For improving the fuel economy of vehicles to counter the environmental crisis, automatic transmissions (ATs) have become multi-step types requiring high-speed revolution in the planetary bearings. On the other hand, planetary bearings for ATs are used under severe conditions regarding such areas as moment and centrifugal force. This article describes characteristics and design techniques concerning planetary bearing and shows newly developed planetary bearings capable of high-speed revolution.

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

1. Introduction
Of the various types of transmissions for passenger cars, automatic transmissions, which have enabled easy driving, have dominated the market. Although an increasing number of compact and subcompact models are adopting belt-type infinitely variable transmissions, the conventional stepped type automatic transmission with a planetary gear mechanism (hereinafter AT) still prevails for full-sized vehicles involving high torque.

In response to various environmental problems, fuel efficiency countermeasures related to ATs are being required, and for that purpose AT lightweightness and the speed-reduction ratios have been pursued along with increasing the number of steps. As a consequence, the needle roller bearings used in AT planetary gears (hereinafter “Planetary bearings”) have been required to cope with higher rotational speeds, as illustrated in Fig. 1.

At the same time, the previously predominant full-complement-type needle roller bearings are increasingly being replaced as planetary bearings by caged needle roller assemblies (cage & rollers) for the sake of lightness and ease of handling.

Fig. 1 Influence of AT multi-stepping
This paper will introduce features and technical trends of the planetary bearings for AT's.

2. Structure of Planetary Gear Unit and Bearing Design

Figure 2 shows an example of an AT utilizing a simple planetary gear mechanism for a FR vehicle. Although various types of mechanisms, such as the double pinion type and Ravigneaux type, have recently been commercialized, the basic issues involving the bearing are the same as those on the simple planetary gear mechanism.

3. Bearing Design to Cope with Moment

3.1 Bearing Life

As the planetary gears of the AT are helical, the planetary bearing inside the planetary gear is subjected to tangential force $F_t$, radial force $F_r$, and axial force $F_a$ due to the helix angle of the gear (Fig. 3). The axial force $F_a$ acts on the bearing as a moment. Because the moment acts to augment the radial load, it tends to incline the gear. Consequently, the contact stress at the end of the roller raceway becomes extremely high, which eventually causes edge loading if it exceeds a certain limit. Since edge loading can shorten bearing life extremely, it is necessary to crown the roller properly to preclude edge loading (Fig. 4).

However, even if edge loading is avoided by crowning the roller profile, increased contact stress in the vicinity of the roller end is still unavoidable. Generally, the life of a roller bearing in terms of total number of rotations $L$ is expressed by the following equation (1):

$$L = \frac{C}{P}$$

(1)

C: Dynamic load rating of the bearing
P: Radial load

However, equation (1) does not take into account increased contact stress around the end of the roller due to the moment, and actual life of the planetary bearing is shorter than that obtained by equation (1).

The incremental contact stress due to the moment varies depending on the gear specifications (helix angle, gear meshing pitch circle diameter, etc.) as well as on the torque transmitted through the gear unit. Therefore, life calculation of the planetary bearing takes into account a life reduction factor based on contact stress at each step of speed calculated from the actual gear specifications and transmitted torque at each speed step, using the actual percentage of usage of each speed step.

It has been known from past experience that the life of a planetary bearing under a moment is reduced to as short as 30%~5% of that under a radial load only.

3.2 Seizure Propensity (Limiting Speed)

The limiting speed of a bearing is often evaluated in terms of the $DmN$ value, i.e. the value obtained by multiplying the pitch circle diameter of the rollers and the rotational speed of the bearing. In case of high load (or if the contact stress is high), however, it is necessary to take into account a correction coefficient depending on the C/P value (Fig. 5).

Fig. 5 Values of correction coefficient of load magnitude

Nevertheless, since the planetary bearing is subject to widely varying contact stress due to the moment, as mentioned earlier, it is not appropriate to simply use the correction coefficient for the C/P value.

Therefore, taking into consideration all the above circumstances, a new parameter called the "rolling PV value," obtained by multiplying the $DmN$ with the contact stress under the above mentioned moment, has been introduced. Figure 6 shows the results of a series of anti-seizure tests under varying lubricant supply conditions to determine what rolling PV value the bearing can withstand.
4. Bearing Design Taking into Account Centrifugal Force

4.1 Centrifugal Force Acting on Cage due to Orbiting of Planetary Gear

Figure 7 shows various action patterns of the simple planetary gears and corresponding bearing behaviors. In patterns A and B, the planetary bearing is subjected to centrifugal force due to its orbiting movement, which has repeated peaks due to its rotating movement.

Supposing, for instance, that the radius and the orbiting speed of the carrier are 50mm and 6 000 min⁻¹, respectively, the centrifugal acceleration due to orbiting will reach approximately 2 000 G. Because of this, the planetary bearing needs to be designed to cope with the load due to centrifugal force on top of the load from the gear meshing.

4.2 Design of Cage

Because of centrifugal acceleration, the cage is subjected to a centrifugal force due to the mass of the cage itself. Also due to this centrifugal force, the cage is pushed against the bore of the gear, and hence tries to rotate at the same speed as the gear. However, since the rollers orbit at approximately half the speed of the gear, the rollers push back on the cage with a force equivalent to the friction force between the cage OD and the gear bore. In addition, as the rollers orbit around the sun gear with centrifugal force generated, each roller exerts such centrifugal force against the cage.

Since these forces act in the form of repeated load, the cage needs to be designed in such a manner that the stress generated by the centrifugal force is equal to or less than the fatigue limit. An example of FEM analysis is shown in Fig. 8.

5. Planetary Bearing for High Rotational Speed

5.1 Lightweight High Strength Cage

In an effort to meet the increased speed of the planetary gear, a new design planetary bearing has been developed, whose features are summarized in Fig. 9. In response to the increase of centrifugal acceleration, the thickness and weight of the cage have been reduced to make the centrifugal force smaller, while the strength of the cage has been increased by improving the design of the ribs.

![Fig. 6 Result of seizure resistance test](image1)

![Fig. 7 Basic motions of planetary gear](image2)

![Fig. 8 Example of FEM analysis](image3)

![Fig. 9 Developed vs. conventional](image4)
5. 2 Evaluation of Lightweight High Strength Cage

5. 2. 1 Fatigue Strength Test (Static Evaluation)

In order to ascertain the strength of the ribs, a compressive fatigue test was conducted using a hydraulic pulsating fatigue tester, with results as shown in Fig. 10.

From Fig. 10, it was confirmed that the developed cage with improved rib design is stronger than the conventional cage, even though it is thinner and lighter.

![Fig. 10 Result of fatigue test](image)

**Fig. 10** Result of fatigue test

5. 2. 2 Centrifugal Acceleration Test (Dynamic Test)

To evaluate the strength of the cage in test conditions closer to those in the actual vehicle, a test was conducted on the planetary gear test machine shown in Fig. 11, which simulates the influence of centrifugal force, such as friction between the gear bore and the cage, as well as the load imposed by the rollers on the cage.

The test results, shown in Fig. 12, confirmed that the developed cage could handle approximately 1.6 times greater centrifugal acceleration than the conventional cage.

![Fig. 11 Schematic of test device](image)

**Fig. 11** Schematic of test device

![Fig. 12 Result of planetary gear test](image)

**Fig. 12** Result of planetary gear test

6. Conclusions

Planetary gear units are currently used in various applications other than ATs, such as the forward/backward changer in belt-type CVTs, the power source changer in hybrid cars, and the speed reducer in electric vehicle motors. Thanks to its compactness and feature of speed changing on the same axle, it is expected that the planetary gear unit will be employed in a broader range of applications.

The author’s team will continue to develop products for a wider range of applications based on our expertise accumulated through development of bearings for ATs.

Reference