perform a step</td>
<td>4 9 6 1 2 2 20</td>
<td>19</td>
<td>Appropriate item number of the requirement summary sheet</td>
</tr>
<tr>
<td>Hazard source due to an error of the position confirmation or navigation</td>
<td>Electric shock, burn</td>
<td>Due to many navigation errors, the user mistakenly enters into a hazardous area (descending stairs, and the car and the hatch)</td>
<td>24</td>
<td>Avoid any such descending stairs as much as possible. A warning on the ceiling warns the descending stairs to prevent the user from falling. No special provisions to prevent and perform a step</td>
<td>4 9 6 1 2 2 20</td>
<td>19</td>
<td>Appropriate item number of the requirement summary sheet</td>
</tr>
<tr>
<td>Hazard source due to an error of the position confirmation or navigation</td>
<td>Robot falls down the descending stairs and collides with people around the bottom of the stairs</td>
<td>Robot falls down the descending stairs and collides with people around the bottom of the stairs</td>
<td>40</td>
<td>Take measures 01-1</td>
<td>2 3 4 1 1 2 12</td>
<td>19</td>
<td>Appropriate item number of the requirement summary sheet</td>
</tr>
<tr>
<td>Hazard source due to an error of the position confirmation or navigation</td>
<td>Loss of control of the robot</td>
<td>Because the user is bigger than the robot, the path of the robot and the user are different. The user collides with an obstacle</td>
<td>45</td>
<td>Make the grip surface safe for a left hand grip</td>
<td>2 3 6 2 1 3 12</td>
<td>19</td>
<td>Appropriate item number of the requirement summary sheet</td>
</tr>
</tbody>
</table>
3.2. Design

Detailed specifications were determined in consideration of the specifications defined by required capabilities, feedback from IA, and design validation. Table 2 shows the representative specification.

As the intended user base is visually-impaired people and elderly people, the average height of Japanese elderly people[10], easy-to-read text size[10], and walking speed[11] were considered for elderly people, and operation was made possible by merely touching the remote controller for visually-impaired people. In addition, for use inside a hospital, it is necessary to satisfy Class B emission of CISPR 11 regarding EMC, which is more stringent than specifications for general industrial machinery.

Design of each part continued to satisfy the users in terms of the detailed specifications that were selected. Figures 3, 4, and 5 show the system block diagram, assembly drawing, and overview of the robot, respectively.

Here the main safety equipment of the robot is shown. As a policy, the following safety equipment does not involve software.

- Items associated with prevention of falling down
  To prevent falling down, the floor in front, right, and left (distance to the floor) shall be detected. Ranging sensors are selected; one sensor is installed on the right and left sides. The data on the distance to the floor detected as an analog signal, and if the signal is determined to be higher than a certain threshold by a comparator circuit, it is digitally displayed. The threshold can be adjusted with a variable resistor in accordance with the usage environment of the robot. The digital output from the sensor is fed into the motor driver. If an floor is judged to exist, the motor driver is stopped and simultaneously the brake is applied on the drive shaft.

![Table 2 Main specifications](image)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer size</td>
<td>D 500 × W 300 × H 940 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>25 kg</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>2 km/h (inside the restricted area: 1 km/h)</td>
</tr>
<tr>
<td>Climbable slope</td>
<td>5°</td>
</tr>
<tr>
<td>Loading capacity</td>
<td>5 kg</td>
</tr>
<tr>
<td>Driving source</td>
<td>Li-ion battery (22.2 V, 450 Wh)</td>
</tr>
<tr>
<td>Interface</td>
<td>Setting of destination: touch panel, remote controller, Displacement: grip (force sensor)</td>
</tr>
<tr>
<td>EMC (emission)</td>
<td>CISPR11 Class II</td>
</tr>
<tr>
<td>Usage temperature/humidity</td>
<td>8–30°C/40–70%</td>
</tr>
</tbody>
</table>

![Fig. 4 Assembly drawing of a robot](image)

![Fig. 3 System block diagram](image)

![Fig. 5 Overview of a robot](image)
3.3. Validation

To confirm that the design specifications are met, validation has been carried out. The contents and validation results are shown for the representative validation test.

3.2.1 EMC

At the NVIAF certification test site, tests were carried out on each test item on emission and immunity, showing that the applied standards were satisfied, as shown in Table S.

Table 5: EMC test results

<table>
<thead>
<tr>
<th>Emission test</th>
<th>Applied standard</th>
<th>Standard value</th>
<th>Frequency (kHz)</th>
<th>Measurement value</th>
<th>Margin</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power source port condition interference immunity test</td>
<td>GSPAR Prot 11</td>
<td>0.001 dBu</td>
<td>1.024 MHz</td>
<td>0.002 dBu</td>
<td>0.001</td>
<td>Applicable</td>
</tr>
<tr>
<td>Communication port condition interference immunity test</td>
<td>GSPAR Prot 11</td>
<td>0.001 dBu</td>
<td>1.024 MHz</td>
<td>0.002 dBu</td>
<td>0.001</td>
<td>Applicable</td>
</tr>
<tr>
<td>Interference wave electromagnetic field test</td>
<td>GSPAR Prot 11</td>
<td>0.001 dBu</td>
<td>1.024 MHz</td>
<td>0.002 dBu</td>
<td>0.001</td>
<td>Applicable</td>
</tr>
</tbody>
</table>

Table 4: Parameter of the running stability test

<table>
<thead>
<tr>
<th>Test</th>
<th>Applied standard</th>
<th>Wheel radius (angular velocity radii)</th>
<th>Test angular velocity radii</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(mm)</td>
<td>(rad/s)</td>
</tr>
<tr>
<td>1a</td>
<td>5.0</td>
<td>5.0</td>
<td>0</td>
</tr>
<tr>
<td>1b</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>2a</td>
<td>5.0</td>
<td>5.0</td>
<td>0</td>
</tr>
<tr>
<td>2b</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>3a</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>3b</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

In all the tests, the running road surface was paved with P as the same as the hospital floor and wood, and the running direction and speed were measured. As a result, it was confirmed that there were no problems in terms of running stability.
To simulate the operational situation of the robot, repeated tests were carried out with test cycles, command speeds, and wheel loads, shown in Table 8. The test torque provided the difference between the torque for the robot to run on the ground and the torque for the robot on the test bed. During the test period of three years (accumulated usage time of 1,016 hours), replacement of service parts should be needed only once. In other words, the judgment condition was the capability of running for more than 607 hours.

The result was a continuous running for about 688 hours, satisfying the judgment condition. The cause of the stop was erosion of the rubber of the driving wheel, the powder of which accumulated on all the parts of the driving unit, and many of them were attached to the bearings, and the running resistance increased. The validation experiments performed in hospitals so far have not shown any powder generation or shedding of powder, leading us to consider that the present test result was due to conditions harsher than those simulated, similar to external tests in a shared space with continuous operation with no replacement. The result has shown that maintenance is required at least once every 1.5 years, which is within the acceptable limit.

Table 6: Cycle of the running endurance test

<table>
<thead>
<tr>
<th>Command speed</th>
<th>Load torque</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>0.02 Nm</td>
<td>0.45 Nm</td>
</tr>
<tr>
<td>Constant speed</td>
<td>0.02 Nm</td>
<td>0.45 Nm</td>
</tr>
<tr>
<td>Deceleration</td>
<td>0.02 Nm</td>
<td>0.45 Nm</td>
</tr>
<tr>
<td>Stop</td>
<td>0.02 Nm</td>
<td>0.45 Nm</td>
</tr>
</tbody>
</table>

Table 6: Parameters of the detecting obstacle test

<table>
<thead>
<tr>
<th>Test No</th>
<th>In煞 speed</th>
<th>Judging standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0 ± 0.15 km</td>
<td>Decrease at 80%, Accuracy at 80%</td>
</tr>
<tr>
<td>2</td>
<td>1.0 ± 0.15 km</td>
<td>Accuracy at 80%, Decrease at 80%</td>
</tr>
<tr>
<td>3</td>
<td>1.0 ± 0.15 km</td>
<td>Accuracy at 80%, Decrease at 80%</td>
</tr>
<tr>
<td>4</td>
<td>1.0 ± 0.15 km</td>
<td>60% Decrease, 80% Accuracy</td>
</tr>
</tbody>
</table>

Fig. 9: Example of the obstacle detecting test

2.5.4 Obstacle detection experiment

Referring to the robot safety validation method and the standard of NEDO for statically stable movable working robots without a manipulator, tests were carried out to confirm detection and avoidance in each obstacle detection area shown in Figure 6. The running surface was concrete, and a white cylinder with a diameter of 40 cm was used for a static obstacle. Table 8 shows the testing conditions. Figure 9 shows an example of the obstacle detection test. The robot was used to approach the static obstacle and stop. The robot behavior was observed to confirm that no problems occurred.

5.5 Compound environmental test

Referring to the standard of the environmental test of industrial machinery, tests were carried out at the Personal Care Robot Safety Validation Center. On the basis of the usage temperature and usage humidity of robots, a robot was exposed to the testing conditions shown in Table 7. After the exposure, operation of safety functions (full detection, etc.) and basic functions (robot control, grip control, etc.) were confirmed without any problems. Figure 10 shows the compound environmental test.

5.4 Manuals and labels

ISO 13485 specifies that manuals are to be also contained. Since this robot will be used in facilities such as hospitals, robot management manuals for training, assembly manuals for robot maintenance, and maintenance manuals, etc. in consideration of future maintenance, were created and submitted for examination for certification. In addition, labels were also the object of examination. After final inspection by JSAC, robots were labeled in reference to the items in the ALARP domain. Visually impaired people are urged by hospital staff to pay attention.

5.5 Design management system, production management system

ISO 13485 is a standard for safety. Its certification presupposes the evaluation of the design management system and production management system. On the basis of the system of the development in our company, which required ISO 9001, the management system has been completed.

For the design management system, general rules and procedures were documented on record management, purchasing management, requirements management, etc.

For the production management system, general rules and procedures were established similarly on record management, the management of defective products, and documentation was made on specification and production documents on the acceptance, assembly, and shipping management.

5.6 Acquisition of certification

On March 28, 2017, certification was given by the Japan Quality Assurance Organization (JQA) (Figure 11). It was the first ISO 13485 certification and the first certification of the world for a guiding robot with human interaction.
4. Structure Forming

4.1 System for rental, lease, and insurance

Even after safety is certified, people have reservations about introducing robots with no or few past records of implementation. Examination of sales systems shows that leasing and renting costs can be processed not as facility costs but as expenses and are more acceptable for hospitals. In addition, we have been strongly aware that whereas leasing, in which mid-term cancellation is impossible in principle, makes implementation difficult, and renting, in which cancellation is allowed at any time in principle, has facilitative implementation. Leasing after renting a leased product at the initial stage of introduction and checking the reality of its maintenance is a matter of common practice, and we consider this as a suitable way our robots can proceed, as we have negotiated with a leasing company and established the system shown in Figure 12.

In addition, insurance for robots was discussed between insurance companies and manufacturers in a working group of the former Association to Promote Robot Businesses. Negotiation between the insurance companies and the robot manufacturer and leasing companies to join product liability insurance and movable insurance, and it has also enabled the facility manager to join facility owner liability insurance and personal liability insurance in addition to the conventional facility insurance.

4.2 Maintenance

The replacement timing is known beforehand for some parts after endurance tests, etc., but unexpected components can arise in a real environment. Accordingly, we have made the following policy. For the time being, robots are introduced in a limited number of facilities so that we can quickly carry out maintenance work. After accumulating experience in performing maintenance on our own, we will outsource the work to maintenance companies.

4.3 Subsidy for introduction

Due to the need to use sensors with certification and parts with low failure rates, reduction of the production cost of the robot itself has a real limit. However, a high cost would prevent hospitals from implementing robots, despite being well aware of their usefulness. We have therefore examined and considered subsidies that facilities can receive. For nursing-care robots, a subsidy system is being established. The Japan Agency for Medical Research and Development (AMED) has applied such a system, but it targets only prescribed kinds of robots and does not cover the wide popularization of robot technology in the fields of nursing care and welfare. No applicable subsidy system of governmental agencies and foundations, satisfying the conditions, exists. We have petitioned for one but have not established any system applicable to all in Japan. Only Kanagawa Prefecture has granted a subsidy system applicable only inside the prefecture. For the popularization of new products such as robots and culture, we believe that support from the government is essential. We hope that this trend will spread across the whole country.

5. Summary

We have reported our activities to acquire ISO 13482 Safety Certification and organize the system for the realization and social implementation of robots guiding visually-impaired people and elderly people inside a facility. So far, we do not have a sales record, but we have introduced a robot for which we have carried out the in-house development product delivery process based on ISO 13482 certification and shipped to the Kanagawa General Rehabilitation Center, our development partner. In March 2017, we have received comments such as inconvenience due to the need of reboots every time after a forced stop occurs when an obstacle approaches and the need for autonomous return to the receptionist after guiding a patient from the receptionist to a clinical department. Autonomous running is not covered by safety certification; however, for the facility using a robot, autonomous running improves return on investment and is in our future agenda.

Acknowledgments

This development was supported by the Development Promotion Project of Self-Reliance Support Equipment for the Handicapped of Ministry of Health, Labor and Welfare for the fiscal years of 2015 and 2016. Support was also provided as a priority project of the Sagami Robot Industry Special Zone of the Kanagawa Prefecture Industry Promotion Department. In addition, we would like to express our deep appreciation for the cooperation from the Kanagawa Prefecture Rehabilitation Center through a series of demonstration experiments and advice, leading to the realization of robots. Finally, we would like to thank Professor Kazuteru Tobita, Associate Professor at Shizuoka Institute of Science and Technology, who has collaborated with us in the development of guidance robots for 14 years.

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Fig. 12 Framework of the sales structure
Development of Omnidirectional Mobile Electric Wheels

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New Field Products Development Center, Technology Development Department

Abstract

Many automatic guided vehicles (AGVs) are being used in warehouses and factories these days. The vehicles must be able to move in any direction for various special uses, but currently only differential motion allows them to turn on their driving wheels. Also, since each wheel is driven by a motor and gear set, the movement of the AGV is faster. To address these problems, omnidirectional mobile electric wheels for both driving wheels and driven wheels were developed and evaluated.

1. Introduction

Currently, many automatic guided vehicles (AGVs) have two parallel driving wheels on either side, and turning an AGV is controlled by the differential motion of those wheels. These AGVs generally run along a pre-programmed path. However, the vehicle must be capable of moving in any direction for a range of special uses. In addition, manual pushing of a truck could be more effective in certain applications, such as the adjustment of position and movement to places that have not been pre-programmed. The wheels on commercialized omnidirectional mobile trucks include Castor wheels and Mecanum wheels. These types of wheels have free rollers, so they are susceptible to vibration and incapable of handling bumpy roads. Also, since they are connected to the motor through a reduction, manual movement of the truck is difficult due to the high-reversing operation torque.

Considering these problems, omnidirectional mobile electric wheels have been developed and evaluated. Omnidirectional movement is realized with an Active-caster®, which can move omnidirectionally by controlling both a driving wheel and a steering wheel by motor. Since the Active-caster structure is similar to that of a swivel caster, the vibration is free, and it can handle bumpy roads well. For manual operation, a direct drive motor (DD motor) will be used in future, and the reduction will not be necessary on the caster due to the DD motor’s high torque. These characteristics will also be useful for manual operation of the truck.

In this article, the omnidirectional movement of an Active-caster is evaluated with a system that applies servomotors and reducers instead of a DD motor. The system has two sluices, one controlling the servomotor to the wheel and the other connecting the servomotor to the steering wheel. By setting up the truck, manual operation with a positive rotation is enabled. The prototype of this omnidirectional mobile electric wheel has also been evaluated.

2. Structure and Kinematics of Active-caster

2.1 Structure of a Double-Wheel Active-caster

The double-wheel Active-caster, shown in Figure 1, is designed to mitigate the steering force for smooth manual operation. Two servomotors are installed on the casters and drives the wheel and in the wheel that steering assistance. The steering axle is driven by a motor and gear set, but differential gear has been inserted to smooth the smoothness of the rotation between the two wheels. In addition, sensors are installed on both wheels to ensure they are in contact with the ground so as to prevent traction loss. Electromagnetic brakes are installed between each motor and the wheel or the steering axle. If the motor is connected to the wheel and steering axle, then the Active-caster can move, but if the motor is disconnected, it can only passively be moved. The wheel diameter is 150 mm, the distance between the double wheel is 60 mm, and the distance between the steering axle and wheel axle is 40 mm.

2.2 Kinematics of Double-Wheel Active-caster

Figure 3 shows the kinematic model of the Active-caster, where $\omega$ is $\omega_x$ and $\omega_y$ are the components of the Active-caster's angular velocity, respectively, $\omega_0$ is the steering wheel's angular velocity, $r$ is the wheel radius, and $d$ is the distance between the steering axle and wheel axle. If $W$ is the distance between the two wheels, and $s$ is the steering wheel's angle, then the average angular velocity and the steering angular velocity of the Active-caster $\omega_0$ and $\omega_0$ are expressed by (1).
\[ \omega_W = \frac{\omega_R + \omega_L}{2} \]  
\[ \omega_B = \frac{\omega_R - \omega_L}{2r} \]  
\[ \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} = \begin{bmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \]  
\[ \begin{bmatrix} V_x^g \\ V_y^g \\ V_z^g \end{bmatrix} = \begin{bmatrix} 1 & 0 & \frac{r}{2} \\ 0 & 1 & -\frac{L_C}{2} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ \omega \end{bmatrix} \]

3. Installation of a Double-Wheel Active-caster on a Truck

3.1. Truck structure

Figures 4 and 5 show the developed truck with an Active-caster. Table 1 shows its specifications. The double-wheel type swivel casters are installed as the truck's front wheels. In addition, lithium ion batteries are installed in the battery box at the front of the truck. Motor drivers and controlling units, such as a controlling PC, are installed on the control rack at the rear of the truck.

Figure 6 shows the controlling system configuration of the truck with two Active-casters. A tablet PC is used as the control unit. The truck can be controlled remotely and has an automatic running function with a path plan. The PC sends out the commands of each motor rotational speed in analog voltage through an A/D interface. The command values are calculated by eqs. (2) and (3). The relative angle (steering angle \( \phi \)) of each wheel to the truck body is measured by the absolute encoder output installed on the Active-casters through a D/A interface. In addition, the clutch-control and mode change as well as automatic running mode and manual mode can be applied with the PC. There are also two automatic running modes: omnidirectional mobile mode and rigid mode. The omnidirectional mobile mode controls movement in every direction, while the rigid mode is used for the steering angle of the wheels, which can be adjusted with this procedure: first drive the truck to where the steering angle of the wheels can be fixed, and when the driving wheels are parallel to the electromagnetic brake, the truck can be steered by the differential rotation of the two driving wheels.
<table>
<thead>
<tr>
<th>Table 1 Specifications</th>
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</thead>
<tbody>
<tr>
<td>Total length</td>
</tr>
<tr>
<td>Total width</td>
</tr>
<tr>
<td>Total height</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Control equipment</td>
</tr>
<tr>
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</tr>
<tr>
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<table>
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<th>Table 2 Experimental parameters and results</th>
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<tr>
<td>-------------------</td>
</tr>
<tr>
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<tr>
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</table>

<table>
<thead>
<tr>
<th>Table 3 Tensile experiment results</th>
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</thead>
<tbody>
<tr>
<td>Unit N</td>
</tr>
<tr>
<td>Manual operation mode</td>
</tr>
<tr>
<td>Forward direction</td>
</tr>
<tr>
<td>Backward direction</td>
</tr>
<tr>
<td>Right direction</td>
</tr>
</tbody>
</table>

3.2. Evaluation of movement after changing modes

After movement in manual mode, the steering angles of two Active-casters are different and the angle becomes automatically fixed when the mode changes to rigid mode. In order to check if the truck is moving straight once the mode has changed, an experiment must be performed.

As shown in Figure 7, the steering angles of the right and left Active-casters $\phi_1$ and $\phi_2$ were set in the initial condition, then a forward movement command was given. After that, the truck traveled for about 500 mm in the $X$ direction, the path was recorded, and the maximum deviation in the $Y$ direction $\delta Y$ was measured.

Table 2 shows the results of the three conditions as examples. In all the experimental conditions, the maximum deviation toward the $Y$ direction $\delta Y$ was 17 mm, a deviation ratio of 3.4% relative to a straight moving distance of 500 mm. As this experiment was undertaken without any truck position control by an internal or external sensor, the deviation could be decreased with the optional position control. Considering that a typical AGV’s deviation is about ±50 mm, the Active-caster can be installed on the AGV.

3.3. Evaluation of smoothness under manual operation

As shown in Figure 1, the electromagnetic clutch of the Active-caster is placed next to the reducer. Because this Active-caster has timing belts, differential gears, and crown gears between the clutch and wheel, how smoothly the truck moves can be affected for the worse in line with the load of its mechanical structure. Therefore, a truck towing experiment has been carried out to evaluate the truck’s smoothness in movement with an Active-caster used in manual mode. In addition, a similar experiment was carried out in order to compare the smoothness of movement of a truck with four passive casters. The manually-moving truck had the same weight, same caster specifications, and same caster position as the Active-caster truck. In the experiment, the trucks were towed at the same velocity from the forward, backward, and right directions, and the maximum towing force required was measured. Table 3 shows the results.

In the table, the required towing forces are almost the same both for the Active-caster truck and the manually-moving truck. The Active-caster truck in manual mode is thus just as smooth as the one that moves manually.
4. Conclusion

We examined the Active-Caster and determined it is feasible to use it with omnidirectional mobile electric wheels, which can be driven both electrically and manually. In addition to omnidirectional movement, the wheels allow for passive manual operation and therefore, the OAVC can be more flexible. The system using an electrical wheel and described in this article ensures smooth movement in manual mode. To simplify the system's structure while also ensuring smooth movement, a prototype with a 12V motor is planned, as shown in Figure 8.

Fig. 8. Drive wheel of the 12V motor type

Acknowledgments

Development of the omnidirectional mobile electric wheels was carried out in cooperation with Dr. Masayoshi Wada, associate professor of the Department of Mechano-SYSTEMS Engineering, Institute of Engineering, Tokyo University of Agriculture and Technology. We would like to express our appreciation to Dr. Wada for his fruitful cooperation in developing the body design and driving control of the Active-Caster.

References


Ko Fujita
Takamasa Oishi

Analysis Prediction Technique of Flaking Expansion in Roller Bearings for Wind Turbines.

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Abstract

Wind power has been rapidly spread as clean energy. In recent years however, profitability has been emphasized. Therefore, bearings for wind turbines are required to have lifetime longer than a general fatigue lifetime. In order to realize it, NGK is conducting research on prediction analysis technology of flaking expansion. This report describes the prediction analysis method in agreement with the reproduction test.

1. Introduction

Wind power generation, like solar power generation, does not exist the greenhouse gases that cause global warming. Accordingly, wind power generation is being implemented globally as a symbol of environmentally friendly renewable energy, and it is expected to expand in the future (Figure 1). As more wind power generation (wind turbines) are implemented, effective O&M (Operation and Maintenance) is required, and CMMS (Condition Monitoring System) has become common. At present, it has been proven to be effective in preventing sudden accidents etc. On top of this, the prediction of EUL (Exhaustion Useful Life) is considered to be one of the market needs. The following three factors are expected from EUL prediction:

1. Cost reduction by the use of parts up to their usage limit
2. Advantage reduction by ensuring the procurement period of the parts
3. Spare cost reduction by simultaneous exchange of large parts of multiple wind turbines

However, EUL prediction methodology based on the technological knowledge that does not rely on rules of thumb or EUL prediction methodology based on theory has not yet been put to practical use. Accordingly, NGK is aiming for the provision of EUL that enables the extension of bearing for wind turbines and is developing analysis technology for the prediction of the deterioration state. Such technology is considered indispensable for that goal, and the status of this development is described as follows.

Fig. 1. Wind turbines
2. Bearings for Speed-Up Gears for Wind Turbines

The drive train of a wind turbine is composed of the main axis, the speed-up gears, and the generator (Figure 2). Among them, the speed-up gears are the equipment for which the most bearings are used; it is common for speed-up gears to use more than 10 bearings. This is because a large speed multiplication factor requires many gears, whose axes require many bearings to support. The cylindrical roller bearing, which can withstand a large radial load, is the most commonly used bearing. Therefore, this report explains the development status of analytical technology for predicting the deterioration status, with the cylindrical roller bearing as the analysis target.

3. Example of Bearing Damage

Figure 3 shows an example of damage of a cylindrical roller bearing for a wind turbine. Flaking, occurring on all inner ring raceway surfaces, expands to a large extent and leads to replacement. For many cases of bearings used in general machines, the operator takes notice of abnormal noise or large vibration and replaces the bearing at a flaking size much smaller than that shown in Figure 3.

A wind turbine is a large device. Preparation of the repair work and procurement of parts take a long time. Therefore, even after an abnormality is found, operation could be continued until the replacement parts are procured, by taking measures such as limiting the output. For that reason, a large flaking, as shown in Figure 3, can be found. If the replacement is delayed and the flaking progresses further, large amounts of flaking debris could get stuck in the gears or the inner ring could crack. In the worst case, this could lead to complete failure, such as a shutdown of the machine.

To avoid that, NSK is developing analytical technology for the prediction of the deterioration status to enable reliable use of wind turbine bearings for a little longer after minor flaking.

4. Reproduction Test

To investigate the mechanism of flaking progress and to realize the prediction of the deteriorated state, reproduction tests were carried out. To shorten the test period, an artificial defect was made on the inner ring, as shown in Figure 4, before the experiment. Next, in a preliminary test, initial flaking was made with an in-house endurance test machine (Figure 5 (a)). An endurance test was started from this initial flaking condition. The flaking reached the status shown in Figure 5 (c) at a similar size and shape closely resembling the replaced part shown in Figure 5, and this indicates that the flaking was successfully reproduced. In the continued endurance test, the flaking expanded in proportion to time up to Figure 8 (d). However, shortly after that, the flaking expanded rapidly (Figure 5 (c)), terminating the experiment.

Fig. 2 Drive-train of wind turbines

Fig. 3 Examples of flaking in roller bearings for wind turbines
(a) Large flaking on the bearing inner ring raceway
(b) Large flaking on the bearing inner ring raceway

Fig. 4 Test bearing with an artificial defect
5. Development of an Analytical Method to Predict the Deteriorated State

5.2 Roller load calculation

In general, bearing life is assumed to be the time up to the occurrence of minor flaking. Therefore, the load on each roller is calculated from the axial load shown in Figure 7 (a). However, this consideration is inadequate after the flaking occurrence because when a roller passes by the flaking, due to the clearance made by the flaking between the roller and inner and outer ring, the load is not applied to the roller. Figure 7 (b) shows the roller load calculation result after the flaking occurrence. It is confirmed that the roller passing the flaking does not receive the load. In addition, due to the lower number of rollers sharing the axial load, the maximum load increases compared to the condition without the flaking. Furthermore, the rotation changes the relative position of the flaking and the rollers. As a consequence, the roller load changed gradually as the flaking expanded.

To summarize, the load calculation of each roller with consideration of these phenomena is important for the prediction of deteriorated state.

6. Calculation flow of the deteriorated state prediction calculation

Figure 6 shows the calculation flow for deteriorated state prediction. After flaking, the roller weight load is calculated with the flaking shape as input. The cracking progress analysis by FEM predicts the flaking shape in the next stage. This calculation process is repeated until the unsafe criteria are met. The time until the criteria are reached is displayed as the time up to the maintenance period.

The details of the calculation are described as follows.
5.3 Cracking progress analysis by FEM

The initial flaking expansion from the minor flaking is caused by the cracking progress due to cyclic fatigue. Accordingly, we have decided to predict the slowly growing flaking size by cracking progress analysis based on fracture mechanics by FEM, as shown in Figure 8. The flaking depth was assumed to be constant. The shape model was as simple as possible. The gradually changing load calculated in detail in section 5.2 was used for the input load on the roller for the analysis.

6. Prediction Results

Figure 9 shows the test results and prediction results of flaking. The vertical axis shows the flaking size (flaking length in the circumferential direction). The horizontal axis shows the elapsed time. Although the predicted result by calculation is a little faster, the prediction was accurate. In addition, the rapid expansion of flaking observed in the reproduction test was reproduced by the calculation.

To investigate the mechanism of this rapid flaking expansion, the roller load at the rapid flaking expansion was confirmed (Figure 10). As shown in Figure 10, the flaking is expanded in such a way that two rollers cannot receive the load simultaneously. As a result, the number of rollers sharing the load decreased even more than depicted in Figure 7 (b), and the load for each roller increased enormously. The large change in the load is considered to be the main cause of the rapid flaking expansion.

In addition, at present, the flaking size of two rollers, which is the start point of this rapid flaking expansion, is one of the criteria for safe operation. On the other hand, the amount of flaking debris, vibration, noise, etc., are also effective parameters to stop the wind turbines safely and preemptively. For that reason, we consider that criteria should be decided for multiple causes, as more experience will be accumulated in the future.
Simultaneous Measurement of Oil Film Thickness and Breakdown Ratio in EHD Contacts—Verification of Electrical Impedance Method

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Core technology R&D center, Lubricant research laboratory
Kan Nishino
Nihon Kochi University

Abstract
An electrical method using the complex impedance analysis has been developed for simultaneously quantifications of the thickness of oil film and breakdown ratio of oil film in electrical dynamic contacts. To verify the proposed measurement principle, oil film thickness measurements were conducted by using the electrical method together with the optical interferometry method in a ball-on-disc type apparatus. As a result, it was confirmed that the measured values obtained by the electrical method agreed well with those obtained by the optical method, under test condition with changing the evaluation speed. Besides, it was also confirmed that the measured values obtained by the electrical method showed consistent correlation with the friction coefficient.

1. Introduction
Rolling bearing in various machines are mainly used for smoothly supporting rotating shafts for a long period of time. The oil film thickness in the electrophysicide dynamic (EHD) contact of the bearing has a significant influence on the bearing torque and life. Accordingly, the measurement technology of oil film thickness in practical bearing is extremely effective to achieve the lower torque and longer life of bearings. Conventionally, in the basic research field, optical interferometry has been used as a precise method for measuring the oil film thickness in EHD contacts. However, to apply the optical method, it is necessary to use a transparent material that transmits light. Due to this limitation, it is impossible to monitor the lubricating condition in practical bearings using the optical method. In this viewpoint, electric methods have an advantage because real practical bearings are made of steel, which is an electrically conductive material. Usually, the electrical resistance method and the electrical impedance method are mainly used as monitoring techniques for electric circuit contacts. The electrical resistance method can evaluate the breakdown of oil films by measuring the electrical resistance in EHD contacts. However, it is impossible to measure the oil film thickness quantitatively. In addition, the electrical impedance method can evaluate the oil film thickness by measuring the electrical impedance in EHD contacts, but its measurement accuracy is insufficient.

This research has improved the conventional electric impedance method, which can measure the oil film thickness with high accuracy comparable to the optical interferometry. To verify the accuracy of the developed method, oil film thickness measurements were conducted by using the electrical method together with the optical interferometry method. Besides, this method can measure not only oil film thickness, but also the breakdown ratio of oil film simultaneously. We have quantitatively evaluated the measured breakdown ratio of oil film by comparison with the friction coefficient occurring in EHD contacts.

2. Measurement Principle
Figure 1 shows a physical model of a ball specimen in contact with a disc specimen under the mixed lubrication. Here, $r$ is ball specimen radius, $a$ is Berman contact radius, $f$ is Berman contact area, $C_{0}$ is function describing the decrease between the ball and disc specimen, $C_{a}$ is oil film thickness in the area where the oil film is formed in EHD contact, and $a_{0}$ is breakdown ratio of oil film. Figure 2 shows an equivalent electrical circuit, which is based on the physical model shown in Fig. 1. Here, $R$ is resistance of the breakdown area in the EHD contact, $C_{e}$ is capacitor of lubricated area in the EHD contact, and $a_{0}$ is capacitor of un lubricated area where the clearance between the two surfaces are filled with oil. In short, the oil film thickness and breakdown ratio were obtained by measuring the complex impedance $Z$, as shown in Figure 2.
3. Experimental Method

Figure 8 is a schematic diagram of the experimental apparatus used in this study. This apparatus uses a sphere sliding contact between a steel ball (diameter 9.5 mm and material: AISI 52100 steel) and a glass disc (diameter 109 mm, thickness 10 mm and BOR). The disk surface in contact with the ball is coated with a silver reflecting layer of 5 μm thick chromium and a spacer layer of 1-μm-thick indium tin oxide (ITO). In this study, the ITO film is used, not only as a "transparent film" in optical measurements but also as a "conductive film" in electrical measurements. For electrical measurements, AC voltage is applied to the contacts, AC current passing through the contact is measured, and the complex impedance (Z = |Z|) is obtained, which is automatically performed with a commercially available impedance meter. From the electrical measurements based on the measurement principle described in the previous section, we can quantify the oil film thickness and the breakdown ratio simultaneously. The test conditions are shown in Table 1. For friction measurements, a torque meter is installed to the vertical shaft, which measures the torque needed to rotate the disc at EHD contact conditions and determines the friction coefficient. As for the oil, two types of polyglycol oil (PAO) with different viscosities were used, as shown in Table 2.

4. Results and Discussion

Figure 4 shows the measurement results of oil film thickness, breakdown ratio, and friction coefficient when the entrainment speed U was changed for the lower-viscosity PAO, as shown in Table 5. The dashed line in the graph shows the theoretical value according to the Hamrock-Dowson equation. We have confirmed that the measured values obtained by the electrical method agree well with those obtained by the optical method. Therefore, we can naturally conclude that the electrical method can measure the oil film thickness in EHD contacts with a high accuracy comparable to that of the optical method. Additionally, Fig. 5 shows the experimental results when U was varied for the higher-viscosity PAO. When U ≥ 0.5 m/s, the measured h values are located below the dashed line with considerable deviations. In addition, we find that the measured values are higher than those extrapolated from the lower-U conditions (i.e., U ≤ 0.1 m/s). From these results, we suggest that the lubricant is stressed at the higher-U condition (i.e., U ≥ 0.5 m/s). However, even when under the stressed lubrication, the measurement error does not seem to be fatal.

5. Summary

Simultaneous measurements of optical interferometry and the electrical impedance method with the use of the ball-on-disc-type apparatus has demonstrated that the developed method can measure the oil film thickness with high accuracy comparable to the optical interferometry. In addition, this method has confirmed that the breakdown ratio of oil films can also be measured simultaneously and qualitatively evaluated by comparison with the friction coefficient.

References

Wireless Vibration Diagnostic Device Bearing Doctor Model BD-2

NSK Bearing Doctor Model BD-2 measures and analyzes the vibration of a rotating machine in operation and diagnoses bearing defects. The advantage of this product is not only evaluation of the effective value, peak value, and ratio of the vibration acceleration but also the extraction of specific vibration components originating from bearing defects by analysis, which enables early defect detection. NSK has been working on developing the sophisticated bearing abnormality diagnosis technology and vibration analysis technology, which has culminated in the development of BD-2 with analysis software ACQUIS NAVI™ installed, and this is described in this article.

1. Structure and Specifications
The Model BD-2 is a vibration diagnostic composed of a compact vibration sensor small enough to fit in a person’s hand and a tablet with Windows OS installed (Photo 1). It can be used for the diagnosis of not only bearings but also all kinds of rotating machines. In particular, to streamline maintenance work at the workplace, Bluetooth connection between the sensor and the tablet allows for a remote control function that enables operation control of the sensor and wireless sensing as well as the receiving of measured vibration data. The transmitted vibration data is analyzed in the tablet and individual results can be stored within. The stored data is transferred to a personal computer with the accompanying management software installed, enabling graphs showing the trends in vibration data for each machine facility and automatic writing of diagnosis reports.

Table 1 shows the specifications of this product.

2. Advantages
The vibration data transmitted wirelessly from the vibration sensor to the tablet is displayed as displacement, velocity, and acceleration vibration values. The device is capable of automatic judgment of the velocity in comparison with the vibration severity standard of ISO 10816 as well as waveform analysis of the acceleration in the frequency domain and time domain. On the basis of analysis of the vibration and waveform, the vibration status of the machine can be evaluated simply. In addition, analysis and diagnosis algorithms automatically judging bearing defects and the NSK standard bearing database of about 5,000 bearings are installed in the tablet of this product, allowing for on-site judgment of the bearing, even without past vibration data. Figure 1 shows the function of this product.

(1) Wireless Sensing
The sensor and the tablet are connected via Bluetooth, which eliminates the need for cables and facilitates the connection and disconnection to and from the machine.

(2) Installation of a Bearing Defect Automatic Diagnosis Algorithm
It allows on-site judgment whether the abnormality is caused by the bearing or whether the bearing has any defect.

(3) Installation of the NSK Standard Bearing Database
Merely selecting the product number of the bearing to be diagnosed and feeding the information on the rotation enables diagnosis of the bearing.

(4) Management Software
The management software makes a folder for each machine measured. Comparison and validation of vibration values, trend graphs, and waveforms allow for understanding of the vibration condition of the machine or bearing. In addition, to make full use of the measurement data and analysis data, this device is capable of providing CSV files of each waveform and the automatic writing of a facility diagnosis report (Figure 2), which are stored in the server and shared with all those involved.

(5) Update of Application
Starting the tablet in a Wi-Fi environment automatically updates the application to the latest version.

3. Fields for Application
This product is suitable for general multi-purpose rotating machines such as motors, pumps, and splindles.

4. Summary
Roller bearings are used in machine systems in an array of environments and operation conditions, and they are essential machine elements that determine a system’s performance. Along with bearing abnormality early detection technology, the development of abnormality prevention technology is considered to be of ever-growing importance.

This product is a wireless vibration diagnostic device with an automatic judging algorithm installed that enables people without any special skills to judge bearing defects on-site.

We would be pleased if this device makes contributions as a supporting tool for walk-around checks of machine facilities.

Fig. 1 Function
(1) Vibration measurement
(2) FFT Analysis/Time domain wave
(3) Bearing diagnosis

Table 1 Specifications

<table>
<thead>
<tr>
<th>Part</th>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
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<td>Bluetooth</td>
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<td></td>
<td>Tailored OS</td>
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<td>Management software</td>
</tr>
<tr>
<td></td>
<td>Power source</td>
<td>Rechargeable lithium ion battery</td>
</tr>
</tbody>
</table>

Fig. 2 Report
(1) Frequency vs. vibration
(2) Acceleration vs. vibration
(3) Temperature vs. vibration
(4) Bearing diagnosis report

Facility diagnosis report
(1) Machine number: 1234567
(2) Measurement date: MM/DD/YYYY
(3) Measurement location: Factory
(4) Measurement condition: Normal operation
(5) Vibration level: Low
(6) Frequency range: 10 Hz-10 kHz
(7) Measurement results: Normal
(8) Diagnostics results: Normal
(9) Remarks: None
Low-Torque Ball Bearings for High-Efficiency Motors

With a growing awareness of the need for global environmental protection, the world is moving toward reducing carbon dioxide and power consumption. It is said that electric power consumption of motors constitutes over 40% of the electric power consumption of the entire world. As reduction of electric power consumption by motors will have a big impact on energy saving, relevant activities are attracting a lot of attention. Consequently, many countries have established new regulations on the efficiency of energy-saving motors. Many motor manufacturers are taking various measures to reduce the loss in order to improve the efficiency by several percent. Although the loss by bearings (motor mechanical loss), converted to the efficiency, is as low as less than 1%, its improvement is expected to be an element for a motor efficiency improvement of several percent.

Optimizing the bearing specifications, NSK has developed bearings that realize a low loss reduction associated with motor efficiency improvement (Photo 1).

In response to the expectation of the implementation of high efficiency motors for energy saving, the product has optimal performance for general industrial machine motors used in pumps, compressors, etc.

1. Composition, Structure, and Specifications

Optimization of the kind and amount of grease has reduced the bearing resistance and friction resistance of the bearing (Figure 1). In addition, low torque and long bearing life have been realized. Also, adopting a plastic cage will allow for further torque reduction and longer life.

2. Advantages

(1) Reduction of Motor Mechanical Loss and Endurance Improvement

Compared with bearings having conventional specifications, the motor mechanical loss has been reduced by a maximum of 60% (maximum reduction of 85% with plastic cages), and at the same time, the bearing life has been extended by a factor of 2.7 (Figure 1 and 2).

(2) Mechanical Loss Dependent on Motor Size

The optimized bearing specifications have a significant impact, especially on large motors (Figure 2).

3. Fields for Application

This product is suitable for high efficiency motors for relatively light load and general industrial motors.

4. Summary

Table 1 shows a lineup of bearings corresponding to a variety of motor sizes (0.5 to 132 kW). These bearings are contributing to lowering the amount of energy consumed by motors.

Table 1: Lineup of low-torque ball bearings

<table>
<thead>
<tr>
<th>Inner diameter</th>
<th>Main size (mm)</th>
<th>Width</th>
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</thead>
<tbody>
<tr>
<td>Standard</td>
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<td>8001</td>
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<td>12</td>
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<tr>
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<tr>
<td>8009</td>
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</tbody>
</table>

Fig. 1: Motor Mechanical Loss Rate

Fig. 2: Grease life
Optimized Long-Life Cylindrical Roller Bearings for Continuous Casting Machines

Recently, higher productivity in metal work has been achieved by operating stable facilities and reducing costs by extending maintenance intervals. Continuous casting machines continuously produce semi-finished pieces from molten metal. The types of products produced include slab (for plates), bloom (for shapes), and billet (for wire). Figure 1 shows an example structure of a slab continuous casting machine. One machine is composed of 10-15 roll segments, each having multiple rollers.

This type of continuous casting machine often has a segmented roll structure to improve product precision. Guide rollers are used as self-aligning roller bearings capable of absorbing roll deflection on both the fixed and free sides. In addition, they are non-separable and easy to handle.

Toroidal roller bearings are often used, especially overseas, because they feature high load capacity and are capable of absorbing elongation by relative displacement of the inner and outer rings. These bearings are used in heavy load conditions over 30% of the basic dynamic load rating at extremely slow speeds (one or two cycles per minute) while exposed to coolant, vapor, scale, and high temperatures. These harsh conditions deteriorate lubrication and cause premature damage such as wear on the raceway surface and flaking. Consequently, there is a need for highly reliable, long-life bearings.

1. Structure and Specifications

These full complement cylindrical roller bearings are composed of an outer ring, inner ring, rolling elements (rollers), and a snap ring.

Figure 2 shows the structure of the developed bearing, while Table 2 lists designations and specifications.

Table 1 Specifications

<table>
<thead>
<tr>
<th>Inner Diameter</th>
<th>Outer Diameter</th>
<th>Width</th>
<th>Bearing Designation</th>
<th>Dynamic Load Rating (KN)</th>
<th>Static Load Rating (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>180</td>
<td>60</td>
<td>120NUXAB04V</td>
<td>450</td>
<td>740</td>
</tr>
<tr>
<td>130</td>
<td>200</td>
<td>60</td>
<td>130NUXAB04V</td>
<td>450</td>
<td>740</td>
</tr>
<tr>
<td>140</td>
<td>210</td>
<td>60</td>
<td>140NUXAB04V</td>
<td>550</td>
<td>980</td>
</tr>
<tr>
<td>150</td>
<td>225</td>
<td>75</td>
<td>150NUXAB04V</td>
<td>550</td>
<td>980</td>
</tr>
<tr>
<td>160</td>
<td>240</td>
<td>80</td>
<td>160NUXAB04V</td>
<td>665</td>
<td>1,190</td>
</tr>
</tbody>
</table>

2. Advantages

- Long life and high load capacity
  A refined full complement design maximizes load capacity. Endurance tests confirmed life triple that of conventional bearings (Fig. 2).
- Self-aligning
  Absorbs deflection generated on the rolls of continuous casting machines. Uniformly distributes contact surface pressure between the roller and raceway in response to inclination (Fig. 4).
- Absorbs roll elongation
  Relative displacement of the inner and outer rings easily handles roll elongation caused by heat.
- Ease of handling
  Since the bearings are non-separable, there is no need for special tools, and assembly is easy (Fig. 5).

3. Applications

Suitable for the guide roll (free side) of a continuous casting machine for slab, bloom, or billet.

4. Summary

We confirmed the positive impact of these optimized long-life cylindrical roller bearings in actual slab continuous casting machines. We will continue our efforts to improve productivity through the stable operation of continuous casting machines.
Large (TL) Spherical Roller Bearings Resistant to Inner Ring Fracture for Paper Machines

Recently, while growth in printing paper and newsprint remains sluggish, paper makers are expecting increased demand for paperboard and sanitary paper. To prepare, manufacturers have been improving productivity by enhancing production facilities (paper machines) and operating them reliably at high speeds. As a result, the number of Yankee dryer rolls (Yankees rolls) are increasing in paper machines.

Figure 1 shows an example structure of a paper machine Yankee roll with a bearing attached. In this structure, a self-aligning roller bearing is set on the bearing bore with a slide between the bearing and bore. Remaining clearance in the bearing can be adjusted by pushing and creating tensile stress (long stress) on the inner ring. However, since this high-temperature medium (vapor) goes through the hollow space of the dryer roll, the area expands during operation and hoop stress increases, possibly causing the inner ring to fracture (Photo 1).

Furthermore, creep damage can occur between the inner ring and bore since bearings are used for a long time in high-temperature conditions. Because inner ring fracture could cause a sudden stop of production, there is a need for bearings with measures to prevent such damage.

NKB developed TL (Tough & Long life) bearings in 1984 to respond to this problem. TL bearings are confirmed to have enhanced inner ring fracture strength and improved dimensional stability due to a uniquely developed technique for self-aligning roller bearings and a special carburizing process. So far, the corresponding size of TL bearings has been limited to the outer diameter of the bearing, or less than φ600 mm (23.6 inches). However, to accommodate bearings for Yankee rolls, we have developed inner ring fracture-resistant large TL self-aligning roller bearings (Photo 2) with a maximum diameter of φ1,360 mm. For details, please see the next page.

1. Specifications
   The new product features enhanced inner ring fracture strength and improved dimensional stability thanks to a uniquely developed steel for large self-aligning roller bearings and a special carburizing process.

2. Advantages
   • Inner ring fracture strength: Improvement of the material strength of the inner ring prevents inner ring fracture.
   • Creep strength: Heat treatment for size stability at high temperatures prevents inner ring creep.

3. Applications
   The main applications in paper machines and representative part number ranges for the new bearings are listed in Table 1. These products are a large self-aligning roller bearing with tapered bore on the inner ring bearing bore. They are particularly suitable for supporting dryer rolls and Yankee rolls with hollow core through which a high-temperature medium (vapor, oil) passes.

4. Summary
   We believe our new product will help improve productivity by making the operation of paper machines more stable. We will continue to develop new products that meet user needs while also contributing to progress in the paper manufacturing industry.

<table>
<thead>
<tr>
<th>Bearing Part Number Range</th>
<th>Bearing Bore Diameter</th>
<th>Main Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL296100-TL2391000</td>
<td>φ500-φ1,320</td>
<td>Press roll</td>
</tr>
<tr>
<td>TL270900-TL306500</td>
<td>φ450-φ1,300</td>
<td>Yankee dryer roll</td>
</tr>
<tr>
<td>TL29090-TL379176</td>
<td>φ450-φ1,360</td>
<td>Yankee dryer roll</td>
</tr>
<tr>
<td>TL37260-TL525600</td>
<td>φ350-φ1,320</td>
<td>Yankee dryer roll</td>
</tr>
<tr>
<td>TL270600-TL407100</td>
<td>φ350-φ1,300</td>
<td>Yankee dryer roll</td>
</tr>
<tr>
<td>TL249784-TL3741160</td>
<td>φ350-φ1,360</td>
<td>Yankee dryer roll</td>
</tr>
</tbody>
</table>
Vibration Control Actuator for Train Cars

Full active suspension systems, systems that entirely control horizontal body vibration in railroad vehicles using pneumatic, hydraulic, and electric actuators, have recently been installed on high-speed trains like the Shinkansen and limited express trains running on regular tracks, as well as many high-speed and regular trains. NSK has developed the Vibration Control Actuator, a new electric vibration prevention actuator with ball screws for full active suspension of railroad vehicles, and it is introduced here.

1. Composition and Structure

NSK's Vibration Control Actuator is composed of an electric motor, a reducing mechanism, a ball screw, and a slide rail (Photo 1). The upper level control equipment (not shown) calculates and sends the drive command to the actuator's motor driver. Figures 1 and Photo 2 show the installation location of the actuator's main body. It is installed between the bogie and the vehicle body, and it drives laterally with respect to the moving direction.

2. Advantages

This actuator addresses technical issues with existing products, lighter, thinner, shorter, and smaller with the effect of making them more compact, lightweight, efficient, and responsive. On the other hand, technological advances in actuating devices have led to the development of higher products, such as durability and anti-vibration strength, needed to be resolved. As a mechanism for converting the rotational movement of electric motors to linear movement of the output shaft, precision ball screws, although they were installed on railroad vehicles that require high drive power, have been applied due to their high efficiency, low inertia, and high retraceability. Highly efficient in normal operation when converting rotational movement to linear movement, and capable of reducing the torque requirement on the electric motor, ball screws can make electric motors more compact while lowering inertia. Therefore, with the advantage of excellent response to the commands from the upper level control equipment, they can constitute a compact and energy-saving actuator. In addition, ball screws are excellent in reverse operation when converting linear to rotational movement. This is very useful for efficiently absorbing the vibrations between the bogie and the vehicle body.

A dust-proof and water-proof design for environmental resistance in indoor measures such as the used packing and seal to prevent the ingress of water and dust. For vibration resistance, structural analysis of the design was performed to ensure it satisfied the requirements for railroad vehicles. Tests equivalent to a real vehicle were confirmed that the requirements had been established.

The design incorporates the design philosophy of the Ring Torque Motor™, the culmination of mechanistic research and development, one of NSK's core technologies.

3. Fields for Application

This product is installed on the China Line new model limited express vehicle (3000 series) of the East 6 am. Railway Company (JR East) and started operating on December 29, 2017 as a new vehicle called Super Azuma (Photo 3). In addition, it is also installed on the Train Suite Shiki-shima, a JR East cruise train that started operating on May 3, 2017 (Photo 4).

4. Summary

Taking full advantage of the ball screw's high efficiency conversion from rotational to linear movement, the Vibration Control Actuator is an electric actuator that suppresses the lateral vibration of railroad vehicles with high response performance. NSK will continue to contribute to the improvement of safety, comfortability, and environmental performance for the railroad industry.