Introduction of Technology for Robot Reduction Gear Bearings

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In recent years, the decrease in the working population emerged as an issue, and there are concerns regarding the impact on product quality due to a decline in skilled workers. Industrial robots are becoming more widespread with the aim of improving productivity through IoT-centered digitization, big data, and AI. This paper will introduce the bearings JTEKT is developing for adoption in precision reduction gears of various robots, as well as their associated technologies.

Key Words*: precision reduction gears, industrial robots, long life, rotational accuracy, high rigidity, ultra-thin*

1. Introduction

Recently, the shrinking working population has become a social issue with particular concern about the impact on product quality due to fewer skilled workers. In response, industrial robots are becoming increasingly common for improving productivity through digitization using IoT, big data, AI, and other technologies. Industrial robots are typically used in fields such as welding, painting, assembly, and transportation. Each joint of these robots uses position control motors and precision reduction gears.

Generally, there are two types of precision reduction gears used in industrial robots: strain wave gears, which are mainly used in small and medium-sized robots, and two-stage reduction gears, which are used in large robots.

This paper presents the performance requirements for robot reduction gears and the technology of the bearings that are used.

2. Required Performance for Robot Reduction Gears

The required performance for the robot and the reduction gears are shown in **Table 1**.

Table 1 Required performance of robots and reduction gears

Robot requirements	Required performance for reduction gears
Maintenance-free	Long life (longer maintenance periods)
Accurate operation	High positioning accuracy
Space-saving design (Compact size)	Compact size
	Reduction gear ratio
Energy-saving design	High efficiency

Reduction gears must have the long life and high positioning accuracy shown in **Table 1**. Also, customers are requesting the use of fewer reduction gears by using a high reduction ratio and smaller sizes for the reduction gear itself for designing more compact (space-saving) robots.

There are also various requirements for the bearings used in the reduction gears. Starting from **Section 3**, this paper describes the required bearing performance for meeting the performance requirements of strain wave gears.

3. Strain Wave Gears

3. 1 Structure of Strain Wave Gears

A cross-sectional view of a strain wave gear unit is shown in **Fig. 1**, and the structure of the strain wave gear is shown in **Fig. 2**.

The strain wave gear consists of a circular spline (internal gear), a flex spline (external gear), and a wave generator (an ultra-thin ball bearing embedded in an elliptical camshaft) that is press-fitted into the flex spline. The number of teeth on the internal gears of the circular spline is several more than the number of teeth on the external gears of the flex spline, and these gears mesh with the circular spline at the major diameter of the elliptically-deformed flex spline[1)].

The deceleration mechanism of the strain wave gear is shown in **Fig. 3**. Generally, when the camshaft, which is the input shaft, rotates by one revolution, the flex spline, which is the output shaft, rotates in the opposite direction of the camshaft by the difference in the number of teeth. This is the output rotational speed[2)].

The ball bearings used in the wave generator are ultra-thin ball bearings that have bearing rings that are even thinner than the conventional thin bearings of the 68 series. The inner ring is deformed from a perfect circle to an ellipse when it is press fitted into an elliptical-shaped camshaft. The ball is used to deform the outer ring to match the elliptical shape of the inner ring. The inner ring is used at the input rotational speed, while the outer ring is used at the output rotational speed synchronized with the flex spline. Consequently, the inner ring press-fitted to the camshaft always has the same position on the inner ring circumference for the major and minor diameters, while the position of the major and minor diameters on the outer ring circumference varies depending on the speed difference between the input and output rotations.

Also, bearings with high rigidity and high loading capacity, such as crossed roller bearings, are often used as the main bearings for the output shaft to support external loads and moments.

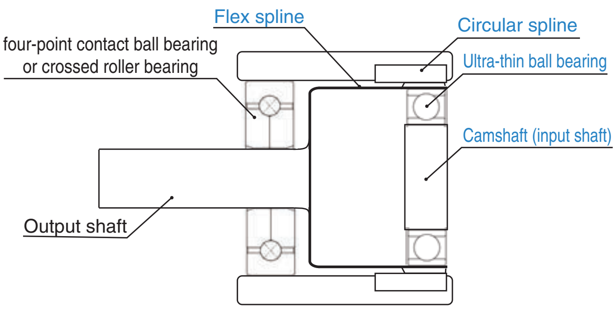


Fig. 1 Strain wave gear unit

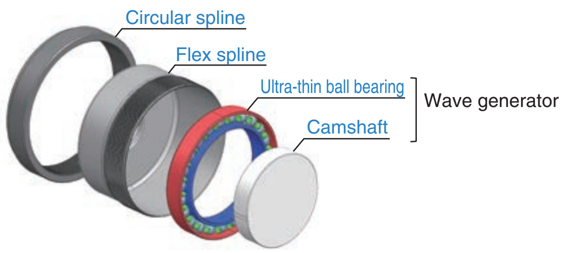


Fig. 2 Structure of strain wave gearing

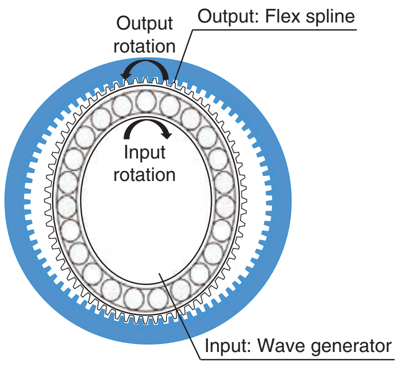


Fig. 3 Deceleration mechanism of strain wave gearing

3. 2 Performance Requirements for Ultra-thin Ball Bearings

The required performance for reduction gears and bearings are shown in **Table 2**.

Table 2 Required performance of reduction gears and bearings

Required performance for reduction gears	Required performance for ultra-thin ball bearings
Long life (longer maintenance periods), Compact size	High loading capacity
	High strength (when elliptically deformed for inner and outer rings)
High positioning accuracy High efficiency	Deformation matching of inner ring when camshaft is inserted Deformation matching of outer ring when camshaft is rotated
	Low dimensional change (outer ring major diameter when rotating)

In order to extend the service life and reduce the size of reduction gears, the loading capacity of the bearings must be increased. Also, because the bearing ring deforms to an elliptical shape, the inner ring must have strength against elliptical deformation caused by the camshaft, and the outer ring must have endurance strength against repeated deformation between the major and minor diameters.

Since the dimensional change of the outer ring affects the gear engagement with the circular spline through the flex spline, the dimensional change of the outer ring major diameter during rotation must be reduced in order to improve the positioning accuracy.

In addition, by smoothly matching the outer ring with the deformation, the rotational resistance of the balls is reduced for allowing deceleration without loss, resulting in higher efficiency.

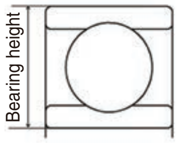
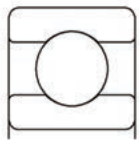
3. 2. 1 Design Specifications for Ultra-thin Ball Bearings

The design specifications for the bearings are shown in **Table 3**.

3. 2. 2 High Loading Capacity Design[3)]

The load is applied to the bearing from the two opposing major diameter locations where the flex spline and circular spline gears engage. By using machining, heat treatment, and assembly technologies for ultra-thin ball bearings, we were able to increase the capacity of the bearing by increasing the ball diameter and the number of balls compared to the same cross-sectional area of the 68 series. Compared to the 6805 equivalent bearing, the bearing capacity was successfully improved by a factor of 1.5 by increasing the number of balls from 50% to 75% of the raceway circumference.

Table 3 Design specifications for ultra-thin ball bearings*1

	Ultra-thin ball bearing (developed product)	68 series ball bearing (general-purpose product)
Bearing cross-section		
Cross-sectional ratio (ball diameter/bearing height)	1.2	1
Bearing ring thickness ratio	0.6	1
Ball count ratio	1.3	1
Loading capacity ratio	1.5	1

*1 Ratio based on the current 68 series product as 1.

3. 2. 3 High Strength Design

The outer ring is repeatedly pulled and compressed by the rotation of the elliptical camshaft. An example of analysis of the stresses occurring in the outer ring is shown in **Fig. 4**.

Fig. 4 Analysis example of outer ring strength (typical example)

The maximum tensile stress and maximum compressive stress occur in the bore diameter of the outer ring and the outside diameter of the inner ring at a 90° offset position. This is the weakest part where breakage can occur.

In this bearing, a special heat treatment was used for the outer ring to enable improved repeat tensile strength and flexural strength, and the safety factor against repeated fatigue was greatly improved compared to the conventional heat-treated bearing. Compared to the 6805 equivalent bearing, the special heat treatment was able to improve the safety factor by 1.3 times.

3. 2. 4 Deformation Matching and Low Dimensional Change

As mentioned earlier in **Section 3.2**, the positioning accuracy of a reduction gear must have characteristics where the outer ring can deform into the same elliptical shape as the camshaft when the camshaft is inserted into the inner ring (deformation matching characteristic) and have characteristics of low dimensional change in the major diameter during rotation. As shown in **Table 4**, the bearing ring thickness and the number of balls were optimized in the design to improve matching to the elliptical shape and enable less dimensional change in the major diameter.

Table 4 Positioning accuracy improvement design

Bearing requirements	Bearing design
Smooth deformation matching for outer ring	Ultra-thin bearing ring
Low dimensional change of outer ring major diameter	Minimizing multi-angular deformation due to large number of balls
	Minimizing change in raceway and ball elastic deformation due to odd number of balls (**Fig. 5**)

3. 3 Performance Requirements for Output Shaft Main Bearings

The required performance for the reduction gear and the output shaft main bearing are shown in **Table 5**.

The main bearing supports a high moment load from the output shaft. In order for the reduction gear to maintain high positioning accuracy, the output shaft tilt must be suppressed even when it is subjected to forces that generate a moment. For this reason, the bearing must

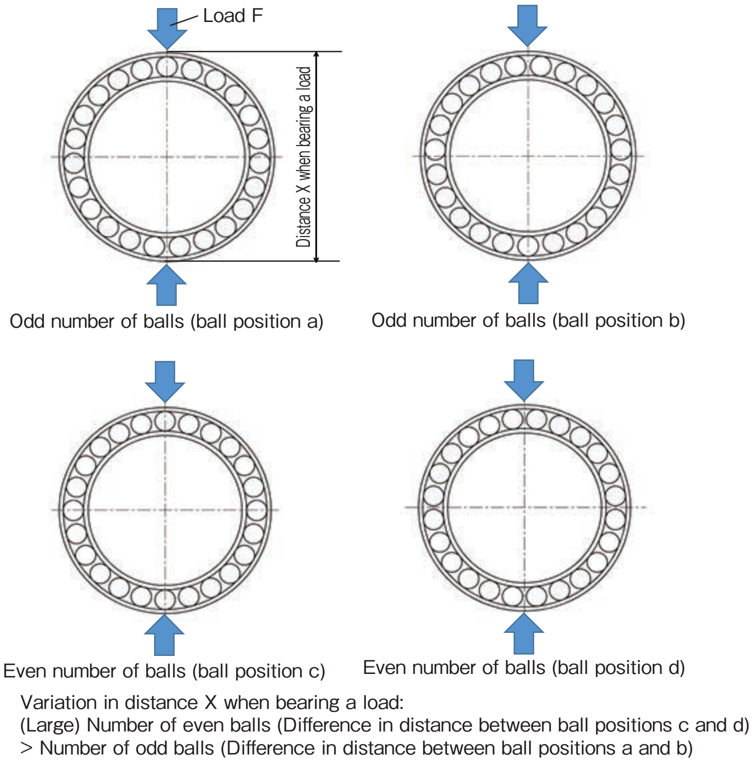


Fig. 5 Amount of change in trajectory and ball elastic displacement depending on the number of balls

have high rigidity even when subjected to forces with a high moment.

Table 5 Required performance of reducer and main bearing

Required performance for reduction gears	Required performance for output shaft main bearing
High rigidity of output shaft (High positioning accuracy)	High rigidity

Crossed roller bearings are primarily used for this main bearing, but because it is difficult to manufacture crossed roller bearings in the small-size range, four-point contact ball bearings are often used.

3. 3. 1 Design Specifications for Four-point Contact Ball Bearings

The design specifications for four-point contact ball bearings are shown in **Table 6** and **Fig. 6**. To increase the rigidity of the four-point contact ball bearing, the number of balls was increased by eliminating the cage and dividing the inner ring into two parts for enabling a larger contact angle. As a result, the moment rigidity was improved by a factor of 1.8 compared to conventional bearings with cages.

Table 6 Design specifications for four-point contact ball bearings*1

	Strain wave gear	Conventional gear design
Ball count ratio	1.7	1
Moment rigidity ratio	1.8	1

*1 Ratio based on the conventional design gear as 1.

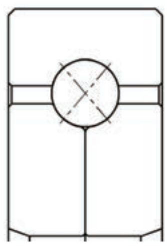


Fig. 6 Structure of four-point contact ball bearings

4. Conclusion

Not only in Japan, but also all over the world, industrial robots are becoming more advanced and being used for a wider array of applications. A variety of needs are expected to emerge for the reduction gears used in these robots. We will strive to further improve the technology presented in this paper for developing bearings to contribute to even better reduction gear performance.

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