Development of Needle Roller Bearing for High-efficiency Planetary Gear

M. TANIYAMA K. KOTANI Y. NAKASHIMA T. SATOU

In order to improve the fuel efficiency of vehicles to counter the current environmental crisis, the development of automatic transmission (AT) has continued to progress for increasing gear steps to multispeed, requiring planetary bearings for high-speed revolution. Moreover, planetary bearings for ATs are used under severe conditions such as high moment and centrifugal force. This paper describes the characteristics and design technique of planetary gear bearing developed by our company which facilitates high efficiency and high-speed revolution.

***Key Words**: needle roller bearing, planetary gear, automatic transmission, cage and roller*

1. Introduction

Automatic transmissions are becoming the mainstream transmission for passenger vehicles as they facilitate a comfortable driving experience. To help solving the global environmental problems highlighted in recent years, a lot of alternatives to vehicles which use reciprocating engines have emerged on the market, including hybrid vehicles combining an engine and motor (HEV) and electric vehicles powered only by motors. There are also efforts to improve the fuel economy of conventional reciprocating engines, such as the advancement of automatic transmission (AT), etc.

Recent years have witnessed an increase in car models adopting continuously variable transmission (CVT), and the market is diversifying with the emergence of dual-clutch transmissions, etc., however in regards to high-torque, large-engine capacity vehicles, a step-type AT which changes speed by a planetary gear set, is becoming mainstream.

Measures to improve fuel economy relating to AT are weight reduction, higher efficiency and a greater reduction ratio by adopting multi-speed. For this reason, the needle roller bearings (planetary bearings) used in AT planetary gear inners are required to rotate at even higher speeds, as shown in **Fig. 1**. In line with this, there is an increasing number of cases in which radial type needle roller bearings with cages (cage and roller) are used as an alternative to the full-complement needle roller bearing, which used to be mainstream.

Planetary gear mechanisms are also being used in the power switching unit of HEVs. HEVs are characterized by the fact lubricant supply is stopped when the oil pump stops during motor-based driving, therefore in order to enhance the lubrication of the planetary bearing, the cage and roller type is increasing in this position.

This paper introduces the development activities underway for the needle roller bearing used in planetary gears which facilitates high efficiency and high speed.

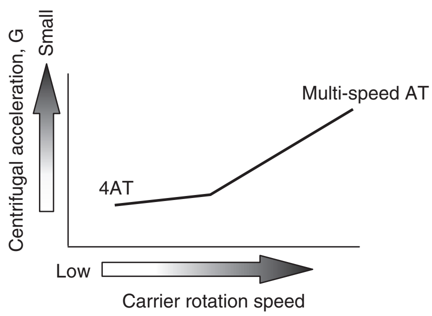


Fig. 1 Effects of multi-speed AT

2. Improvement for Planetary Bearings

Figure 2 shows the mechanisms of a single pinion-type planetary gear. Recently, many multi-speed ATs use various types of structures, such as double pinion and Ravigneaux, however the issues relating to bearings are the same in any type of planetary structure as in the single pinion-type.

In response to the global environmental problems highlighted in recent years, the centrifugal acceleration and rotational speed of bearings are increasing. Accordingly, there is an increased potential requirement for planetary bearings to have longer life, stronger cages and anti-seizure performance (**Fig. 3**). This section introduces the long-life planetary bearing, high-speed planetary bearing and ultra-thin thrust needle roller bearing developed to satisfy such demands.

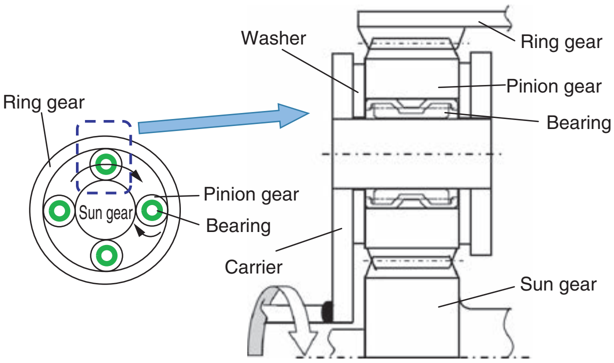


Fig. 2 Mechanism of single pinion type planetary gear

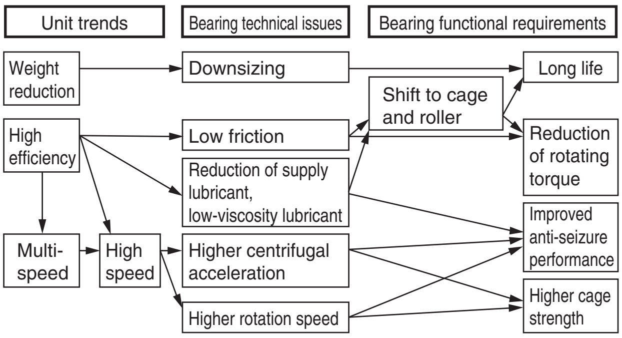


Fig. 3 Required functions of planetary bearing

2. 1 Long-Life Planetary Bearing

Helical gears are used as AT planetary gears therefore the planetary gear, as the gear inner, is subjected to tangential force (Ft), radial force (Fr) and axial force (Fa) due to the helix angle (**Fig. 4**). The axial force (Fa) acts on the bearing as moment load. Moment load acts together with radial load and causes the gear to tilt. For that reason, if the contact surface pressure on rolling surface of roller end portion increases and exceeds the limit, edge load will occur. Edge load drastically reduces life and therefore must be controlled by appropriate crowning shape on roller.

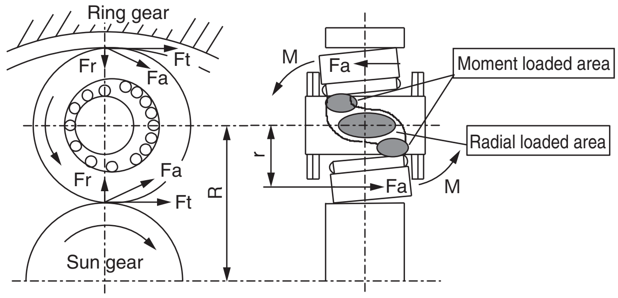


Fig. 4 Forces acting on pinion gear

One feature of the conventional full complement roller bearing for planetary is the large load capacity compared to the cage and roller bearing. However, the adjacent rollers repeatedly slide and collide, therefore if the bearing rotates at high speed, problems such as large rotational torque and seizure occur.

Meanwhile, in the case of the cage and roller, there is no direct contact between the rollers therefore high-speed rotation is capable. However, cage and roller bearings had the issue of a short life due to having less rollers than the full complement roller bearing, hence a small load capacity. In light of these circumstances, the life of the cage and roller has been improved.

Of the components comprising a planetary gear, pinion gear (outer ring), rollers, and shaft (inner ring), the shaft is the most susceptible to damage. Typical radial needle roller bearings are used with the outer ring fixed and the inner ring rotating. In this case, the contact surface pressure of the inner ring is greater than that of the outer ring due to curvature, however the number of cycles to failure is greater on the fixed outer ring than the inner ring. As such, from the perspective of impact on life, there is no significant difference between the load on the inner ring and the load on the outer ring. In contrast, planetary bearings are normally used with the pinion gear (outer ring) rotating and the shaft (inner ring) fixed. Not only is the contact surface pressure of the shaft high, it also has a large number of cycles to failure, therefore has the most severe load conditions.

Moreover, due to moment load, the contact surface pressure of the roller rolling surface end portion is high, causing the lubricant film to become thinner, therefore surface spalling may occur due to the oil film shortage. JTEKT has focused on these issues and developed a bearing with significantly longer life than conventional bearings. Bearing life was improved by combining the two measures explained below.

The first measure was to improve the lubricant film parameter, Λ, by improving roller surface roughness and achieving a mirror finish. But this alone is not enough to improve life satisfactorily. As such, a second measure of improving fatigue strength of the shaft was implemented.

Conventionally, life was improved by applying special heat treatment to the shaft, however by adding surface modification with shot peening, it was possible to apply a high residual compressive stress (**Fig. 5**) thereby extending life by 8 times that of standard bearings (**Fig. 6**).

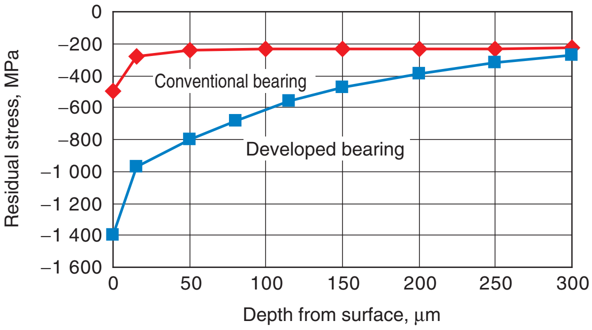


Fig. 5 Example of residual compressive stress measurement

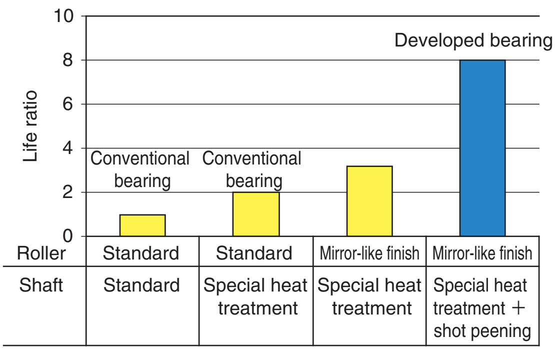


Fig. 6 Life test results

2. 2 High-Speed Planetary Bearing

Due to centrifugal acceleration, centrifugal force acts on the cage depending on the mass of the cage itself. As such, the cage is pressed to the pinion gear bore and rotates together with the pinion gear. However, the rollers revolve at around half the speed of pinion gears, hence push the cage back with a force equivalent to the frictional force of the cage's outer face and pinion gear's bore.

Moreover, the roller is subjected to centrifugal force due to the revolution around the sun gear, therefore each roller applies a load which comes from this centrifugal force on the cage.

These forces act repeatedly due to cage rotation, therefore the bearing design must be such that the stress which occurs on the cage is less than the fatigue limit. JTEKT uses the types of cages shown in **Fig. 7** depending on load. A resin cage will be used if centrifugal force is small and a steel cage will be used if centrifugal force is high. There are standard types and high-speed types of cages available, depending on the operating condition.

In development projects to date, there is a tendency for the stress at the cage rib and cage pillar base to be high, and it was recognized that performing design verifications on these sections was difficult. In order to reduce this stress, JTEKT applied its proprietary forming technology to form the optimal cage cross-section and developed a high-strength cage.

Figure 8 is a table comparing the performances of the standard, high-speed (conventional bearing) and high-speed (developed bearing) cages. The cage of the developed bearing has high strength, therefore stress is reduced by 12% compared to that of the conventional bearing. This makes it possible for the developed bearing to respond to 12% higher centrifugal acceleration compared with the conventional bearing.

Moreover, the cage has higher strength under the same operating conditions as those of the conventional bearing, making it possible to increase the number of rollers and raise the dynamic load ratings of the bearing, therefore it is also possible to improve bearing life.

Based on the increase in dynamic load ratings, C, life was calculated as being around 1.25 times longer, and by combining this with the long-life planetary bearing technologies introduced in the preceding section, the life of the developed bearing is 10 times greater than that of the standard bearing.

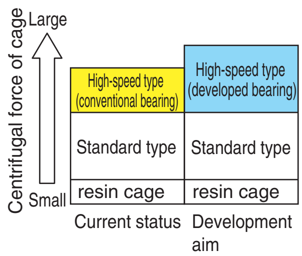


Fig. 7 Types of planetary bearing cages

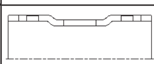
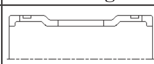
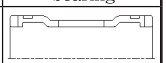
	Standard type	High-speed type	
		Conventional bearing	Developed bearing
Shape			
Mass, g	4.9	4.4	4.2
No. of rollers	12	12	13
Stress occurring at 2 000 G, MPa	270	170	149
Rated load C/C0, kN	17.5/22.9	18.0/24.0	19.3/26.0

Fig. 8 Comparison of steel cage performance

In line with the shift to multi-speed ATs of recent years, cage centrifugal force is increasing due to a larger carrier revolution radius and bearing size. It is considered that, if there is a large cage centrifugal force and the cage is rotating at high speed, then there will be a large frictional force between the pinion gear bore and cage outer face, hence seizure may occur on the outer face of the cage.

To prevent such seizure, it is necessary to increase the amount of lubricant supplied to the planetary bearing in an AT unit however from the perspective of increasing AT efficiency, there are cases where significant increases in lubricant supply are not possible. In such cases, the cage may be coated in order to reduce the friction between the pinion gear bore and cage outer face.

It has been confirmed through evaluation that, by coating the cage, the friction index, PV, which is the multiplication of contact surface pressure between the pinion gear bore and cage outer face, P, and the sliding speed, V, improved by 1.3 times.

3. Ultra-Thin Thrust Needle Roller Bearing

JTEKT develops the peripheral components of planetary bearings also.

Planetary bearings generate axial load internally as a result of skew, which is unique to roller bearings (the roller rotating axis tilts relative to the bearing central axis). This is referred to as skew force. It is possible that the skew force may increase due to the impact of pinion gear accuracy and carrier rigidity. Skew force acts on the side washer from the cage end face. The side washer has high frictional torque due to being used as a sliding portion, therefore the compact, ultra-thin thrust needle roller bearing (**Fig. 9**) was developed to reduce torque by replacing to a rolling bearing. The thrust needle roller bearing developed by JTEKT is one of the smallest in the world with two races totaling a thickness of 2mm. It adopts small diameter rollers with an O.D. of 1mm and length of 2.5mm.

Typically, thrust needle roller bearings use rollers with an O.D. of 2mm as the standard dimension. As such, JTEKT aimed to reduce the roller O.D. by half to 1mm, however the machining of thrust bearing rollers was difficult initially due to their short length. However, JTEKT succeeded in developing an ultra-thin thrust needle roller bearing through the establishment of a machining technology enabling the roller O.D. to 1mm.

Figure 10 provides the test results comparing the frictional torque of the current copper washer and thrust needle roller bearing, respectively. Unit test of bearing shows torque has been reduced by 80% or more. If there is a large skew force in the planetary bearing, the frictional torque on the pinion gear end face can also be reduced by adopting the developed bearing.

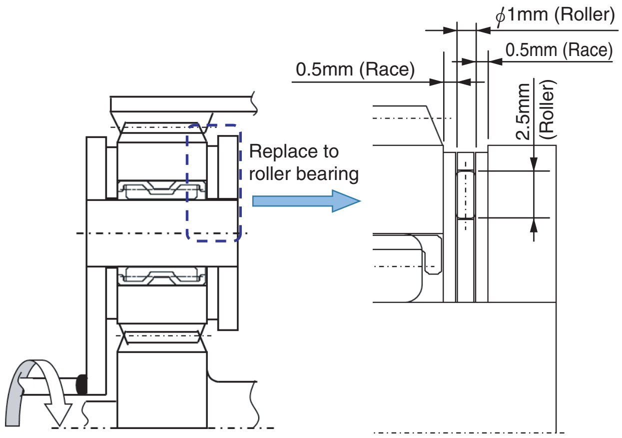


Fig. 9 Ultra-thin section thrust needle bearing

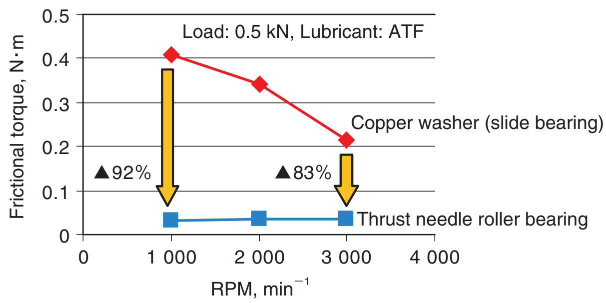


Fig. 10 Bearing bench test results

4. Conclusion

Figure 11 summarizes the effects of the needle roller bearings for planetary gears developed to satisfy high speed and high efficiency demands. The need to enhance fuel economy further will continue to intensify, therefore JTEKT wishes to develop bearing products in response to future trends based on the developments introduced here.

<table>
<tr><th>Bearing</th><th colspan="3">Effect of developed bearing</th></tr>
<tr><td>Long-life planetary bearing</td><td colspan="2">Life improvement:
8 times of standard bearing</td><td rowspan="2">Life improvement (total):
10 times of standard bearing</td></tr>
<tr><td rowspan="3">High-speed planetary bearing</td><td>No. of rollers:
1 additional roller</td><td>Life improvement:
1.25 times</td></tr>
<tr><td colspan="3">Cage stress: 12% less
→ Centrifugal acceleration response: 12% higher</td></tr>
<tr><td colspan="3">Coating of the cage outer face
→ Friction index PV: 1.3 times improved</td></tr>
<tr><td>Ultra-thin thrust needle roller bearing</td><td colspan="3">Replace to side washer rolling bearing
→ Over 80% reduction in frictional torque (bearing bench test result)</td></tr>
</table>

Fig. 11 Summary of effects of developed bearing

References

1) K. Chihara, T. Satou : Koyo Engineering Journal, No.168E (2005) 39.
2) M. Kitamura : Koyo Engineering Journal, No.164E (2004) 19.


M. TANIYAMA*


K. KOTANI**


Y. NAKASHIMA*


T. SATOU***

* *NRB Business Development Dept., Bearing Operations Headquarters*
** *Central JAPAN Technical Center, Bearing Operations Headquarters*
*** *East JAPAN Technical Center, Bearing Operations Headquarters*