Extremely High Load Capacity Tapered Roller Bearings

1. Foreword

People around the world have been increasingly concerned with prevention of global warming and improvement in air quality. In this context, the level of allowable vehicle emissions has been increasingly more stringent, and a Japanese target value for improvement in fuel economy for cars has been established—average 23.5% improvement in fuel economy by the end of fiscal year 2015 relative to the fiscal year 2004 level \(^1\)). While automakers have been more deeply committed to efforts for improved fuel economy, engineering people specializing in automotive transmission and differential gearing have been attempting to use less viscous oil and more compact, lighter weight designs aimed at reduced friction of automotive transmissions and differentials. To help contribute to this trend, the bearing industry has been challenged with a life and rigidity requirement for compact, light-weight bearings. To address these challenges, NTN has developed and marketed a line of extreme high load capacity tapered roller bearing products\(^2\), which result in lighter, more compact bearings at the same bearing life or a longer bearing life bearing size.

NTN developed a tapered roller bearing with extremely high load capacity to improve the fuel efficiency of cars. This new bearing has improved capacity from increasing the number and length of the rollers. This bearing is used for transmissions and differential gears. This article introduces the design and performance of this product that we have developed.

2. Structure of NTN extreme high load capacity tapered roller bearing

In addition to these structural features of the previous high load capacity bearing products, our newly developed extreme high load capacity tapered roller bearings (the example in the right in Fig. 1) have a resin cage and maximized-length rollers, and are available in two structural types: (1) bearing without inner ring small side rib, and (2) bearing with inner ring small side rib.

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2.1 Bearings without inner ring small side rib

Fig. 2 schematically shows the structure of a bearing without an inner ring small side rib, and Fig. 3 illustrates a 3D model of this bearing. A bearing design without an inner ring small side rib is intended to be used in space constrained applications where the additional geometry required for the rib would make the overall bearing too large. The features of this bearing structure are as summarized below:

(1) Cage: The small side rib has a minimum width just sufficient for satisfying the mechanical strength required of it.

(2) Roller length: The length of rollers may be increased to the maximum width of inner and outer ring raceways provided that the maximum allowable cage protrusion is not exceeded.

(3) Lock structure using teeth on cage: So that an inner ring/rollers/cage ASSY can remain non-separable, a lock structure is provided which consists of teeth on the large diameter side on cage, wherein these teeth are engaged with the grooves formed on the outer circumference of inner ring large side rib.

2.2 Bearings with inner ring small side rib

Fig. 4 shows one example of a bearing structure with an inner ring small side rib. There may be cases where the dimension of inner ring width can be increased even though the allowable dimension of protrusion of cage is limited. Then, the bearing with inner ring small side rib may be adopted, and its features are described below.
Cage: The cage is designed with the minimum rib width necessary to satisfy the mechanical strength required of the cage small diameter rib under the intended bearing operation conditions.

Roller length: The length of rollers are maximized while leaving sufficient room for the small rib and having a cage small end protrusion which is acceptable.

3. Features of NTN extreme high load capacity tapered roller bearings

Thanks to increase in quantity and length of rollers, the NTN extreme high load capacity tapered roller bearings boast functions improved over the NTN standard tapered roller bearing products, and the examples of improvement in functions are as described below:

(1) Greater load rating
  ● Basic dynamic load rating: 16% increase at maximum (64% increase at maximum in calculated life)
  ● Basic static load rating: 21% increase at maximum (21% increase at maximum in safety factor)

(2) Greater rigidity
  ● Bearing rigidity: 14% improvement at maximum (14% reduction at maximum in elastic displacement)

(3) Longer bearing life
  ● Useful life under clean oil lubrication condition is extended.

  The use of an increased number of longer rollers helps reduce the maximum bearing stress, leading to an increased oil film thickness and alleviation of stress that occurs in a metal-to-metal contact mode. Consequently, occurrence of surface initiated flaking, which can occur from metal-to-metal contact under a condition where formation of oil film is difficult, has been prevented and bearing life has been extended.

  Useful life under contaminated lubrication condition is extended.

  The use of an increased number of longer rollers helps reduce the maximum bearing stress, limiting the size of dent mark caused by trapped foreign matter. The stress occurring on the raised material around a dent mark is also reduced thereby resulting in longer life under contaminated lubrication conditions.

4. Performance of NTN extreme high load capacity tapered roller bearings

The NTN extreme high load capacity tapered roller bearing differs from other NTN tapered roller bearings in having an increased number of longer rollers and a lock structure on the large side diameter of the cage. To study the effects of these special features on the bearing, we have performed a function assessment test comparing the standard tapered roller bearing and extreme high load capacity tapered roller bearing (without inner ring small side rib) shown in Table 1.

(1) Result of pumping performance test

The NTN extreme high load capacity tapered roller bearing features a unique lock structure on the larger diameter side of cage as well as increased number of rollers and roller length. Fig. 5 provides visual comparison between both bearing types in terms of the space volume. It is apparent that the clearance between rollers is smaller on the NTN extreme high load capacity tapered roller bearing owing to increase in the number of rollers and as a result, the space volume in the bearing is smaller.

We have compared the flow rates of lubricating oil flowing through both bearing types in running mode. Fig. 6 schematically illustrates concept of the pumping performance test. When a bearing is run with the interior of bearing and housing filled with lubricating oil, a pumping function takes place on the bearing, thereby the lubricating oil flows from the large diameter side of the bearing. Fig. 7 graphically plots the measured amounts of lubricating oil pumped through the bearings after operating for a fixed duration. Though having a smaller space volume within its interior, the NTN extreme high load capacity tapered roller bearing offers a flow rate comparable to that of the standard roller bearing sample.

(2) Roller settling performance comparison test

When an NTN extreme high load capacity tapered roller bearing without inner ring small rib is used, the
Fig. 5 Space volume of bearing inside

Let us describe roller settling performance. When an inner ring assembly is fitted into an outer ring from above, a clearance will occur on the inner ring large side rib since the length of rollers is usually smaller than the inner ring raceway width (see Fig. 8).

Because the rollers in a running bearing rotate while being guided by the inner ring large side rib surface, the bearing needs to be subjected to a seating operation in order to allow the rollers to shift to normal

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**Table 1** Comparison of bearing internal design

<table>
<thead>
<tr>
<th></th>
<th>Standard tapered roller bearing</th>
<th>High load capacity bearing</th>
<th>Extreme high load capacity bearing</th>
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<tbody>
<tr>
<td>Schematic view</td>
<td><img src="image" alt="Schematic view of bearing" /></td>
<td><img src="image" alt="Schematic view of bearing" /></td>
<td><img src="image" alt="Schematic view of bearing" /></td>
</tr>
<tr>
<td>Bearing size</td>
<td>$\phi 25 \times \phi 52 \times 16.25$</td>
<td>$\phi 25 \times \phi 52 \times 16.25$</td>
<td>$\phi 25 \times \phi 52 \times 16.25$</td>
</tr>
<tr>
<td>Load rating (comparison with standard tapered roller bearing)</td>
<td>Basic dynamic load rating $C_r = 31.5kN$</td>
<td>Basic dynamic load rating $C_r = 34.0kN$ (8% increase)</td>
<td>Basic dynamic load rating $C_r = 36.5kN$ (16% increase)</td>
</tr>
<tr>
<td>Basic static load rating $C_{0r} = 34.0kN$</td>
<td>Basic static load rating $C_{0r} = 37.0kN$ (9% increase)</td>
<td>Basic static load rating $C_{0r} = 41.0kN$ (21% increase)</td>
<td></td>
</tr>
<tr>
<td>Number of rollers</td>
<td>16 rollers</td>
<td>17 rollers</td>
<td>17 rollers</td>
</tr>
<tr>
<td>Length of rollers</td>
<td>10.5mm</td>
<td>10.5mm</td>
<td>11.8mm</td>
</tr>
<tr>
<td>Cage material</td>
<td>Steel plate</td>
<td>Steel plate</td>
<td>Resin</td>
</tr>
</tbody>
</table>

**Fig. 6** Evaluation of oil flow through bearing inside

**Fig. 7** Test result of oil flow
locations where they remain in contact with the inner ring large side rib surface (considered fully seated). The lower the number of bearing revolutions needed for the bearing to be fully seated means easier preload setting for the bearing.

**Fig. 9** schematically illustrates the test method used for investigating roller seating performance on the NTN extreme high load capacity tapered roller bearing, and **Fig. 10** graphically plots the test results for roller seating performance. The test result in **Fig. 10** shows that the rollers in the NTN extreme high load capacity tapered roller bearing fulfill settlement in about five revolutions while the rollers in the standard tapered roller bearing reaches settlement in about 13 revolutions. The reason the NTN extreme high load capacity tapered roller bearing achieves good roller settlement performance can be explained as follows:

**Fig. 11** provides schematic diagrams for situations where the rollers in both NTN extreme high load capacity tapered roller bearing and standard tapered roller bearing are in settled state.

On the NTN standard tapered roller bearing, the dimension of roller displacement is limited by the end face of inner ring small side rib. In this state, the cage remains in contact with the roller large diameter side end faces of rollers: consequently, as soon as break-in operation begins, working forces occur between associated components and generate a thrust that forces each roller toward the inner ring large side rib; thereby while this thrust continues to lift up the cage, the rollers shift toward the inner ring large side rib.

In contrast, on the NTN extreme capacity tapered roller bearing, the dimension of roller displacement is limited by the end face of cage pocket small diameter side. As soon as break-in operation begins, the rollers shift toward the inner ring large side rib by a distance equivalent to the distance between the rollers and cage pockets, causing them to come into contact with the cage pocket large side end faces; then like in a movement on the standard tapered roller bearing, the
rollers shift to the inner ring large side rib end face while lifting up the cage.

As described above, the dimension of roller displacement in the extreme high load capacity tapered roller bearing is greater owing to the structure of this bearing: at the earlier stage of break-in operation, the rollers alone, independent of the cage, shift toward inner ring large side rib; thereby the shift per revolution of the bearing is greater and the rollers will settle in a shorter time.

5. Compact, light-weight design technique for NTN extreme high load capacity tapered roller Bearing

Demands will continue to grow for improved fuel economy and riding comfort with automobiles, as well as higher engine power and greater number of transmission speeds. To help satisfy these demands, automotive bearings have to be capable of withstanding greater loads with no changes to the envelope dimensions, or feature compact size and lighter weight with a given load bearing capacity. In this paper, Table 2 below summarizes technical data for studies into compact size, lighter weight design for a same set of a given load bearing capacity and a given shaft diameter. Because a compact size, lighter weight design helps a tapered roller bearing to achieve lower running torque, this paper includes the facts about the bearing torque reduction with the NTN extreme high load capacity tapered roller bearing: Table 3 summarizes the parameters adopted for calculating the running torque of bearing samples.

The high load capacity tapered roller bearing boasts 16.2% reduction in bearing weight and 2% reduction in running torque.

Adoption of the NTN extreme high load capacity design helps achieve 25.3% reduction in bearing weight and 7.5% reduction in running torque. Thus this tapered roller bearing technology contributes to the goal of reduced size (more compact), lighter weight, and reduced torque.

Table 3 Calculation condition of rotating torque

<table>
<thead>
<tr>
<th></th>
<th>Radial load $F_r$</th>
<th>Axial load $F_a$</th>
<th>Bearing speed $1L$</th>
<th>Lubrication</th>
<th>Lubricating oil temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5000N</td>
<td>5000N</td>
<td>5000min$^{-1}$</td>
<td>ATF</td>
<td>90˚C</td>
</tr>
</tbody>
</table>

Table 2 Study of down sizing under same load capacity

<table>
<thead>
<tr>
<th></th>
<th>Standard tapered roller bearing</th>
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<tbody>
<tr>
<td>Load rating</td>
<td>Basic dynamic load rating $C_r$ = 31.5kN</td>
<td>Basic static load rating $C_0r$ = 34.0kN</td>
<td></td>
</tr>
<tr>
<td>Bearing size</td>
<td>$ϕ.25 × ϕ.52 × 16.25$</td>
<td>$ϕ.25 × ϕ.49.3 × 15.4$</td>
<td>$ϕ.25 × ϕ.49 × 15$</td>
</tr>
<tr>
<td>Bearing mass (reduction in comparison with standard tapered roller bearing)</td>
<td>0.154kg</td>
<td>0.129kg (16.2% reduction)</td>
<td>0.115kg (25.3% reduction)</td>
</tr>
<tr>
<td>Calculation result for running torque (reduction in comparison with standard tapered roller bearing)</td>
<td>0.293Nm</td>
<td>0.287Nm (2.0% reduction)</td>
<td>0.271Nm (7.5% reduction)</td>
</tr>
</tbody>
</table>

Schematic view

*Does not include stirring resistance on lubricating oil.*
6. About special cage structure

By adoption of toothed lock structure on the large diameter side and narrower rib on the small diameter side on the cage of the NTN extreme high load capacity tapered roller bearing, the length of rollers can be maximized. The shape of this cage is very unique, and the cage cannot be shaped with steel plate; therefore, it is made of a resin. Information about the resin used for this purpose and mechanical study about the special cage structure are hereunder discussed.

(1) Resin material

Lubricating oil in a transmission and/or differential sometimes contains phosphorus or sulfur content as extreme pressure additive which are known to be detrimental to some resin materials. Therefore, the resin material for the cage needs to be resistant against oils containing these additives.

When considering ease of assembly into bearing and durability in bearing, each needed for a material of tapered roller bearing cage, the resin material of the cage also needs to have excellent physical properties including mechanical strength, toughness and heat resistance. Beginning with these considerations, NTN has performed a necessary research and has successfully developed a PPS (polyphenylene sulfide) resin cage that features physical properties needed for the cage on the NTN extreme high load capacity tapered roller bearing.

Fig. 12 graphically plots the results of oil resistance test with various resin cage materials. The PPS resin does not exhibit deterioration in tensile breaking strength even after undergoing immersion for 2,000 hours: it is apparent that this resin material has sufficiently high oil resistance performance.

If our extreme high load capacity tapered roller bearing is used in a lubricating oil that does not contain a lot of phosphorus or sulfur content, it is possible to adopt PA46 (polyamide 46) or PA66 (polyamide 66) each often used as a resin material for a bearing cage.

(2) Dynamic analysis of extreme high load capacity cage

We have attempted to determine the mechanical strength needed for the cage small diameter side rib that is a unique feature of the cage for the NTN extreme high load capacity tapered roller bearing, and have found a minimum necessary rib width. To be able to determine the stress occurring on the cage in the running bearing, we have used an NTN-developed 3D dynamic analysis tool for tapered roller bearings.

Fig. 13 shows one typical example of model for dynamic analysis of tapered roller bearing. This diagram shows that the largest stress occurs at the small diameter side rib among various areas on the cage. In designing the small diameter side rib on the cage, we have determined the size of rib that has necessary mechanical strength by reflecting the findings obtained from the dynamic analysis.
7. Conclusion

As the challenge to prevent global warming and improve air quality continues, people committed to automotive technologies have been more strenuously involved in improving fuel economy. Thus, demand for smaller, lower torque, longer-life automotive bearings will continue to increase.

This paper has presented information about the “NTN extreme high load capacity tapered roller bearing” that boasts compact size, lighter weight and higher rigidity by reflecting novel bearing design techniques—“maximized roller length” and “adoption of newly developed resin cage”—in the NTN high load capacity tapered roller bearing that has been already running on actual automobiles.

By remaining committed to development of bearing technologies and products, NTN will further cope with increasingly demanding operating conditions and diversifying structures where NTN bearing products will be used.

References
1) Website of Ministry of Land, Infrastructure, Transport and Tourism
   http://www.mlit.go.jp/kisha/kisha07/09/090702_.htm

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