HIGH PERFORMANCE ZERO-BACKLASH SPEED REDUCERS
(ROLLER DRIVE)

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Abstract
Since the accuracy of industrial applications are becoming a big issue in the industry, the high performance speed reducers are immense necessary part for the industrial applications such as multi-axis machining centers, robots, special purpose machines and etc. These speed reducers are yet in the developing stage. In this report, a speed reducer driven by roller gear cam mechanism is introduced and the characteristics of that are discussed by comparing them with the characteristics of worm gear mechanism and direct drive mechanism. As the characteristics, the positioning accuracy and repeatability, rotational fluctuations and influence of unbalance mass on motion are presented. Furthermore, two case studies are discussed.

Key words: Roller gear cam, Accuracy, Speed reducers, Worm gear, Direct drive

1. Introduction
In the present, most of the manufactures are using multi-axis machining centers [1], robots, and etc to fulfill the demand of productivity and also retarding the cry of accuracy of the products. The product accuracy mainly depends on the motion accuracy of the units such as speed reducers, linear guide ways and etc, which used to assemble the machine tools, robots and etc. In this paper high performance speed reducers for multi-axis machines, robots and etc are discussed. This type of speed reducers are yet in the developing stage. The accessory manufacturers pay their fullest effort to introduce high performance speed reducers to machine tool industry, robot industry and etc. When concerning the rotary axis, there are number of features [2,3] such as, backlash, rotational fluctuation, positioning accuracy and repeatability, and etc affect on the motion accuracy.

This paper explains about the configuration of rotary table driven by roller gear cam mechanism [4] and why it shows the better performances. Furthermore, the performances of the rotary table driven by roller gear cam mechanism are discussed by comparing them with the performances of the rotary table driven by worm gear mechanism and direct drive mechanism. Furthermore two case studies are discussed.

2. Structure of rotary table driven by roller drive
2.1 Roller drive mechanism
The roller drive mechanism, from the point of view of power transferring, is not different from their more conventional counterparts. However, in many ways the similarities end there. It is there specific differences that give this mechanism its unique advantages for industrial applications.

The roller drive mechanism is a very special mechanism which consists of globoidal cam and roller gear as depicted in Fig.1. The roller gear consists of number of cam followers which are fixed at equal spacing around the turret as shown in the figure. These cam followers, as depicted in Fig.2, capable of rotating about its own axis as needle bearing and hence provide the smooth rolling contact. The globoidal cam has a very unique cam profile which provides a smooth path for cam followers. As a combination, this reduces the rotational fluctuation in the motion. The most important feature of this mechanism is that backlash is avoided within the mechanism by applying preload at the assembly level as illustrated in Fig.3. As well this elevates the value of speed reducer by providing high stiffness, high torque, high speed values compared to other available speed reducers, and low ware and maintenance. Furthermore, compact size compared to other available driving systems is providing flexibility for industrial machine manufactures to find optimal configurations of their machines.

2.2 Cross roller bearing
It is very important to support the rotating parts and driving
mechanism with high rigidity to achieve high accuracy. Therefore in the rotary table driven by roller gear cam which manufactured by Sankyo Seisakusho Co.,[4], the cross roller bearings fill the gap between fixed and rotating parts of the rotary table as depicted in Fig.1. The important feature is that this bearing guide way is machined in the same turret which is used as roller gear and thus it reduces the misalignment errors. Typical misalignment error range is around ±0.01 mm. However, by using this technique it can be reduced to 0.001~0.002 mm range and leads to design smaller sizes. These cross roller bearings increase moment stiffness as well as bear the high axial and radial loads.

3. Available sizes
Rotary tables with roller gear cam are available in a wide range of sizes, with diameters from smaller than 100 mm to greater than 1500 mm and also different types such as single rotary axis, rotary table with tilting axis, customize products, etc as depicted in Fig.4. This enables the machine designers a wide range of rotary table sizes and types to satisfy the requirements of the given application.

4. Measured characteristics
In order to evaluate the systems, the characteristics of rotary table driven by roller drive and another same size conventional rotary table driven by worm gear and direct drive motor were measured. The experiment setup consists of four units that are table with rotary encoder, servo motor, servo amplifier, and personal computer with DSP board. A high resolution encoder (0.001°) was used in order to reduce the measurement errors which directly affect to the performance of rotary table. For the tables except the table with direct drive motor, the feed back units, motor, amplifier, and controller were set same to avoid any interference to the measuring data.

4.1 Positioning accuracy and repeatability
The positioning accuracy and repeatability is an immense necessary test for moving parts of machine tool industry. This test is explained in ISO 230-2 standard [5] for machine tools. According to the standard, test was carried out and the mean reversal value (B̅), repeatability of positioning (R̅) and accuracy (A) were calculated. The calculated values are given in Table 1 and illustrated in Fig. 5. The mean reversal value gives an indication of backlash and hysteresis loss. As illustrated, the table driven by worm gear shows very large backlash value. According to the Table the rotary table driven by roller drive shows relatively higher performance than the rotary table driven by worm gear and direct drive motor.

4.3 Rotational fluctuations
The rotational fluctuations which categorized as systematic deviation in the mechanism causes due to pitch error of
Table 1. Summary of results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Worm gear</th>
<th>Direct drive</th>
<th>Roller gear cam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Semi-closed</td>
<td>Full-closed</td>
<td>Semi-closed</td>
</tr>
<tr>
<td>Positioning accuracy</td>
<td>12.8</td>
<td>7.25</td>
<td>6.65</td>
</tr>
<tr>
<td>(arc second)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repeatability of positioning R</td>
<td>34.3</td>
<td>13.6</td>
<td>3.01</td>
</tr>
<tr>
<td>Accuracy A</td>
<td>38.6</td>
<td>1.39</td>
<td>3.26</td>
</tr>
<tr>
<td>Rotational fluctuation</td>
<td>exist</td>
<td>exist</td>
<td>Comparatively small</td>
</tr>
<tr>
<td>Influence of unbalance mass</td>
<td>Influenced</td>
<td>Influenced</td>
<td>nil</td>
</tr>
<tr>
<td>Backlash</td>
<td>exist</td>
<td>nil</td>
<td>nil</td>
</tr>
</tbody>
</table>

Fig. 9 Micro-milling machine with tilting rotary table

(a) machining of corn-frustum
(b) setup of work-piece

Fig. 10 Machining of corn-frustum

Fig. 11 Roundness of corn frustum

4.4 Influence of unbalance mass

Rotary table uses in the machine tool at varies configurations such as horizontal, vertical or inclined under fluctuating loads. Therefore a test was designed to identify the effect of position of rotary tables on motion by getting in to consideration of gravitational force acting on work. The experimental setup is depicted in Fig. 7. The measured results are illustrated in Fig. 8. According to the figure, table with worm gear drive shows a step like deviation, while the rotary table driven by direct drive motor shows a sine variation. The influence on roller drive is comparatively small.

5. Summary of Results

The results can be summarized as in Table 1. According to the table, it can be said that the performances of rotary table driven by roller drive are significantly good and therefore it can be said that the rotary table with roller gear cam mechanism elevates the accuracy level of the industrial applications.

6. Case studies and customer applications

Probably the best way to illustrate the performances of rotary table driven by roller gear cam in industrial applications is to show some real-world examples of their successful implementations. Therefore two case studies are discussed in this paper.

6.1 Case study 1 - Precision five-axis milling machine (Courtesy of Mitsubishi Heavy Industries Ltd. Japan)

High precision micro-milling machines are necessary for machining precision moulds, and etc. As explained...
throughout the paper, to build these machines, high precision rotary table is an immense necessary part. Fig.9 shows a micro-milling machine (μV1-5X) with tilting rotary table in which both rotary axes are driven by roller gear cam mechanism. The working table diameter is 100mm. Trunnion axis can be controlled within 130deg range in 75 min⁻¹ speed. Work table can be controlled within 360deg in 100 min⁻¹ speed.

The machining test that employs a corn-frustum specified by NAS 979 standard [6] and positioning accuracy and repeatability test which is specified in ISO 230-2 [5] were conducted to illustrate the performance of the machine. Fig.10 shows the setup of work-piece for machining of corn-frustum. Table 2 shows the conditions that used in the cutting test. Table 3 shows the results of positioning accuracy and repeatability test. Fig.11 shows the results of corn-frustum test. As according to results it can be said that the accuracy level of the machine is significantly high.

6.2 Case study II - Precision tilting rotary table
(Report from Tsutsumi lab – Tokyo University of Agriculture and Technology - Japan)

Tilting rotary table supported by both sides is measured by means of ball bar device. Trunnion axis and the vertical axis of this table are driven by roller drive mechanism. Fig. 12 and 14 shows the ball bar setting for three-axis simultaneous motion carried out on C-axis (vertical) and A-axis (trunnion) respectively. Fig. 13 and 15 shows the measurement results. One division of polar plot is 2μm. The circularity values which are extracted according to ASME B5.54 – 1992 standard are given with the results. These results include the simultaneous two-axis linear interpolation deviations which illustrated in Fig.13(c). Fig.15(c) shows the measurement result of only C-axis motion. The circularity value is 1.6μm. One of the main problems of this type of tables is that with trunnion axis rotation the center of the work table is moving in the direction of trunnion axis due to the unpredictable saddle motion which caused by many reasons. This can be measured by means of trunnion axis (A-axis) axial direction measurement. It is very clear that this deviation is within 2.8μm as illustrated in Fig. 15(b).

Reference

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