Technological Trends and Outlook of Automotive Bearing

K. YOKOTA

The automotive industry is said to be facing a once-in-a-century time of major change, as represented by the key words of CASE (Connected, Autonomous, Shared, Electric). Among these, further enhancement of bearing performances in response to expanding electric motorization and also new mechanisms and sensing technologies for advancing autonomous driving technologies are required.

This paper introduces JTEKT's automotive bearing technologies responding to these needs.

Key Words*: automotive bearing, trends, bearing technology, tribology*

1. Introduction

The auto industry is said to be facing a once-in-a-century time of great change represented by the keywords "Connected, Autonomous, Shared, Electric." Automakers and auto parts makers face the major issues of responding to such change.

Of these keywords, "Electric" in particular is triggering structural change, and has the biggest impact on our bearing products. It goes without saying that worldwide environmental regulations are pushing electric motorization. In Europe, for example, the CO_2 emission regulation of 130 g/km will become 95 g/km in 2021. Moreover, due to regulations regarding zero-emission cars and new energy cars as well as sales promotion measures, it is predicted that electric vehicles such as EV/PHV/HV will increase to 35% of the global number of passenger vehicle sales in 2030 (**Fig. 1**).

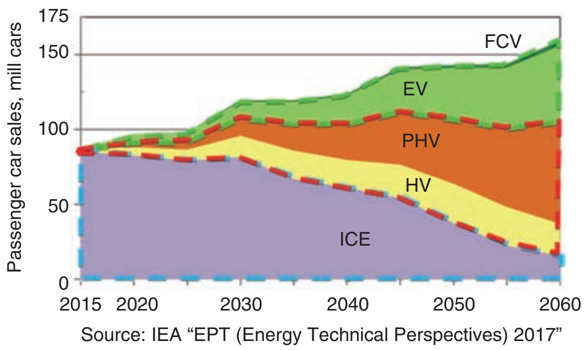


Fig. 1 Global car sales forecasts by car type

In line with this electric motorization, the performances required of bearings are changing. For example, compared to conventional engine-powered vehicles, the electric powertrains of EV/PHV/HVs must endure dramatically higher rotational speed and solve the new issue of electric pitting. Moreover, in addition to changes in required bearing types and proportions, there is a need to further reduce torque, as well as reduce size and weight.

Meanwhile, vehicles equipped with engines will continue to account for a major percentage of sales due to factors such as the predicted rise in engine-powered vehicles in newly-emerging countries and global expansion of PHV/HVs. We cannot overlook initiatives to increase reliability and reduce torque for bearings used in these engine-powered vehicles. Moreover, we are also engaging in product development completely different from before in response to electric motorization in the broad sense; i.e. sophistication of motor-based control.

This report will introduce development trends of automotive bearings responding to the abovementioned electric motorization trend, and JTEKT's bearing products which satisfy functions and performance requirements as well as the evaluation technologies by individual application (**Fig. 2**).

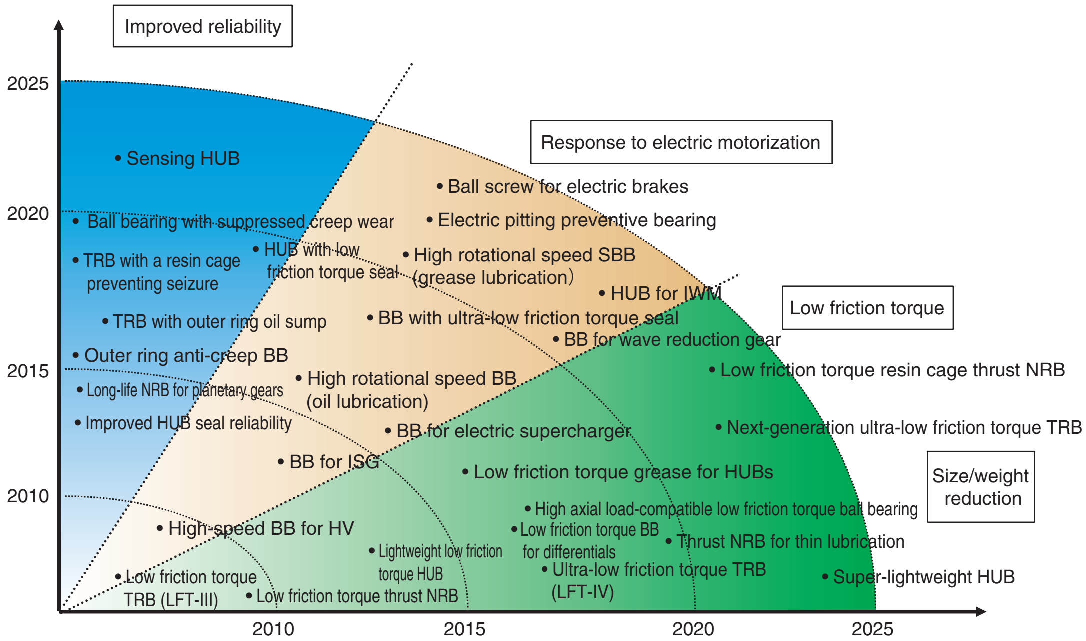


Fig. 2 Development trends of automotive bearings

2. Bearings for Powertrains

2. 1 Response to Electrification of Powertrains

The powertrain could be considered to have changed the most due to the impact of electric motorization. There are powertrains such as those of PHVs and HVs whereby the engine and motor are used in combination, as well as powertrains such as those of EVs, which only convey the motor output as driving force. Both are electric powertrains using the motor as a power source, which had never been used as a power source before, and are predicted to increase significantly moving forward.

In the case of such electric powertrains, as the level of output's dependence on the motor increases, need for high-speed motor rotation grows to achieve higher output as well as reduce size and weight. To meet such needs, JTEKT developed a high rotational speed ball bearing (**Fig. 3**). When conventional ball bearings were subjected to high rotational speed, centrifugal force would cause cage deformation, and heat generation caused by interference between the cage and balls would result in bearing seizure. In contrast, the high rotational speed ball bearing features a cage consisting of two identical resin parts which hold the balls from both sides, minimizing cage deformation upon high-speed rotation, as well as reducing heat generation by eliminating interference with balls. This design enables the bearing to accommodate a high rotational speed of 2 million $d_m n^{*1}$ or more under oil lubrication conditions (**Figs. 4 & 5**).

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

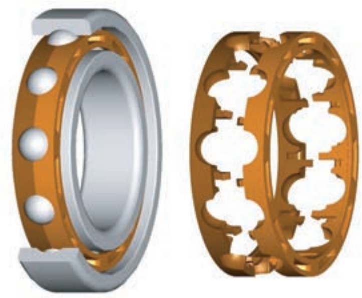


Fig. 3 High rotational speed ball bearing

Moreover, the operating environment of motor bearings differs from that of conventional gear support bearings, and sometimes an electric current flows between the inner and outer rings due to a potential difference created by the motor. Damage referred to as "electric pitting" occurs on the contact surfaces between the inner ring and the rolling element as well as between the rolling element and the outer ring when electric currents flow between them (**Fig. 6**), and there is a possibility of this leading to abnormal noise or premature failure if the damage progresses.

For industrial applications, as a means of preventing the passage of electricity through insulation, we commercialized bearings coated with resin molding or ceramic, ceramic ball bearings, etc. (**Fig. 7**). However, for automotive applications, these bearings have problems in cost, durability, and mass productivity. As such, JTEKT is engaging in the development of a ball bearing using a special coating for preventing electric pitting for electric powertrains. The special coating is applied to this ball

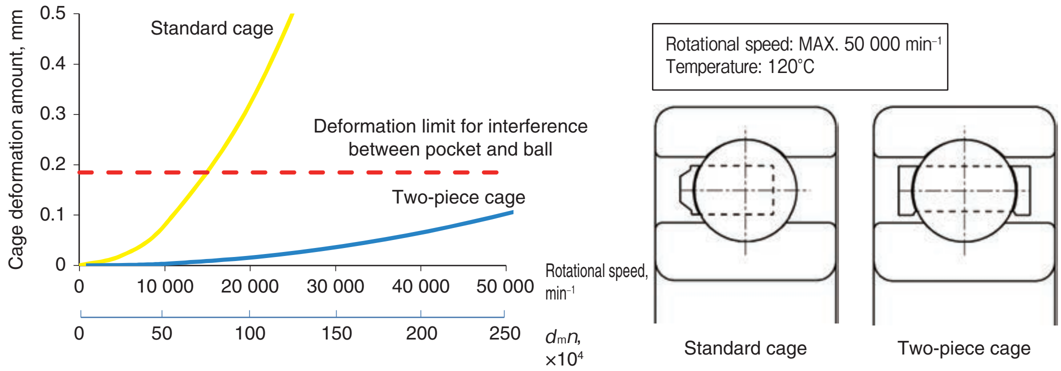


Fig. 4 Results of high-speed performance (cage deformation) evaluation

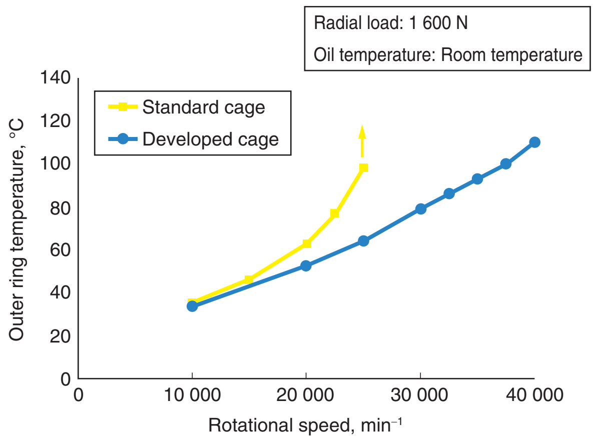


Fig. 5 Results of high-speed performance (outer ring temperature) evaluation

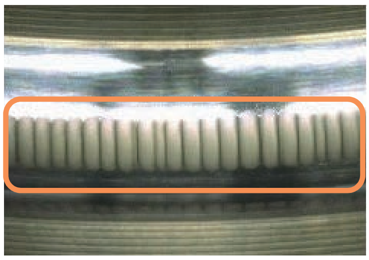
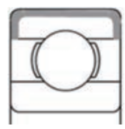
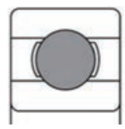


Fig. 6 Electric pitting on raceway

Type		Resin mold	Ceramic coating	Ceramic balls
Shape				
Features	Cost	△	×	×
	Durability	△	◎	◎
	Mass productivity	△	×	◎

Judgment ◎: Extremely good, ○: Good, △: Normal, ×:Bad

Fig. 7 Existing electric pitting preventive bearing

Fig. 8 Ball bearing coated with special coating for preventing electric pitting

bearing's O.D. surface and is unlike any used previously (**Fig. 8**).

2. 2 Response to Gear Trains

Many bearings are used not only in the speed reduction mechanisms of electric powertrains, but also to support gears in gear trains of current AT/MT/CVT, etc. To achieve high efficiency of the unit, low friction torque, as well as size/weight reduction are required of such bearings. Particularly in the case of electric powertrains, there is a strong demand for thin section ball bearings at the same time as a response to high-speed motor rotation. However, durability issues, such as life and creep wear, existed.

Bearings used in gear trains are normally lubricated with oil sealed into the unit. As such, when used for an extended period of time, abrasion powder from the gear, etc. may infiltrate into the bearing, and shorten bearing life. Potential countermeasures for this issue are increasing bearing size, and adding a seal to prevent infiltration of abrasion powder, etc. into the bearing. However, increasing size conflicts with the need to reduce size and weight, while adding a seal conflicts with the need to reduce torque.

In response to these issues, JTEKT developed a ball bearing with a low friction torque seal capable of accommodating high-speed rotation. By optimizing seal lip shape, we succeeded in reducing the force that the seal tightens the shaft with, and practically halved seal torque (**Figs. 9, 10 & 11**). Moreover, by bearing size reduction enabled by the effect of improved bearing life against contaminants, the weight was reduced by around 50% compared to conventional open-type bearings (**Figs. 12 & 13**).

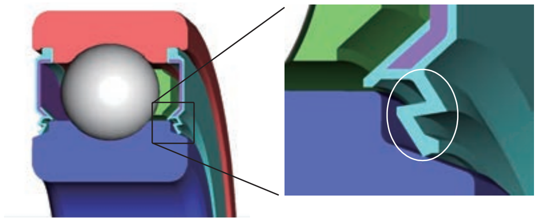


Fig. 9 Ball bearing with ultra-low friction torque seal

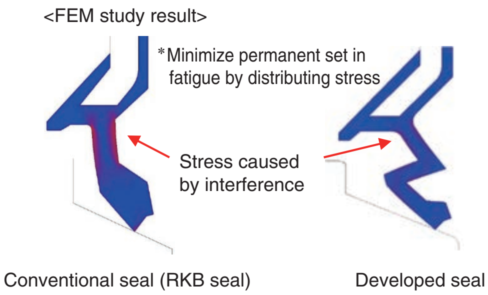


Fig. 10 Results of CAE analysis

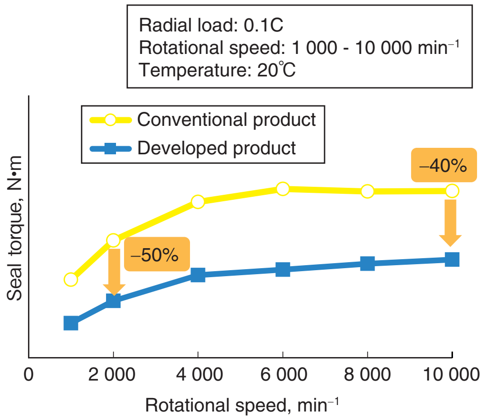


Fig. 11 Results of seal torque evaluation

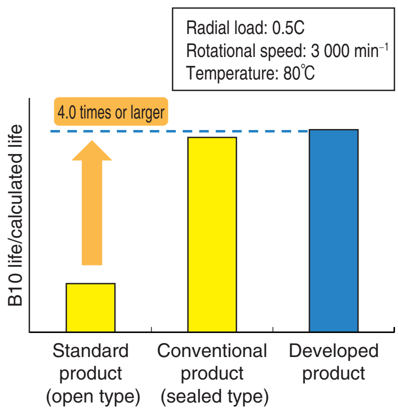


Fig. 12 Life test results in contaminated oil

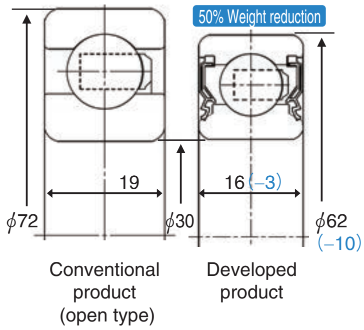


Fig. 13 Example of weight reduction

Another issue associated with thin section ball bearings is that they are susceptible to creep caused by strain under large radial loads. Creep caused by strain is a phenomenon whereby, in the case of general inner ring rotation, outer ring strain and its adhesion to the housing occur continuously whenever the rolling element passes on the outer ring raceway, causing the outer ring to rotate in the bearing rotational direction relative to the housing (**Fig. 14**). When creep occurs, wear progresses between the bearing and the housing. Therefore, abnormal noise and premature failure may occur due to displacement of the bearing axis or large inclination.

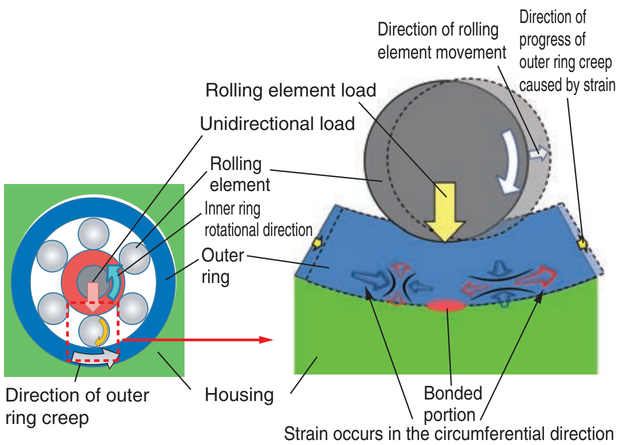


Fig. 14 Mechanism of creep occurrence

The conventional countermeasure was to thicken the outer ring to suppress outer ring strain. However, this conflicted with size/weight reduction needs, and led to larger, heavier units. As a solution, JTEKT quantitatively analyzed the creep occurrence mechanism using CAE and by experimental verifications, and then, became the first in the world to adopt a structure with an ultra-shallow groove in the center of the outer ring O.D. (**Fig. 15**). This groove makes the distances from the contact points of the balls and the outer ring raceway to the contact point of the outer ring O.D. and the housing equivalent to those of a bearing with a thicker outer raceway (which was the conventional solution), and minimizes the effect of outer ring strain on the housing (**Figs. 16 & 17**).

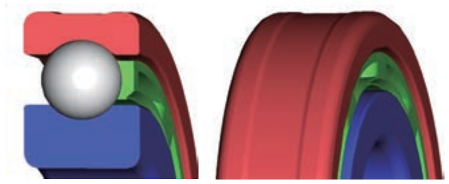


Fig. 15 Anti-creep bearing

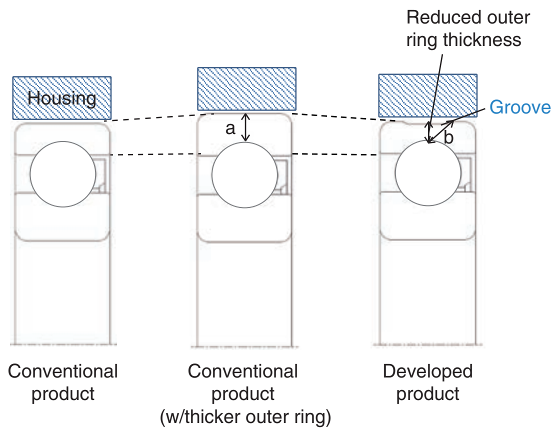


Fig. 16 Characteristics of developed bearing

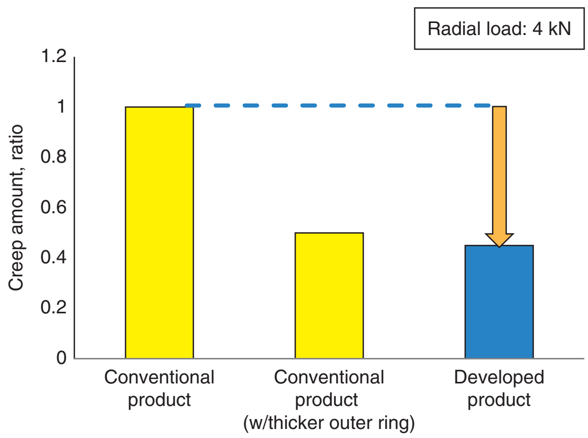


Fig. 17 Comparison of creep amount

This new model eliminated the conventional need for increasing outer ring thickness used as a countermeasure for creep and made the size and weight reduction of the reduction gear possible.

As mentioned above, many ball bearings are used in electric powertrains. However, in final gear support parts, etc. which support high power output, sometimes large size ball bearings are required. On the other hand, tapered roller bearings have higher load capacity than ball bearings. Therefore, if a tapered roller bearing is used instead of a ball bearing, it is possible to reduce bearing size and weight in the high load portions. However, since tapered roller bearings have larger rotating torque and lower anti-seizure performance than ball bearings, JTEKT continued technical development to overcome these issues. Particularly in the case of the electric powertrain, low-viscosity lubricating oil is used in small quantity in order to improve unit efficiency, and bearing performance with such lubricating oil could be a potential issue. In response to this, JTEKT developed an ultra-low friction torque tapered roller bearing, LFT-IV, which also offers improved anti-seizure performance (**Fig. 18**).

Focusing our efforts on reducing tapered roller bearing torque, we applied the technology we developed to the creation of the LFT (Low Friction Torque) series. The LFT-IV bearing adopts a resin cage with a high degree of design freedom, and has achieved 65% less rotating torque than standard models by strengthening the function to control oil inflow into the bearing. Additionally, in the oil groove in the cage, oil accumulates when the bearing rotation is stopped, and is released from the groove when bearing rotation starts. Thus, three times longer oil-free seizure time was achieved compared to the conventional TRB (**Fig. 19**).

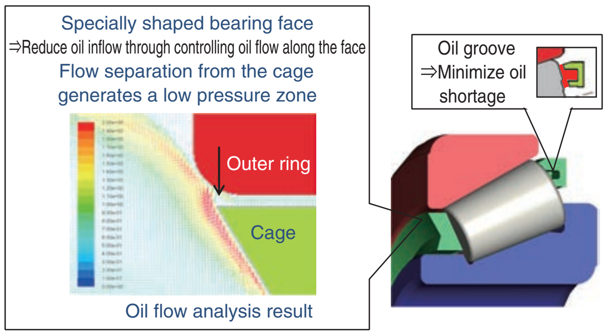


Fig. 18 Ultra-low friction torque tapered roller bearing (LFT-IV)

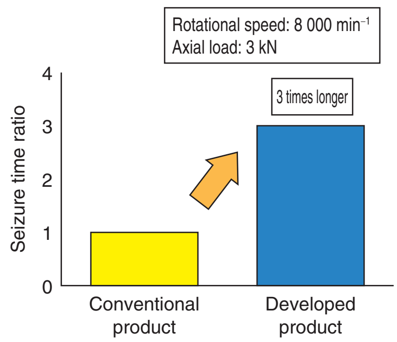


Fig. 19 Seizure test result

Furthermore, as a technology to support rotation of ball bearings under large gear load, JTEKT developed a high axial load compatible bearing with asymmetrical inner/outer rings (**Fig. 20**). Specifically speaking, by expanding raceway depth on the axial load side, we have improved axial load capacity by 80% compared to the conventional model. Also, in the case of equivalent axial load capacity, the O.D. can be reduced by 15% compared to the current deep groove ball bearing (**Fig. 21**). Moreover, regarding the issues of shortened bearing life due to contaminated oil and increased torque loss due to oil agitation, we improved cage shape to control the amount of oil that penetrates the bearing, thus reducing the contaminants passing through the bearing and reducing oil agitation resistance (**Fig. 22**). This reduced torque loss by up to 48% compared to a deep groove ball bearing with equivalent load capacity (**Fig. 23**).

In regards to bearings for planetary gears also, JTEKT has engaged in technical development to reduce the size and weight of the unit. The planetary gear mechanism has a speed variation function for a section to switch power between the engine and the motor and for motor efficiency enhancement. Inside the planetary gear mechanism, a radial needle roller and cage assembly and a planetary shaft are used. There is a need for size/weight reduction of the bearing to reduce the overall weight of the unit. However, bearing size reduction would lead to decreased load capacity, and then, the issue of insufficient bearing life. At JTEKT, we have addressed such issue by developing a long-life bearing with our original special heat treatment performed on the planetary shaft. However, recently we also developed a super-long life bearing featuring surface modification technology (**Fig. 24**).

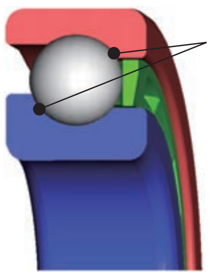


Fig. 20 High axial load-compatible ball bearing

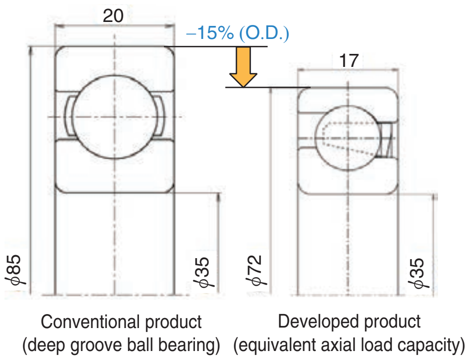


Fig. 21 Example of downsizing

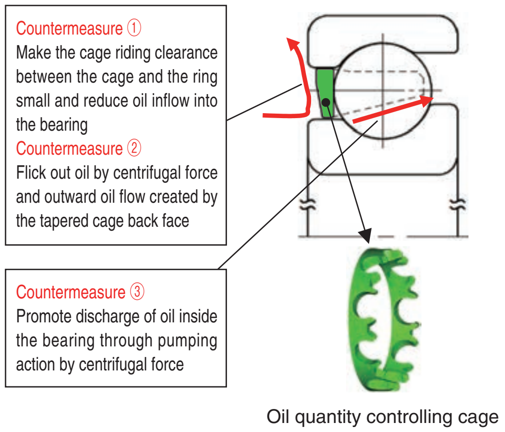


Fig. 22 Oil quantity controlling cage

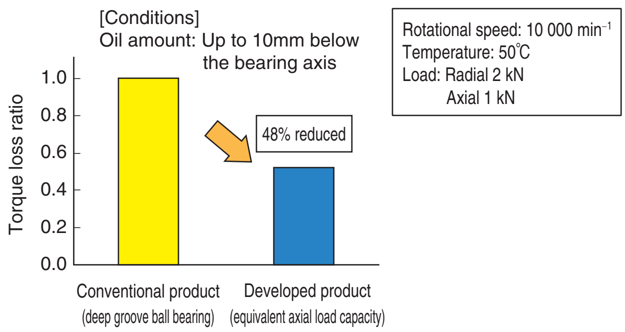


Fig. 23 Torque comparison results

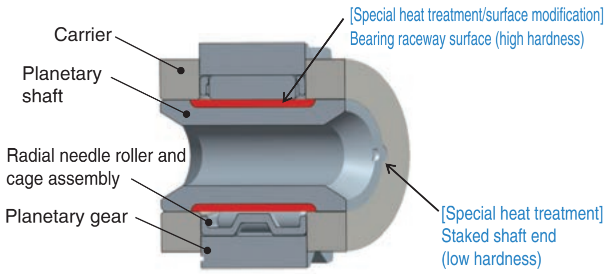


Fig. 24 Super-long life bearing for planetary gear

By applying special heat treatment, we enhanced the hardness of the raceway surface and optimized the amount of retained austenite, thus successfully extending bearing life. Moreover, with the aim of reducing the size and weight of the planetary gear mechanism, we maintained the low hardness of the end portion of the planetary shaft to deal with fixing it to the planetary carrier by staking. Additionally, through surface modification of the raceway surface, we further improved the hardness of raceway surface, and suppressed crack growth by forming high residual compressive stress layer in the surface layer. As a result, super long life, equivalent to five times that of the conventional model, has been achieved (**Fig. 25**). This enabled study to reduce bearing width by up to 40% and to reduce the number of pinions in the planetary mechanism to contribute to reduction of unit size and weight (**Fig. 26**).

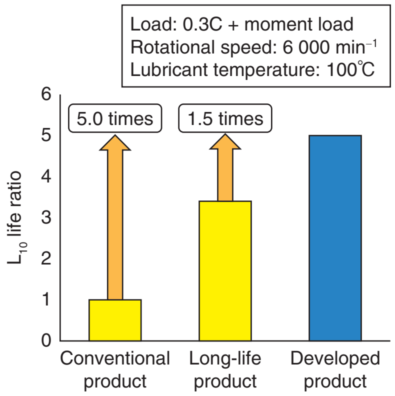


Fig. 25 Comparison of bearing basic rating lives

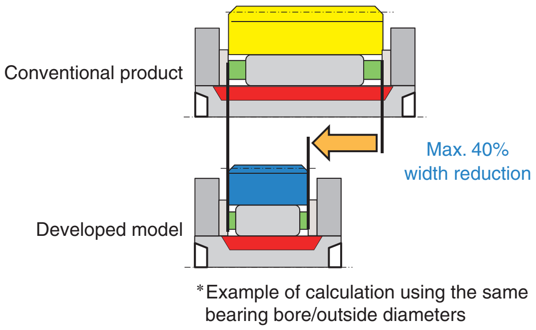


Fig. 26 Image of bearing downsizing

2. 3 Response to Engines

In the markets of newly emerging countries, the percentages of engine-driven vehicles and engine-equipped vehicles such as PHV/HV are high, and increasing engine efficiency is still a major issue. One feasible solution is a variable valve timing mechanism elaborately controlling engine gas intake.

Conventional variable valve timing (VVT) mechanisms featured hydraulic control utilizing hydraulic pressure produced by the engine. However, there was a limit to response speed depending on engine RPM and temperature. To overcome this issue, VVT mechanisms using motor drive are increasing instead of hydraulic drive. Motor drive makes optimal control of valve timing possible due to improved response speed as well as control even at low temperature and low rotational speed of the engine, which makes high output and high fuel economy possible.

Movable mechanisms adopt a motor reduction gear with a large reduction ratio.

Figure 28 shows the principle of the wave reduction gear mechanism using thin section ball bearings (**Fig. 27**) as a typical example. The inner ring, pressed onto the elliptical shaft, is deformed into an elliptical shape, and the position of outer ring deformation varies as the elliptical shaft rotates since the outer ring is also deformed via balls due to the inner ring deformation. Compared to the inner ring, which requires only simple deformation analysis, the outer ring requires cyclic bending fatigue strength verification. However, at JTEKT, we perform CAE (**Fig. 29**) and experimental verifications to offer bearings with even higher reliability.

Engine downsizing, a known approach to improving the fuel efficiency of engine-driven vehicles, requires a supercharging system. Recently, in order to improve fuel efficiency even further, electric superchargers have been added to conventional turbochargers utilizing exhaust to sophisticate supercharging systems with improved turbo efficiency through solving turbo lag, etc. This electric

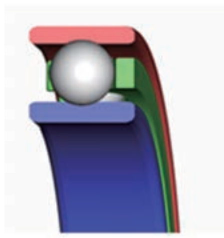


Fig. 27 Thin section ball bearing for wave reduction gear

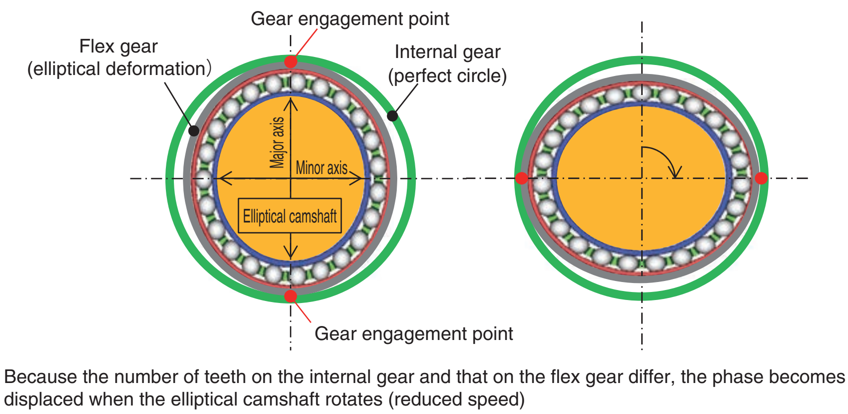


Fig. 28 Principle of wave reduction gear

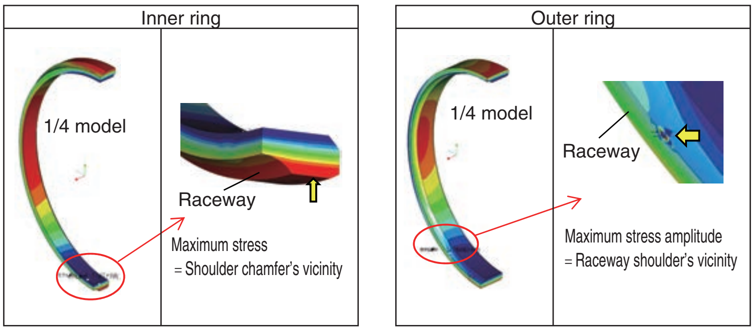


Fig. 29 CAE analysis examples

supercharger uses two ball bearings supporting the motor shaft. These ball bearings use grease lubrication. However, due to operating in extremely harsh conditions, namely ultra-high-speed and rapidly accelerated/decelerated rotation, conventional bearings faced the issue of seizure in a short time as a result of improper lubrication.

The ball bearing for electric superchargers developed by JTEKT recently (**Fig. 30**) has 1.5 times longer life than the conventional model by an internal design suited to high-speed rotation, and improved cage and seal lip shape, as well as adopting JTEKT's original grease for high-speed rotation (**Fig. 31**).

In order to improve engine efficiency, we have engaged in not only the electrification discussed here, but also replacement of the sliding bearings used for the cam shaft, balancer shaft and turbocharger by rolling bearings. With this, we anticipate not merely torque reduction, but also the secondary effects of pump reduction, oil hole/groove elimination, etc. although pumps and oil holes/grooves have been considered necessary for sliding bearings to produce hydraulic pressure. JTEKT will continue proactively engaging in efforts to achieve higher engine efficiency.

3. Bearings for Chassis

The hub unit (**Fig. 32**) is a unit bearing located in a vehicle's wheels to support the wheel, while supporting vehicle weight. Even amidst the electric motorization trend, wheel bearings are essential and there is a strong demand to reduce hub unit torque loss not only to improve fuel consumption, but also to improve electrical consumption. A hub unit comprises a bearing, which has a function to smoothly rotate tires, and a seal, which prevents muddy water splashed up by the tires from entering the bearing. Two types of torque loss exist; namely, bearing rolling resistance and seal sliding resistance. JTEKT has halved hub unit torque by developing low friction torque grease and a low friction torque seal (**Fig. 33**) as measures to reduce these individual resistances causing torque loss.

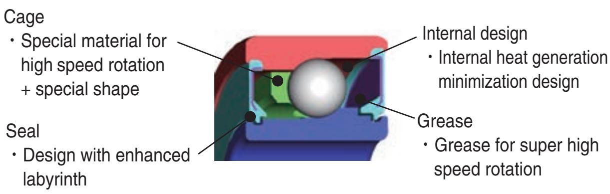


Fig. 30 Bearing for electric supercharger

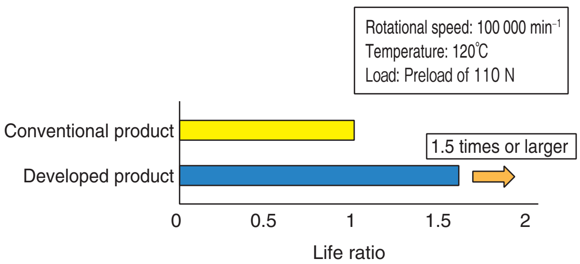


Fig. 31 Durability test result

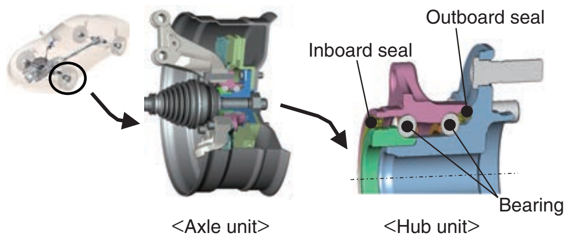


Fig. 32 Hub unit

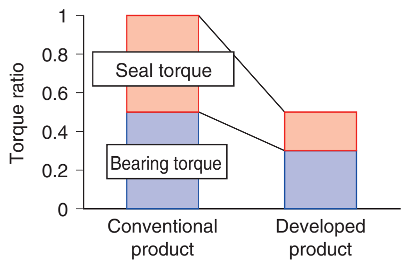


Fig. 33 Hub unit torque

First, in the development of low friction torque grease, bearing rolling resistance can be broadly divided into base oil viscous resistance, bearing rolling/sliding resistance, and agitation resistance of the grease itself. JTEKT achieved torque reduction by implementing measures for these three loss types.

①In regards to base oil viscous resistance, the kinematic viscosity of the base oil is the controlling factor. Therefore, we reduced kinematic viscosity to the bare minimum with consideration to securing oil film thickness even when the bearing is subjected to high surface pressure.

②As for bearing rolling/sliding resistance, we focused on the coefficient of friction of the interface, and revised the molecular structure of the base oil in order to reduce the coefficient of friction. Moreover, because there is correlation between the coefficient of friction and oil film thickness, we added to the grease an additive able to thicken oil film even at low speeds at which rolling/sliding resistance is large.

③Grease agitation resistance can be lowered by increasing grease consistency (softening). However, if grease fluidity increases, there is a conflicting issue such as grease leakage from the seal. As such, we adopted a special thickener able to lower grease shearing resistance without increasing consistency.

Next, in the development of a low friction torque seal, there is a need to reduce sliding resistance in order to reduce torque. However, in addition to this, there is a need to curb rust on the sliding surface of the outboard seal which is problematic in extremely cold regions and areas without adequate infrastructure. When rust is formed on the seal sliding surface, bearing life will be shortened because it will cause lip wear, which allows muddy water entry into the bearing. To address these two issues, we performed fluid analysis aiming to improve the environment of water exposure around the sealing lip (**Fig. 34**), and quantified water flow direction and flow volume, which we had been unable to confirm previously. Consequently, with consideration also to the surrounding structure of seal, we achieved 75% torque reduction and significant extension of bearing life in muddy water environment compared to the current model by improving five points (**Fig. 35**) on the outboard seal alone.

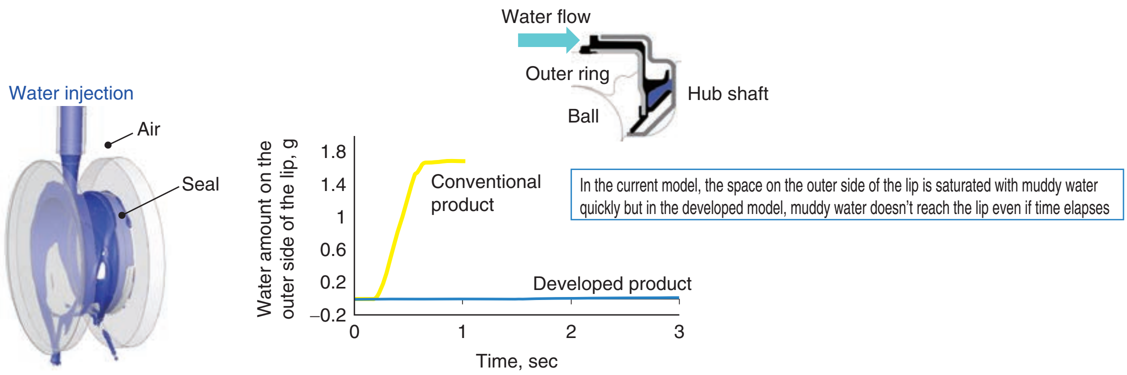


Fig. 34 Results of fluid analysis

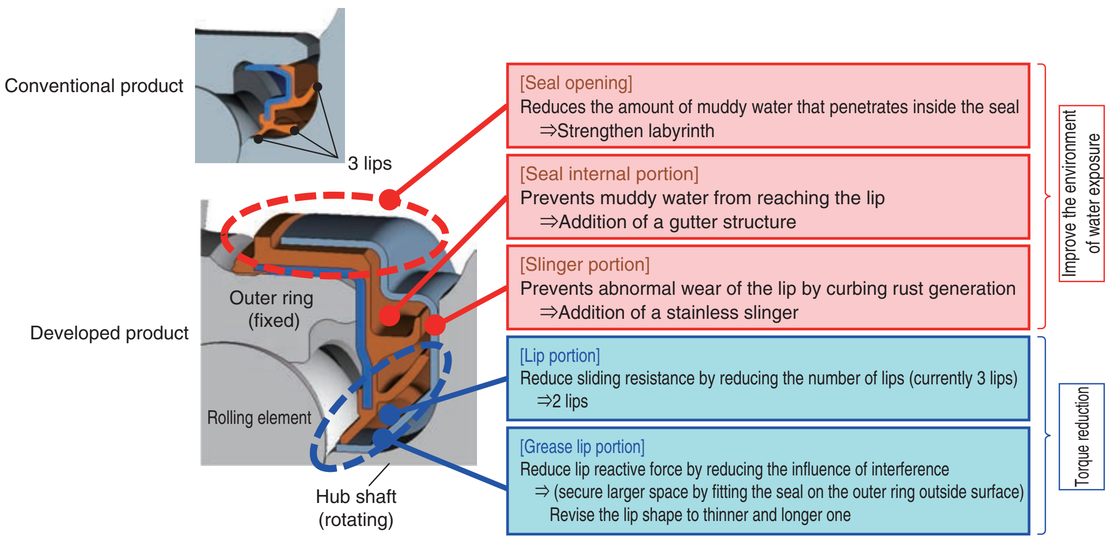


Fig. 35 Development points of seal on the hub unit outboard side

4. Future Outlook

The above sections have discussed development trends for various torque reduction technologies as well as downsizing/weight reduction technologies primarily focusing on JTEKT's response to electric motorization. At the same time as electric motorization, however, we believe that autonomous driving will also have a major impact on our bearing products. In regards to autonomous driving, there are outstanding issues such as establishment of infrastructure and legislation, which are the premise of popularization. However, technical progress is remarkable, and currently SAE Level 2 vehicles (partial automation where vehicle operation is led by a human driver) have been put to practical use. At the fully autonomous level, safety is of utmost priority, and sophisticated vehicle control technology is essential. Due to the fact that grasping road condition information is important in improving vehicle control accuracy, JTEKT is aiming to develop a road condition detection system leveraging the hub unit. By swiftly acquiring information from the hub unit, which is the closest to the road surface among all JTEKT products, we believe we can utilize such information for improving vehicle line traceability, braking control, and so forth.

Moreover, as a technology for the brake portion that can contribute to autonomous driving, we are also pushing ahead with ball screw development. For HVs, etc. electric brake boosters cooperatively controlled with energy regeneration (EHB: Electro Hydraulic Brake), etc. are being introduced to the market. However, in the near future, it is expected that electric calipers suitable for EVs, etc., which render hydraulic power source unnecessary (EMB: Electro Mechanical Brake), will also be released on the market. Ball screws are a promising item as a mechanism to convert motor rotary motion into linear motion and can contribute to reduction of motor size, etc.

JTEKT focused on the fact that the stroke is short when the EMB operates, and is developing a non-recirculating type ball screw with limited functions. We eliminated the ball circulating mechanisms such as tubes required in regular ball screws and arranged several springs internally (**Fig. 36**). As a result, we have succeeded in maintaining high efficiency without inhibiting ball rolling motion and in securing sufficient durability in maintenance-free grease lubrication conditions (**Fig. 37**). In EVs, etc., the EMB will be used as a brake-by-wire system connected with an electric cable alone, so it is easy to secure battery mounting space and passenger space. We believe this will greatly contribute to the realization of autonomous driving.

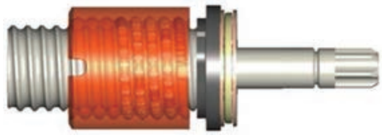


Fig. 36 Appearance of non-recirculating type ball screw

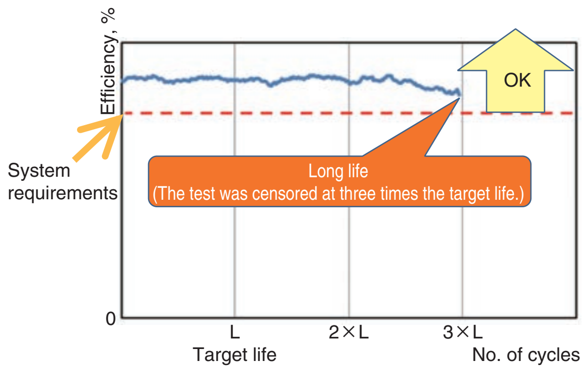


Fig. 37 Durability test result

5. Conclusion

In this once-in-a-century time of major change, the nature of automobiles is drastically changing. This report has introduced responses to electric motorization and autonomous driving as forms of that change. High rotational speed ball bearings, anti-creep ball bearings, etc. which are technologies responding to electric motorization, can all contribute to energy reduction, and thus preservation of the global environment, while sensing hub units, a technology responding to autonomous driving, can help to make human life more convenient. Moving forward, there will be a greater need for even more sophisticated mechanisms and systems such as those in FCVs, fully-autonomous vehicles, etc., which are called ultimate eco-friendly automobiles. JTEKT will deepen our unique tribological technologies and focus on developing not only low friction torque and size/weight reduction technologies, but also various sensing technologies and system products using actuators, etc. The change of automobiles in this age of revolution will make people's lives safer, more convenient, and more affluent. As a bearing manufacturer, JTEKT will steadily respond to such change and support realization of prosperous life.

* LFT is a registered trademark of JTEKT Corporation.

References

1) K. MIYAKE, T. TSUDA, K. YOSHIZAKI: JTEKT ENGINEERING JOURNAL, No. 1015E (2018) 26.
2) Y. TANIGUCHI, T. UMENO: JTEKT ENGINEERING JOURNAL, No. 1015E (2018) 52.
3) M. TANIYAMA, K. KOTANI, Y. NAKASHIMA, T. SATOU: JTEKT ENGINEERING JOURNAL, No. 1014E (2017) 54.
4) Y. ISHII, T. JINBO: JTEKT ENGINEERING JOURNAL, No. 1014E (2017) 59.
5) S. YAMANE, T. OGIMOTO: JTEKT ENGINEERING JOURNAL, No. 1014E (2017) 64.
6) D. OKAMOTO, A. SUZUKI, T. AIDA, K. NAITOU: JTEKT ENGINEERING JOURNAL, No. 1014E (2017) 69.
7) M. KAWAMURA: MACHINE DESIGN Vol. 60 (2016) 35.
8) ABeam Consulting: EV·Jidouunten wo koete “nihon-ryuu” de katsu, −2030nen no aratana kyousou-jiku towa−, Nikkei BP (2018) (in Japanese).

K. YOKOTA*

* *Executive Managing Officer*