Performance of Rear Differential Depending on Vehicle Driving Mode

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JTEKT has developed a tapered roller bearing with super-low-friction torque having 80% less friction torque than standard tapered roller bearings. To confirm the driving performance of rear differentials equipped with the developed bearing, the developed bearings were tested under all assumed driving modes using a newly designed drive unit simulator. The results show that they have lower friction torque at simulated actual driving modes compared with current bearings. Accordingly, we can accurately develop and provide super-low-friction tapered roller bearings from the perspective of actual application units and also can contribute to improvement of fuel efficiency.

Key Words: *tapered roller bearing, low friction torque, drive unit simulator, efficiency, driving mode*

1. Introduction

In recent years, with the advancement of awareness for global environmental issues, environmental regulations on automobile related items are becoming more and more severe. In particular, the approach towards improvement in fuel consumption and energy efficiency for the purpose of CO_2 reduction is considered as one of the most important subjects among vehicle manufacturers. Under such movement among vehicle manufacturers, expectation for lower bearing torque is high due to the fact that more than 100 bearings are mounted in a vehicle.

In order to meet such needs from vehicle manufacturers, our company has aimed its target to tapered roller bearings used extensively in automobile driving units (transmissions and differentials) and developed[1), 2)] super-low torque tapered roller bearings LFT®-Ⅲ (Low Friction Torque Tapered Roller Bearing 3rd Generation, the developed bearing) with reduced friction torque (torque) while maintaining such typical tapered roller bearing characteristics as compactness, long life and high rigidity (**Fig. 1**), which have been put into practical use.

Most driving units in vehicles use lubricating oil. The oil flow inside the unit varies depending on driving conditions of vehicles (environments, vehicle postures, acceleration, speed, etc.). This is considered to influence the unit performance to a great extent. As it is difficult to simulate the oil flow inside the unit by bearing component evaluation alone, an evaluation with an actual unit or actual vehicle is necessary. Therefore, if a unit evaluation reproducing a wide range of driving conditions becomes possible, it also becomes possible to verify effects and trade-offs prior to actual vehicle evaluation, enabling the development of low friction torque bearings with higher accuracy.

This paper presents the outline of a driving unit simulator (simulator) developed for the evaluation of rear differential (rear-diff) by reproducing driving conditions of vehicles. In addition, the results of rear differential performance tests under various driving conditions using this simulator are also reported with the developed bearing and conventional low torque bearings[3), 4)] (the conventional bearing) mounted on the pinion shaft of rear differentials.

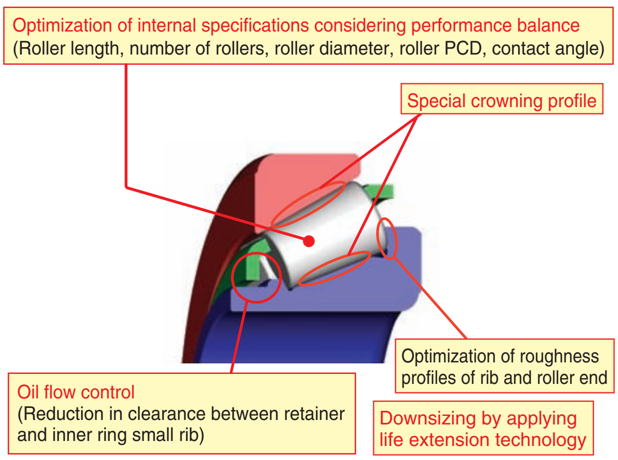

Fig. 1 Features of developed bearing

2. Actual Unit and Simulator

2. 1 Actual Unit

This time, a rear differential for rear wheel drive vehicles sold in the market was used as a sample. **Table 1** shows the difference between the conventional bearing and the developed bearing mounted on the pinion part of differential. Here, the internal specifications of the bearings correspond to **Fig. 2**. As the bearings were mounted on the same rear differential, the main dimensions of the bearings (bore, outer diameter and assembled width) were made the same. Also, the preload for assembling the bearings to the pinion part was set at 4 kN for both of the conventional and the developed bearings and a certain predetermined amount of gear oil was filled into the sample.

Next, in order to visualize the oil flow inside the rear differential, 3D data of differential gear was obtained using an industrial CT scanner and a transparent differential vehicle carrier was made using an optical molding method. Afterwards, rear differential was assembled and oil flow was visualized as shown in **Fig. 3** by mounting internal components (driving pinion, ring gear, seal and differential mechanism) into the transparent differential carrier.

Table 1 Differences between conventional bearing and developed bearing

Factor		Tapered roller bearing: Low torque (conventional bearing)	Tapered roller bearing: Super-low torque (developed bearing)
Internal design specifications	Roller length, LWR	Large	Small
	Number of rollers, Z	Many	Few
	Outer ring contact angle, α	Small	Large
	Pitch circle diameter of roller, dm	Large	Small
	Outer ring raceway Crowing radius, RCo	Large	Small
	Inner ring raceway Crowing radius, RCi	Large	Small
	Roller radius, DW	Small	Large
Oil inflow control	Clearance between retainer and inner ring	Large	Small

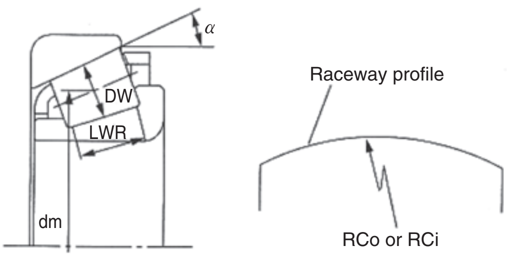

Fig. 2 Internal specifications of tapered roller bearing

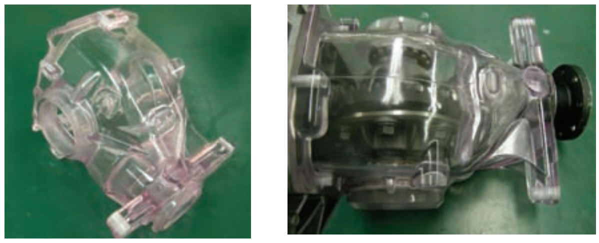

Fig. 3 Transparent rear differential gear

2. 2 Simulator

In order to verify the torque characteristics of differential, a simulator to reproduce actual vehicle driving postures (**Fig. 4**) was developed. With this simulator, four kinds of actual vehicle driving conditions can be simulated.

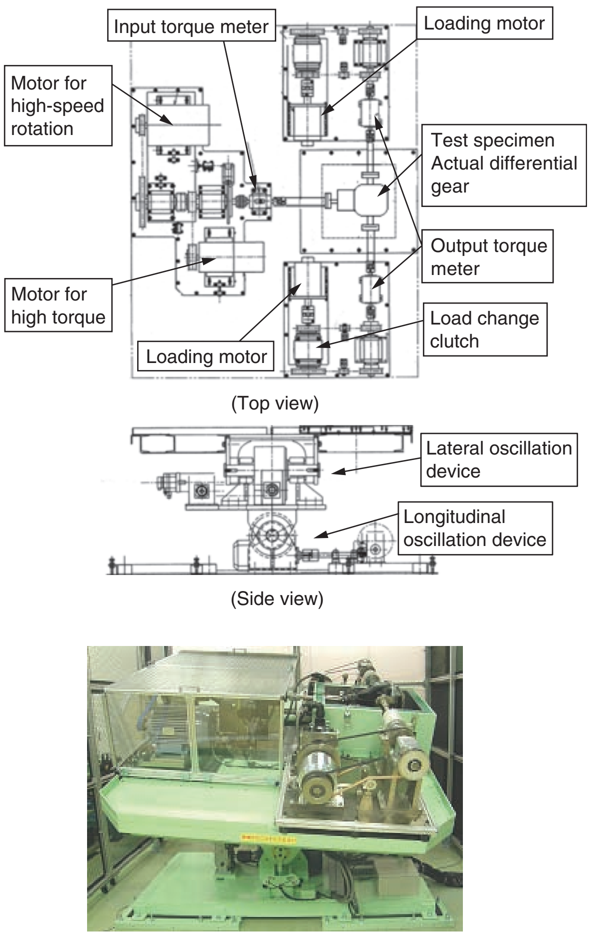

Fig. 4 Simulator

① Simulation reproducing up- and down-hill driving on mountainous roads

It is possible to simulate up- and down-hill driving by longitudinal oscillating device and driving speed by a driving motor.

② Turning simulation reproducing high-speed turning (on autobahn, etc.)

It is possible to simulate positional deviation of gear oil in the differential due to acceleration at turning by a lateral oscillating device and to simulate high-speed running by the driving motor.

③ Fuel consumption simulation reproducing urban driving

It is possible to measure torque loss (unit efficiency) of the differential under loaded condition on the tire by a loading motor.

④ Simulation reproducing outside environments

It is possible to execute up- and down-hill simulation, turning simulation and fuel consumption simulation under hot or cold environment.

These four kinds of driving simulations as described above can be executed automatically by inputting actual vehicle driving conditions to the program as shown in **Fig. 5**. As a result, differential torque, temperature of each part (bearing and gear oil) and unit efficiency can be measured under conditions closer to actual vehicles.

Fig. 5 Driving program

3. Torque Characteristics on Vehicle Driving Postures

Torque of a normal pinion bearing is said to occupy[5), 6)] 50% of the whole torque of a rear differential. For pinion bearings, tapered roller bearings are used mainly, whose torque generation factors and their contribution ratios were examined by an experiment and a calculation. The contribution ratio of viscous rolling resistance is the largest as shown in **Fig. 6**, followed by that of agitation resistance of gear oil. This shows that the amount of gear oil flowing into the pinion bearing part in rear differential fluctuates depending on actual vehicle's driving postures e.g. (up- and down-hill driving or turning condition, etc.) and influences the torque of rear differential.

3. 1 Torque Characteristics under Hill-Climbing Condition

In order to reproduce hill-climbing, the required climbing angle was set using the longitudinal oscillation device and the rear differential was set to a prescribed rotational speed by the driving motor. The torque of the rear differential was measured by the torque meter placed between the driving motor and the rear differential. An example of the test results is shown in **Fig. 7**. The unit mounted with the developed bearings (the developed unit) showed 10 to 20% of torque reduction effects at whole climbing angle range compared with the unit mounted with the conventional bearings (the conventional unit). In particular, more the gear oil is supplied to the pinion bearing part under the down-hill condition, higher the rotational torque with the conventional unit due to a lack of oil in-flow control in the bearing (clearance between retainer and inner ring is smaller compared with the conventional bearing). While, with the developed unit, there was no increase in rotational torque thanks to oil in-flow control. Thus the reduction effect of agitation resistance was verified.

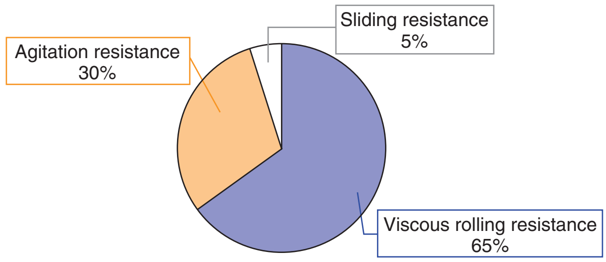

Fig. 6 Torque generation factors and each contribution ratio

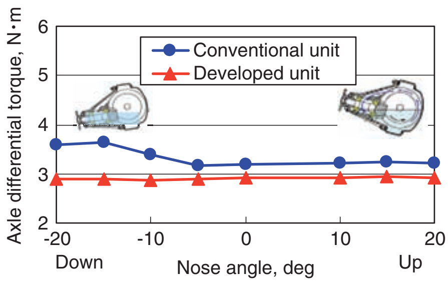

Fig. 7 Rear differential gear torque under hill-climbing condition

3. 2 Torque Characteristics under Turning Condition

In order to simulate high-speed turning condition in actual vehicle driving, it is necessary to consider positional deviation of gear oil to one side due to turning acceleration. In this simulator, it is possible to simulate positional deviation of gear oil by inclining the differential while controlling the lateral oscillation device instead of turning acceleration. An example of the test results is shown in **Fig. 8**. The developed unit showed torque reduction effect of 10% compared with the conventional unit even in the turning simulation.

Under left-turn condition, torque tends to go down for both the conventional and the developed units. Under left-turn condition, gear oil inside the rear differential moves to the opposite side of the ring gear and the gear oil supply amount to the pinion bearing part by the ring gear is reduced. Thus, gear oil agitation resistance by the pinion bearing is reduced. Further, as gear oil agitation resistance by ring gear is also reduced, unit torque is also considered to have been reduced. This was also the same for right-turn condition. As described above, the effect of reduction in agitation resistance was verified as same as for hill-climbing condition.

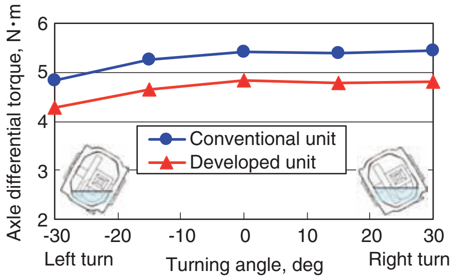

Fig. 8 Rear differential gear torque under turning condition

4. Influence of Ambient Temperature on Performance

4. 1 Verification of Oil Flow Change by Oil Temperature

Even if operated under the same rotational speed and torque condition, oil temperature changes due to ambient temperature and accordingly oil viscosity also changes. This influences the gear oil movement inside the differential to a great extent. For this reason, oil flow was observed at different oil temperatures using the transparent rear differential. As it is impossible to make a significant change in oil temperature in the resin made transparent differential, oil temperature difference was simulated by filling oils with different viscosity as shown in **Fig. 9** instead of changing oil temperature for the evaluation this time. The rear differential filled with the specified amount of oil was accelerated from half to the specified rotational speed and the time for gear oil to reach the input-side bearing (the tail-side bearing) of the pinion bearing was measured. The test condition was set at up-hill climbing condition (climbing angle: 15°) where it was difficult for gear oil to reach the tail-side bearing and the speed condition was set at 20 km/h equiv. Also, gear oil viscosity was set at 3 levels of –10℃, 30℃ (normal oil) and 80℃ equiv. Test results are shown in **Fig. 10**. With high viscosity oil of –10℃ equiv, the supply amount of gear oil by ring gear was small for both the developed and the conventional unit and it took more than 30 seconds for the gear oil to reach the tail-side bearing. In case of 30℃ oil temperature, it was confirmed that the developed unit could supply more gear oil to the tail-side bearing thanks to the oil in-flow control structure of the bearing. In the case of low viscosity oil with oil temperature of 80℃ equiv, the time for gear oil to reach the tail-side bearing tended to become shorter compared with the conventional unit. From these findings, it can be judged that the anti-seizure performance of the developed unit can be confirmed at low temperature condition where gear oil viscosity becomes high. While, at high temperature, as the time for gear oil to reach the bearing in the developed unit is shorter than that in the conventional unit, improvement in anti-seizure performance can be expected.

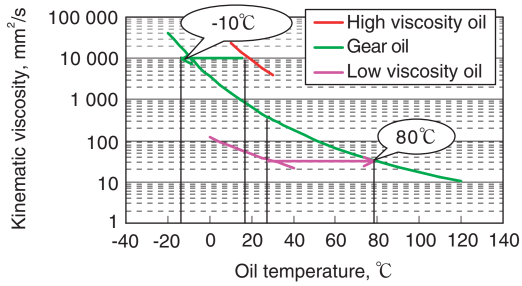

Fig. 9 Physical properties of test oil

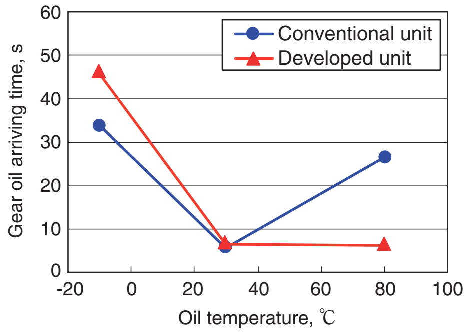

Fig. 10 Gear oil viscosity and gear oil arriving time

4. 2 Verification of Anti-Seizure Performance at Low Temperature Start

Torque reduction effects by means of oil in-flow structure of the developed bearing could be verified through the developed unit. But, seizure due to lack of gear oil becomes a concern as a trade-off of gear oil in-flow control. Therefore, the risk of pinion bearing seizure was verified with the developed unit under low temperature start condition which is considered to be most unfavorable as explained in above verification result of oil flow. As shown in **Fig. 11**, the developed unit was covered with a chamber and was cooled to a temperature of –40℃ using a cooling system. After cooling the developed unit, the unit was rotated to high speed with a driving motor to see if there is any sudden temperature rise (temperature peak) as a sign of pinion bearing seizure. As shown in **Fig. 12**, no significant temperature rise could be seen in the developed unit, thus it was judged that there was no problem in anti-seizure performance.

Fig. 11 Overview of low-temperature anti-seizure test

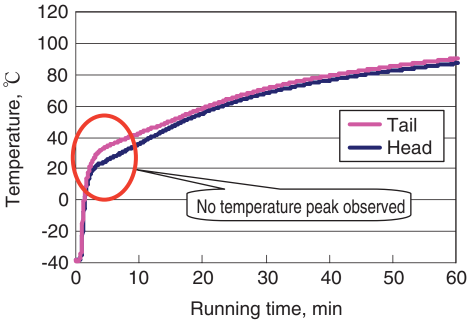

Fig. 12 Results of low-temperature anti-seizure test

5. Conclusion

A driving unit simulator for differentials able to reproduce a wide range of driving modes of actual vehicles has been developed. Utilizing rear differentials assembled with the developed bearing and the conventional one, the torque characteristics under hill-climbing and turning modes of actual driving conditions and the influences of ambient temperature on oil flow have been verified. As a result of the evaluation, the following findings have been obtained.

(1) Gear oil amount supplied to pinion bearings varies largely depending on driving modes of vehicles as well as the torque of rear differentials.
 - On down-hill driving, large amount of gear oil flows into pinion bearing part. Under this condition, the difference of 20% in torque value was observed depending on the presence or absence of oil in-flow control.
 - Under right- and left-turn driving, about 10% of torque difference was noted.

(2) The ambient temperature in which vehicles are used varies widespread from cold regions of –40℃ to tropical regions of 50℃.
 - Under cold region conditions, viscosity of gear oil became high and it took longer time for the gear oil to reach the tail-side bearing for pinion.
 - With the developed unit, verification of anti-seizure property at low temperature start condition was executed. No temperature peak, indicating a sign of seizure occurred. From this fact, it was judged that there was no risk of seizure for the developed bearing.

With the use of the simulator that was developed this time, it has become possible to implement the unit test of differential bearings under the same conditions as actual vehicles before actual vehicle evaluation and it can be expected to achieve the target in a short time for bearing development. We aim to utilize this simulator for the product development that leads to further improvement in vehicle fuel efficiency and contribute to society as well as global environmental protection.

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