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Prototype and Evaluation of Performance for Pivot Bearings with Multiple Degrees of Freedom*

Shoji NOGUCHI*1, Tohru KANADA*2, Masakazu OHNUKI*2 and Fumika SUZUKI*2

This paper deals with the prototypes of new pivot bearings having multiple degrees of freedom. The idea of the pivot bearing is based on a constant velocity joint (CVJ). First, two types of the pivot bearings with 2 degrees of freedom (DOF) are designed and produced. Their design and some static specifications are described. Then, applying the pivot bearing with 2 DOF, three types of the pivot bearings with 3 DOF are prototyped. A full complement ball bearing mechanism is used in order to make smooth motion and downsizing is also aimed. Furthermore, process accuracy of the elements is examined.

Keywords: pivot bearing, prototype, 2 DOF, 3DOF, performance, accuracy.

1. Introduction

The possibility of a parallel mechanism for a new driving mechanism as shown in **Fig. 1** is increasing in the area of machine tools [1]. The parallel mechanism controls the attitude or movement of a tool and a stage by expanding or contracting several links. Alongside of the conventional mechanism, which is constructed by a combination of several linear motions, high speed, high stiffness and high precision positioning can be achieved by the parallel mechanism [2], [3]. In order to realize such a performance, the most important thing is to develop the supporting element (bearing).

High stiffness, high accuracy, wide swinging angle and low torque are expected for such a supporting element. To realize multiple degrees of freedom for the swinging movement, ball joint or spherical sliding bearing has been applied so far. Furthermore, the combination of rolling bearings such as a universal joint has also been applied in the case in which a sufficient setting space can be secured. However, due to the clearance gap in the ball joint and spherical bearing, stiffness and swinging accuracy are unsatisfactory. Moreover, in the combined mechanism of rolling bearings, stiffness markedly decreases as the size of the rolling bearing decreases.

To solve these problems, a multi-degree-of-freedom bearing has been developed [4], [5]. In such a bearing, a swinging element (referred to as a sun ball) is circumscribed by several rolling elements (referred to as planetary balls) and its stiffness is upgraded by adding a preload. However, the movement of the sun ball may be locked by the position of the ball cage, which is for rolling elements. Therefore, structural problem is unsolvable. The scope of this research is to develop a practical pivot bearing with multiple degrees of freedom.

2. Design of pivot bearing with 2 DOF

2.1 Design of mechanism

The following requirements were set for the prototype.

(1) The mechanism can restrain the motion of the ball cage (including the rolling element).

(2) The tensile stiffness and the compressive one are almost the same.

In consideration of the above conditions, prototype of the pivot bearing with 2 degrees of freedom (DOF) was designed.

A simplified mechanism of the constant velocity joint (CVJ) as shown in **Fig. 2** is considered to design a prototype. When the two parts, which have some circular-arced grooves, are brought together upon contact with balls, the rotation motion can be carried in constant velocity between the two noncoaxial axes. Originally, it is used for transmission of uniform motion. If one part is fixed, the other part can swing in 2 DOF. The balls are rolling with differential slip motion in time of swinging.

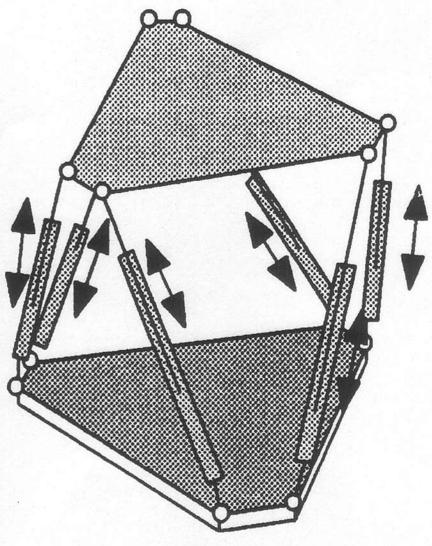

Fig. 1 Example of parallel link mechanism

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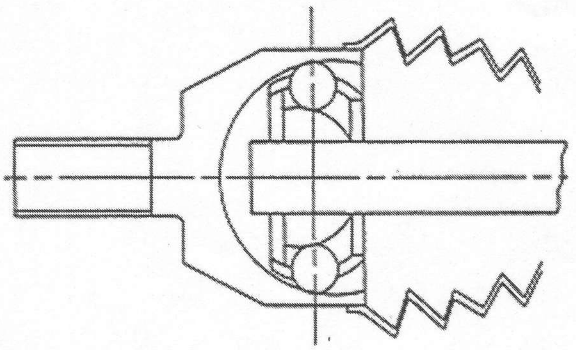


Fig. 2 Example of constant velocity joint (CVJ)

By applying this mechanism, the swinging motion with 2 DOF can be realized with restriction on the rolling direction of balls.

However, if the CVJ is not modified, it cannot be a bearing. Then, the following views are checked in the design procedure.

(1) If the balls are monostichous, the fixing of the position of rolling element and loading of the axial force can not be guaranteed. Therefore, the balls are drawn up in two lines and the rolling element is interleaved between the two-lined balls.

(2) If the balls are drawn up in two lines and both parts have concave grooves, the swinging motion is not realized. Then, concave groove is worked on one part, and the surface of other part is convex.

(3) Considering (1) and (2), if the housing is integrated with such a mechanism, it is hard to assemble. Thus, the housing should be separated into two bodies. Herewith, a preload becomes possible within the bearing structure.

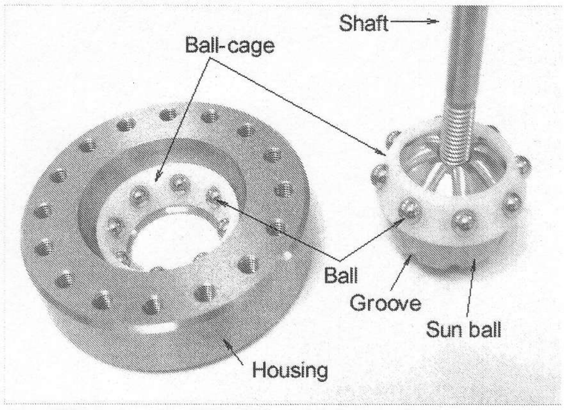
(4) To hinder free movement of the balls, ball cage, the same as that used in a rolling bearing is fixed between the sun ball and the housing.

Specifications of the bearing are described later and **Fig. 3** shows the structures of the pivot bearing with 2 DOF. One structure has eight grooves in the rolling element and the other has eight grooves in the housing.

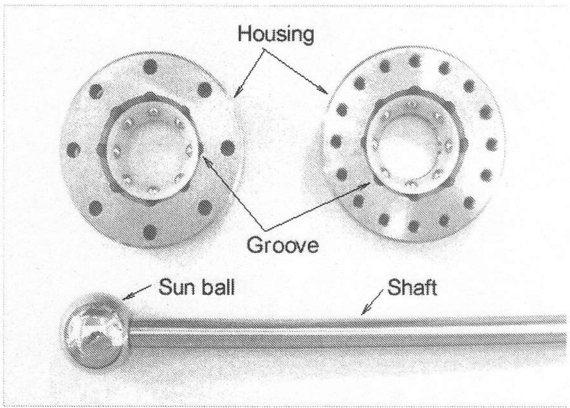
2.2 Stiffness design

Although dynamic stiffness should be investigated in the application to the parallel mechanism, the calculations of axial displacement and contact surface pressure should be performed as static stiffness is important in practical use. Under the assumption that the material is bearing steel, the attributes of bearing steel are used, such as the modulus of longitudinal elasticity (Young's modulus) and Poisson's ratio. The same design method as the rolling bearing can be applied directly to the structure [6]. So, the calculation of contact surface pressure and stiffness is simple.

The axial stiffness of the prototype pivot bearing is assumed to be 100N/μm. Furthermore, considering the accuracy, the availability of sphere balls and the workability of the bearing, the specifications of the prototype pivot bearing was determined as shown in **Table 1**.



(a) When sun ball (swinging element) has grooves



(b) When housings have grooves

Fig. 3 Prototype of pivot bearing with 2 DOF

Table 1 Specifications of pivot bearing with 2 DOF

Dimension	ϕ 60mm, height 30mm
Angle of swing	-25 degree to +25 degree
Diameter of sun ball	25.4mm (1")
Diameter of swinging shaft	10mm
Diameter of rolling element (ball)	4.7625mm (3/16")
Diameter of concave curvature	34.925mm
Disposition of balls	8 balls every 45degrees
Arrangement of balls in orthogonal direction to disposition of balls	2 (contact angle to –30 degrees to +30 degrees)
Diameter of groove	5mm (depth 1mm), by the design basis for a deep-groove ball bearing

2.3 Design of ball cage

The ball cage was made of engineering plastics. It has laddered pocket holes along a thin-walled taper with a diameter of 5.5mm, which is larger than that of installed balls. The prototype bearing is the same as a rolling bearing with a rotating inner ring, considering the cross section of the swinging direction. Letting the rotating angle measure of the swinging element be 1, the orbital angle measure of the rolling element is as small as 0.4. Then, the movement of the rolling element becomes relatively small.

The prototype bearing with grooves in the housing, had no problems, but the other one with grooves in the swinging element was different. That is, the rolling elements were positioned in a direction different to the swinging direction and pressed against the ball cage. Thus, if the pocket hole was narrow, the ball cage tended to move in the same motion angle as the swinging element. Therefore, the shape of the pocket hole became that of a landscape as shown in **Fig. 4**.

3. Prototype and evaluation of bearing with 2 DOF

3.1 Techniques for working process and assembly of bearing

The most important factor in the swinging performance is the working process of the grooves for the rolling elements (balls). The dimension and accuracy of the groove influence the capability of assembly and dynamic performance. In the prototype of this research, a ball-end mill with a diameter of 5mm was used to make the grooves by a three-dimensional CNC milling process. Since grinding was not performed, the surface roughness and form accuracy were not sufficient. However, in investigating the capability of swinging, it was considered that the ball-end milling was sufficient.

Techniques for assembly and adjustment of bearing were performed in the following procedure.

(1) Preparing the rolling elements (balls) having slightly different diameters (from −10μm to +10μm at integrals of 2μm, on the basis of a reference diameter).

(2) Choosing adequate balls in order to preload lightly and not to form a clearance in the bearing.

(3) Tightening up the screws for coupling the upper and lower housings with constant torque.

Thus, the accuracy of the groove dimensions should be within the limits of −10μm to +10μm .

3.2 Measurement of torque for swinging

Torque required for swinging was examined quantitatively. The torque could be calculated by measuring the force loaded on the swinging shaft. The absolute magnitude of torque cannot be argued due to the measuring technique applied here, but it can be said that the oscillation of torque to swing was within +0.7Nm to −0.7Nm.

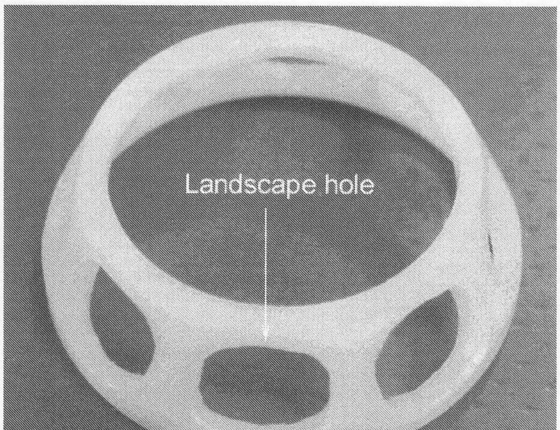


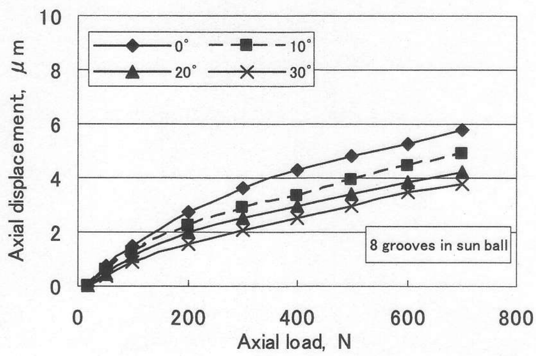
Fig. 4 Ball cage with landscape holes

3.3 Experimental verification of stiffness

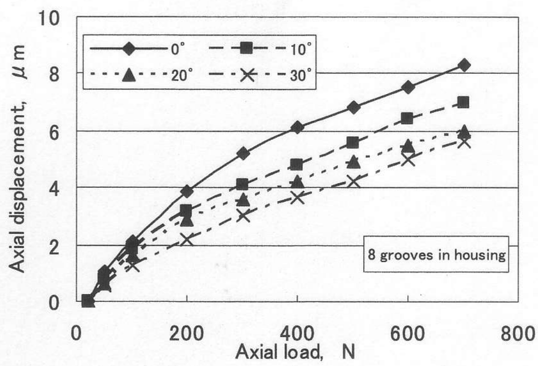
In order to investigate the stiffness of the bearing, with keeping the swinging shaft vertical, the housing was declined by 0, 10, 20 and 30 degrees. Then, when the axial force was loaded to the shaft, the axial displacement was measured using a displacement sensor. The declinations of housing were given by purpose-built pedestals, which had predefined angles.

Fig.5 shows the relationship between axial load and displacement. By increasing the declination, the axial displacement becomes smaller and the stiffness becomes larger. This reason is believed as follows. The axial displacement, δ_a of the bearing is expressed by δ / sinα. Here, δ is a displacement on the direction of the rolling element and α, declination angle. If the housing is allocated horizontally, the force is distributed uniformly. However, when the housing is declined, the rolling elements tend to move. Then, the contact angles of the rolling elements to the loading direction (vertical) differ from each other and the axial displacement, which comes under the influence of the contact angle and the partial charging force, also differs. The angle of declination increases with increasing ratio of magnitude for the partial charging force. This is because the contact angle becomes larger.

Hence, in the stiffness design, the lowest stiffness is



(a) When sun ball (swinging element) has grooves



(b) When housings have grooves

Fig. 5 Relationship between axial load and displacement